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Abstract: In this work, case of rotations transformation between arbitrary crossed shafts (axes of rotations) by means of high kinematic joints, which elements configure active tooth surfaces of hyperboloid gear mechanisms is treated. Analytical dependencies, defining the law of transformations are illustrated. This law of transformation in this concrete case is a constant function of the relations of the angular velocities of the movable links of the spatial three-link gear mechanism. The shown functions are applicable both to the synthesis of the studied transmissions, and for the determining and control of the kinematic errors of these transmissions, caused by manufacturing and assembly errors.

Keywords: SPATIAL GEARING, HYPERBOLOID GEAR DRIVES, INSTANTANEOUS TANGENTIAL CONTACT, INSTANTANEOUS ANGULAR VELOCITY RATIO

1. Introduction

The Science of Spatial Gearing, that studies the processes of rotations transformation upon a preliminary defined law between non-coplanar (in the most common case) axes by means of three-links mechanisms, having high kinematic joints, essentially can be considered as an independent direction of the science Applied Mechanics. It studies kinematic and dynamic behavior of these body systems, in relation to the geometric characteristics of the elements of the constituting high kinematic joints.

Three-links mechanisms, for which the transformation of rotations between non-coplanar axes is accomplished through a system of high kinematic joints, which elements come into and go out of tangent contact (instantaneous contact), by observing a definite law of order, are named hyperboloid gear mechanisms. This name is derived from the fact that their axoids are two revolution hyperboloids, which geometric axes coincide with the axes of rotations of the movable links of the three-links gear mechanism. For them the transformations is realized as a result of the action of normal forces in the places of tangent contact of the elements of the kinematic joints. The process of sequential occurrence and disintegration of kinematic joints is a permanent and regular one, and during its realization over time there should be more than one configured kinematic joint. The state in which kinematic joints exist is called gearing. For gear sets, when their axes of rotations do not lie in one plane, is talked about spatial gearing.

The main focus of the current research is put on defining of specific characteristics of the instantaneous contact of the elements of high kinematic joints, when the processes of the rotations transformation by means of hyperboloid gear mechanisms are realized.

2. Instantaneous Velocity Ratio in the Pitch Contact Point

The exactness of the realization of a preliminary given law of rotations transformation between shafts with crossed axes by means of three-links gear mechanism, is in a direct dependency on geometric and kinematic conjugation of the active tooth surfaces, which come in and go out of contact. In this process, every occurred instantaneous contact point (for gear mechanisms with a point contact) or instantaneous contact line (for gear transmissions with linear contact) is characterized by an instantaneous velocity ratio. The main requirement to the synthesis and design of gear mechanisms are that their instantaneous velocity ratio should correspond to a preliminary given design value, by observing an adequate exactness. Hence, the defining of the instantaneous velocity ratio, as a function of the geometric parameters of spatial gear sets, is of a great importance, especially for the kinematic types of gear mechanisms, when it is necessary to study their sensitivity, while these parameters are changing.

Main interest, from view point of the synthesis of spatial gear drives upon a pitch contact point, is to be defined the instantaneous velocity ratio when the instantaneous conjugated contact point, respectively the instantaneous conjugated line, passes through the pitch contact point. For this case it is necessary to define the instantaneous velocity ratio by means of the geometric parameters of the pitch contact point [1, 2].

Considering the symbols given in Fig. 1, for the instantaneous velocity ratio at one arbitrary contact point it can be written [3, 4]:

$$i_{12} = \frac{\omega_1}{\omega_2} = \frac{d_2}{d_1} = \frac{e_2 \sin \varepsilon_2}{e_1 \sin \varepsilon_1} \quad (1)$$

Fig. 1. Kinematic scheme for determining the instantaneous velocity ratio of a hyperboloid gear mechanism.
Here $\omega_i$ ($i = 1, 2$) are the magnitudes of the instantaneous angular velocities $\overrightarrow{\omega_i}$ and $\overrightarrow{\omega_2}$; $d_i$ ($i = 1, 2$) - minimal distance between the points of piercing $O_n$ ($i = 1, 2$) of the normal $n - n$ with planes $\Pi_i$ ($i = 1, 2$) and the rotations axes $i - i$ ($i = 1, 2$); $n - n$ is a normal line to the tooth surfaces $\Sigma_1$ and $\Sigma_2$ passing through the conjugated contact point $P$. The planes $\Pi_i$ ($i = 1, 2$) are perpendicular to the axis $O_1O_2$ of the crossed axes of rotations $1 - 1$ and $2 - 2$ and contain as well the corresponding crossed axes $i - i$ ($i = 1, 2$); $\epsilon_i$ ($i = 1, 2$) - minimal distances between $n - n$ and the crossed axes $i - i$; $\epsilon_i$ ($i = 1, 2$) - angles between the normal $n - n$ and the axes of rotation $i - i$ ($i = 1, 2$).

Here, it will be reminded that in general case, in order to realize rotations transformation between fixed crossed axes $i - i$ ($i = 1, 2$) by means of the conjugated contact point $P$ it is appropriate the instantaneous contact in it to be considered by means of two infinitely small regions from the surfaces $\Sigma_1$ and $\Sigma_2$, respectively. Actually, these regions have a relative motion, determined by the vector of the relative velocity $\overrightarrow{V}_{\Sigma_{i2}}$, which is a result of the rotation of $\Sigma_i$ ($i = 1, 2$) around axes $i - i$ ($i = 1, 2$) (see Fig. 1). The fact, that one of the surfaces $\Sigma_i$ ($i = 1, 2$) transmits motion to the other one, means that the $\overrightarrow{V}_{\Sigma_{i2}}$ lies in their common tangent plane $T_n$. If this condition is fulfilled, from it follows the equality of the normal components of the absolute velocities of $P$, considered as a point from $\Sigma_i$ ($i = 1, 2$) and vice versa. Both conditions are equivalent ones for the kinematically conjugated action in the point $P$, namely:

$$\overrightarrow{V}_{i,n} = \overrightarrow{V}_{2,n},$$

where $\overrightarrow{V}_{i,n}$ is a normal component of the absolute velocity $\overrightarrow{P}_i$ and of the circumferential velocity $\overrightarrow{V}_i$.

Let’s first show how equality (1) is obtained, from the condition (2), and taking into account Fig. 1:

- From $\overrightarrow{V}_{i,n} = \overrightarrow{V}_{2,n} \Rightarrow \overrightarrow{V}_{i,n} = \overrightarrow{V}_{2,n} \Rightarrow \omega_i d_i = \omega_2 d_2$ and

$$i \zeta = \frac{\omega_i}{\omega_2} = \frac{d_2}{d_1};$$

- From $\overrightarrow{V}_{i,n} = \overrightarrow{V}_{2,n} \Rightarrow V_{i,n}\sin \epsilon_i = V_{2,n}\sin \epsilon_2 \Rightarrow$

$$\omega_i \epsilon_i \sin \epsilon_i = \omega_2 \epsilon_2 \sin \epsilon_2$$

and

$$i \zeta = \frac{\omega_i}{\omega_2} = \frac{\epsilon_2}{\epsilon_1} \frac{\sin \epsilon_2}{\sin \epsilon_1}.$$

When taking into account the symbols, given in Fig. 1 and Fig. 2 (assuming that the conjugated contact point is a pitch contact point) then from (2) it can be written:

$$V_{i,n} = V_{i}\cos \beta_i \cos \alpha_i = \omega_i r_i \cos \beta_i \cos \alpha_i,$$

where $V_i$ is the magnitude of the circumferential velocity $\overrightarrow{V}_i$; $r_i$ - radius of the pitch circle $H_i$; $\beta_i$ - angle of inclination of the longitudinal line of the tooth in the pitch contact point $P$; $\alpha_i$ - normal profile angle of $\Sigma_i$ in the pitch contact point $P$ (a pitch normal angle); $V_{i,n}$ - magnitude of the projection of $n - n$ on the common normal $n - n$.

Then from (2) and (3), the well-known dependency is obtained [5, 6, 7, 8]:

$$i \zeta = \frac{\omega_i}{\omega_2} = \frac{r_i \cos \beta_i}{r_j \cos \beta_j}.$$

When the rotations transformation between crossed axes $1 - 1$ and $2 - 2$ by means of contacting in pitch contact point $P$ tooth surfaces $\Sigma_1$ and $\Sigma_2$ with an opposite orientation of the longitudinal lines $L_1$ and $L_2$ (see Fig. 2) is realized, then the equation (4) can be presented in the type [1, 2]:

$$i_{i,\Sigma_1} = \frac{\omega_i}{\omega_{i,\Sigma_1}} = \frac{r_{i,\Sigma_1} (\cos \mu \pm \tan \beta_i \sin \mu)}{r_i},$$

where $i = 1, 2$ is the number of the gear, and $\mu$ - hypoid angle.

For the case of spatial rotations transformation between crossed axes, by means of contacting in the pitch contact point $P$ tooth surfaces $\Sigma_1$ and $\Sigma_2$ with one-way orientation of their longitudinal lines $L_1$ and $L_2$ (see Fig. 3), then the equality (4) is of the type [2]:

$$i_{i,\Sigma_1} = \frac{\omega_i}{\omega_{i,\Sigma_1}} = \frac{r_{i,\Sigma_1} (\cos \mu \pm \tan \beta_i \sin \mu)}{r_i}.$$

![Fig. 2. Geometric-kinematic scheme of a spatial gear pair with an opposite orientation of the longitudinal line of the teeth](image-url)
In equations (5) and (6) the above signs refer to $i = 1$, and below ones – $i = 2$.

For the case when the analysis of the instantaneous velocity ratio requires estimations to be made on the basis of the analytical dependence (1), it is necessary the defined distances $e_i$ and $d_i$ to be expressed, by means of the geometric parameters of the tooth surfaces $\Sigma_i$ and $\Sigma_2$ in the pitch contact point.

Then from (1), taking into account the symbols shown in Fig. 1, Fig. 2 and Fig. 3, it can be written

$$V_{i,n} = \cos \Delta,$$

$$V_{i,e} = \omega_i r_i \cos \beta_i \cos \alpha_n,$$

$$V_{i,n} = \omega_i d_i.$$

From (9) it is obtained

$$d_i = \frac{r_i \cos \beta_i \cos \alpha_n}{\cos \Delta},$$

where $\Delta$ is an acute angle between the normal $n \cdot n$ and the direction of the line $O_1 O_2$ of the crossed axes of rotations $i-i$ ($i = 1, 2$).

Analogically, for the distance $e_i$, the following expression can be received:

$$V_{i,n} = \sin e_i,$$

$$V_{i,e} = \omega_i r_i \cos \beta_i \cos \alpha_n,$$

whence

$$e_i = \frac{r_i \cos \beta_i \cos \alpha_n}{\sin e_i}.$$ (12)

When (10) and (12) are solved together, then the following relation between the distances $d_i$ and $e_i$, (for the case when the instantaneous contact is realized in the pitch contact point $P$) is obtained:

$$\frac{d_i}{e_i} = \frac{\sin e_i}{\cos \Delta}.$$ (13)

3. Geometric–Kinematic Model of the Object of the Research

As it has already been mentioned, the transformation of rotations according to a preliminary defined law is a basic process, to the realization of which are oriented to the predominant part of the three-links hyperboloid gear mechanisms. From a theoretical view point, the most common process is the process of spatial rotations transformation with the crossed placement of the axes of the movable links of the three-links transmission mechanism, which determines the predominant interest of the researchers. For this reason, for the current study, a mechano-mathematical model will be illustrated, that treats this most common case, but in an aspect determined by its practical application. In other words, the study will consider a hyperboloid gear mechanism, transforming rotations with constant angular velocities between crossed shafts (axes). The model presented below illustrates geometric-kinematic characteristics - an object of the current work.
On Fig. 4 a geometric-kinematic scheme of three-links gear mechanism, transforming by means of movable links (gears) 1 and 2 rotations with angular velocities \( \omega_1 \) and \( \omega_2 \), between fixed crossed axes \( 1-1 \) and \( 2-2 \) (placed in the static space) of the links \( 1 \) and \( 2 \) is illustrated. The studied case of the process of rotations transformation is characterized by the following conditions:

\[
\begin{align*}
\omega_i &= \text{constant}, \quad i = (1, \ 2), \\
\delta &= \angle(\overrightarrow{\omega}_1, \overrightarrow{\omega}_2) = \text{constant}, \\
a_w &= \text{constant}, \\
i_{12} &= \frac{\omega_1}{\omega_2} = \frac{1}{i_{12}} = \text{constant},
\end{align*}
\]  

(14)

where \( \omega_i \) is a magnitude of the angular velocity vector \( \overrightarrow{\omega}_i \) of rotations of the movable link \( i \); \( \delta \) - crossed angle of the axes \( 1-1 \) and \( 2-2 \); \( a_w \) - minimal distance between the crossed axes \( 1-1 \) and \( 2-2 \) (offset); \( i_{12} \) (\( i_{21} \)) - velocity ratio.

The rotations transformation is realized by means of high kinematic joint \((\Sigma_1; \Sigma_2)\), which elements are the surfaces \( \Sigma_1 \) and \( \Sigma_2 \), that in a given moment have a conjugate contact point \( P \) (the tangent point of contact \( P \) can belong to the conjugated instantaneous contact line \( D_{12} \)). Here, it should be mentioned, that in the case of a real gear mechanism, in every moment more than one pair of tooth surfaces \( \Sigma_1 \) and \( \Sigma_2 \) exists, forming kinematical joints \((\Sigma_1; \Sigma_2)\). When one of the movable links, for example \( i = 1 \), is put into rotation with an angular velocity \( \overrightarrow{\omega}_1 \), then the other movable link \( i = 2 \) starts to rotate. And if the obtained rotation of the second movable link is determined by the angular velocity \( \overrightarrow{\omega}_2 \), (for which the condition \( \omega_1 = \omega_2, i_{12} = \text{constant} \) is fulfilled, that is equivalent to the last equality of conditions (14)), then it can be affirmed, that the kinematic joints \((\Sigma_1; \Sigma_2)\) (illustrated on Fig. 4), and the studied gear mechanism respectively, are kinematically conjugated.

The research is realized with introducing the right-handed coordinate systems \( S(O, x, y, z) \) and \( S_i(O_i, x_i, y_i, z_i) \) \((i = 1, \ 2)\), from which \( S \) is a static coordinate system (connected with the non-movable link (posture) of the three-links gear mechanism), and \( S_i \) \((i = 1, \ 2)\) are the coordinate systems, firmly connected with the movable links \( i = 1, \ 2 \). The mentioned above coordinate systems are not shown in Fig. 4. The current position of \( S_1 \) and \( S_2 \) towards \( S \) is given by the parameters of rotations (meshing) \( \Phi_i \) \((i = 1, \ 2)\).

Let’s the elements \( \Sigma_1 \) and \( \Sigma_2 \) of the high kinematic joint are described parametrically in the static coordinate system \( S \) \([2, 5-8]\):

\[
\begin{align*}
\overrightarrow{p}_{i,s} &= \overrightarrow{p}_{i,s}(u_i, \Theta_i, \phi_i), \\
\overrightarrow{n}_{i,s} &= \overrightarrow{n}_{i,s}(u_i, \Theta_i, \phi_i),
\end{align*}
\]

(15)

where \( \overrightarrow{p}_{i,s} \) is a radius-vector of the contact point \( P \), considered as a point from \( \Sigma_i \); \( \overrightarrow{n}_{i,s} \) - normal vector to \( \Sigma_i \) at the same point; \( u_i, \Theta_i \) - independent parameters, determining the location of point \( P \) on \( \Sigma_i \).

As it has already been mentioned, at the point of geometric conjugation of the surfaces \( \Sigma_1 \) and \( \Sigma_2 \), the following conditions are fulfilled:

\[
\begin{align*}
\overrightarrow{p}_{1,s}(u_1, \Theta_1, \phi_1) &= \text{const} \tan t = \overrightarrow{p}_{2,s}(u_2, \Theta_2, \phi_2) = \text{const} \tan t, \\
\overrightarrow{n}_{1,s}(u_1, \Theta_1, \phi_1) &= \text{const} \tan t = \overrightarrow{n}_{2,s}(u_2, \Theta_2, \phi_2) = \text{const} \tan t.
\end{align*}
\]

(16)

For concrete values of the parameters of rotation \( \phi_1 \) and \( \phi_2 = \phi_f, \dot{j}_{21}, u_1 \) and \( \Theta_1 \) are pair of independent parameters, defining point \( P \) as a point from \( \Sigma_1 \), which has a tangent contact with the corresponding point \( P \) from \( \Sigma_2 \), defined by the parameters \( u_2 \) and \( \Theta_2 \).

In the process of motion of the kinematic conjugated joints for the current points \( P \), the conditions (16) are constantly fulfilled for the \( \Phi_i = \text{varia}, \ i = 1, \ 2 \). Then \([5 - 8]\)

\[
\begin{align*}
\dot{\overrightarrow{p}}_{1,s}(u_1, \Theta_1, \phi_1) &= \dot{\overrightarrow{p}}_{2,s}(u_2, \Theta_2, \phi_2), \\
\dot{\overrightarrow{n}}_{1,s}(u_1, \Theta_1, \phi_1) &= \dot{\overrightarrow{n}}_{2,s}(u_2, \Theta_2, \phi_2), \\
\ddot{\overrightarrow{p}}_{1,s}(u_1, \Theta_1, \phi_1) &= \ddot{\overrightarrow{p}}_{2,s}(u_2, \Theta_2, \phi_2), \\
\ddot{\overrightarrow{n}}_{1,s}(u_1, \Theta_1, \phi_1) &= \ddot{\overrightarrow{n}}_{2,s}(u_2, \Theta_2, \phi_2),
\end{align*}
\]

(17, 18)

where \( \dot{\overrightarrow{p}}_{i,s} \) is an absolute velocity of the contact point \( P \), joined to the \( \Sigma_i \); \( \dot{\overrightarrow{n}}_i \) - an absolute velocity of the tip of the normal vector \( \overrightarrow{n}_i \) in the contact point \( P \), joined to the \( \Sigma_i \); \( \ddot{\overrightarrow{p}}_{i,s} \) - an absolute acceleration of the contact point \( P \), considered as a point from \( \Sigma_i \); \( \ddot{\overrightarrow{n}}_i \) - an absolute acceleration of the tip of the \( \overrightarrow{n}_i \), in point \( P \), joined to the \( \Sigma_i \).

Here and further under conjugation of the kinematic joints, and functioning through them transmission mechanisms, it will be understood their theoretically kinematic conjugation. The systems (17) and (18) are the vector conditions for conjugation of the studied hyperboloid gear mechanism. The first equality from (7) can be presented easily in the form \([5 - 8]\):

\[
\overrightarrow{v}_{i,2} = \overrightarrow{v}_{i,1} + (\overrightarrow{v}_{i} - \overrightarrow{v}_{i}) = \overrightarrow{v}_{i,1} + P_{i,2},
\]

(19)

As it can be seen, these vector equations are determining for both the circumferential and the relative motion of the conjugated contact points. Moreover, (19) shows, that vectors \( \overrightarrow{V}_{i,2} \), \( \overrightarrow{V}_{i,1} \), and \( \overrightarrow{V}_{i} \), as well as the vectors \( \overrightarrow{V}_{i,12} \), \( \overrightarrow{V}_{i} \) and \( \overrightarrow{V}_{i} \) are two triplets of coplanar vectors.
The first triplet determines the tangent plane $T_a$ in the conjugated contact point $P$ of $\Sigma_1$ and $\Sigma_2$. The second triplet of vectors, determines plane $T_m$, which under concrete conditions contains the pole of meshing/pitch contact point of the synthesized gear set. The above comment is illustrated on Fig. 4.

Fig. 4. Kinematic scheme of the conjugated action of the active tooth surfaces $\Sigma_1$ and $\Sigma_2$ of the three-links hyperboloid gear transmission in the contact point $P$; $i - i$ (i = 1, 2) - rotation axes of the movable links; $\delta$ - offset; $\delta$ - crossed angle of the axes 1-1 and 2-2; $T_a$ - common tangent plane of $\Sigma_1$ and $\Sigma_2$ at point $P$; $n-n$ - common normal of $\Sigma_1$ (i = 1, 2) at point $P$; $\vec{\rho}_{i,s}$ - radius-vector of point $P$, joined to the $\Sigma_i$ in the static space $S(O,x,y,z)$; $\vec{\rho}_i$ is an absolute velocity of the contact point $P$; $\vec{V}_{i,2}$ - relative velocity of point $P$; $\vec{V}_{i,1}$ - relative velocity of the motion of point $P$ on the tooth surface $\Sigma_i$; $\vec{V}_{n,i}$ - normal components of $\vec{\rho}_i$.

The model of the process of spatial transformation of rotations, described briefly in this paragraph, by means of a hyperboloid gear drive with arbitrary crossed axes of rotation, is in the basis of the current work.

4. Conclusion

For the synthesis of hyperboloid gear transmissions, it is necessary to be defined an analytical approach for determining the kinematic error in the spatial gearing, which as a rule occurs as a result of manufacturing and assembly inaccuracies during the realization of these transmissions. In the present work it is illustrated sequentially:

- A generalized mathematical model of the hyperboloid transmissions (based on their geometric and kinematic features) is defined.
- The analytical relations, for the instantaneous velocity ratio in an arbitrary contact point of the instantaneous tangent contact of the gear drives with an arbitrary crossed axes are illustrated in the current reserach.
- Generalized dependencies for determination of the instantaneous velocity ratio in the pitch contact point are written. Dependencies by which kinematic and geometric estimations of the synthesized spatial gear mechanisms (upon a pitch contact point) by introducing geometric-kinematic parameters of the pitch contact point, are also written.
- Generalized expressions for the angles, defining the inclination of the longitudinal lines of the teeth (when their synthesis is realized upon a pitch contact point) are expressed by the obtained analytical dependencies for the instantaneous velocity ratio in the pitch contact point.

The received analytical dependencies are applicable for the realization of the process of synthesis of spatial gear mechanisms, as in the case of application of the mathematical model for synthesis upon a pitch contact point, and when in the process of synthesis, the change of the velocity ratio at instantaneous tangent contact points (different than the pitch one) is also taken into account.

References

OPTIMISATION OF GEAR GEOMETRICAL PARAMETERS USING KISSSOFT

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Abstract:
In this study, optimisation of speed gears for a tractor transmission was performed with KISSsoft software. Optimisation was carried out under three constraints. These constraints are input power-torque, volume for system in transmission and gear ratio for each speed. The purpose of this study was to optimize the module, face width, gear quality, centre distance, number of teeth, helix angle, addendum modification coefficient and pressure angle for each speed considering the constraints. Tooth bending stress, tooth contact stress, contact ratio and specific sliding were considered for evaluation during optimisation. Strength calculation of gear pairs which were optimized and defined all geometrical parameters with KISSsoft were also calculated with mathematical model indicated in ISO 6336. Then, the results were compared.

KEYWORDS: GEARS, GEOMETRICAL PARAMETERS, OPTIMISATION, KISSSOFT

1. Introduction

Gears are used for many mechanical system in particular to automotive at the present time. Gears can be designed more reliable, lighter, quieter with optimisation studies. Also, gears can be more competitive in terms of cost during optimisation. In this study, optimisation of speed gears for a tractor transmission was performed with KISSsoft software. Input power-torque, volume for system in transmission and gear ratios for each speed were considered during optimisation. Module, facewidth, gear quality, centre distance, number of teeth, helix angle, addendum modification coefficient and pressure angle of eight quantity of gears for four speed were defined considering tooth bending stress, tooth contact stress, contact ratio and specific sliding during optimisation. Strength calculation of gear pairs which were optimized and defined all geometrical parameters with KISSsoft were also calculated with mathematical model indicated in ISO 6336. Then, the results were compared.

2. Calculating the load capacity of helical gears

Gears face the tooth bending stress and the tooth contact stress during power-torque transfers. Therefore, some damages can occur on gears. The damages which can arise from stress on gears should be considered during design phase.

2.1. Tooth bending stress

Distribution of forces on gears are shown in Fig.1. The tooth bending stress according to ISO 6336 standard is calculated as the following

\[ \sigma_F = \frac{F_t}{b m_n} Y_F Y_r Y_h K_A K_V K_F \]  

where \( F_t \) is the nominal tangential load [N], \( b \) is the facewidth [mm], \( m_n \) is the normal module [mm], \( Y_F \) is the form factor [-], \( Y_r \) is the stress correction factor [-], \( Y_h \) is the helix angle factor [-], \( K_A \) is the application factor [-], \( K_V \) is the dynamic factor [-], \( K_F \) is the face load factor [-], \( K_R \) is the transverse load factor [-].

The permissible bending stress, \( \sigma_{FP} \) is calculated as the following:

\[ \sigma_{FP} = \sigma_{F\text{lim}} Y_T Y_N Y_Y Y_R Y_X \]  

where \( \sigma_{F\text{lim}} \) is the nominal stress [N/mm²], \( Y_T \) is the stress correction factor [-], \( Y_N \) is the life factor [-], \( Y_Y \) is the notch sensitivity factor [-], \( Y_R \) is the relative notch sensitivity factor [-], \( Y_X \) is the size factor [-].

The safety factor for bending stress, \( S_F \) is calculated as the following:

\[ S_F = \frac{\sigma_{FP}}{\sigma_F} \]  

2.2. Tooth contact stress

Surface pressure which occurs on gears is calculated according to ISO 6336 standard as the following [1-6]:

\[ \sigma_H = \frac{F_t}{b m_n} Z_H Z_g Z_h \sqrt{K_A K_V K_R K_H} \]

The real tooth-root stress, \( \sigma_H \) is calculated as the following:

\[ \sigma_H = \frac{F_t}{b m_n} \frac{u+1}{u} Z_H Z_g Z_h \sqrt{K_A K_V K_R K_H} \]  

where \( u \) is the number of meshed teeth, \( Z_H \), \( Z_g \), \( Z_h \) are the number of teeth of gear, pinion and gear, \( K_A \), \( K_V \) are the application factor and dynamic factor [-], \( K_R \), \( K_H \) are the relative surface factor [-].
where \( u \) is gear ratio [-], \( Z_H \) is the zone factor [-], \( Z_E \) is the elasticity factor \([\sqrt{N/m^2}]\), \( Z_r \) is the contact ratio factor [-], \( Z_F \) is the helix angle factor [-], \( K_{HF} \) is the face load factor, \( K_{Ht} \) is the transverse load factor [-].

The permissible contact stress, \( \sigma_{HP} \) is calculated as the following:

\[
\sigma_{HP} = \sigma_{Hlim} Z_N Z_L Z_V Z_R Z_W Z_X
\]

(5)

where \( \sigma_{Hlim} \) is the allowable stress \([N/mm^2]\), \( Z_N \) is the life factor [-], \( Z_L \) is the lubrication factor [-], \( Z_V \) is the velocity factor [-], \( Z_R \) is the roughness factor [-], \( Z_W \) is the work hardening factor [-], \( Z_X \) is the size factor [-].

The safety factor for contact stress, \( S_H \) is calculated as the following:

\[
S_H = \frac{\sigma_{HP}}{\sigma_H}
\]

(6)

3. Optimisation with KISSsoft

In this scope of work, four speed gears of a tractor transmission were optimized via KISSsoft software. Input power is 50 kW and torque is 238 Nm for speed gears which is optimized in this study. These four speed gears have ratios like in Table 1 with tolerances of \(%4\).

<table>
<thead>
<tr>
<th>Speed</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.1</td>
</tr>
<tr>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Maximum volume which can be used in transmission for these speed gear group as Fig.3.

![Fig.3 Volume](image)

Firstly face width, quality and module range were defined so that optimum gear pairs can be determined for volume constraint. In beginning, other gear geometrical parameters were accepted as constant. Then, other gear parameters were optimized. Material of gears was preferred as 16MnCr5. Distance for synchroniser (\( s_1 \) and \( s_3 \)), assembly distance (\( s_2 \)) and volume constraint were considered for determining of gear face width.

\[
b_1 + s_1 + b_2 + s_2 + b_3 + s_3 + b_4 = 210 \text{ mm}
\]

(7)

Then, all possible gear pairs according to ratios were calculated with KISSsoft considering input values and constraints.

![Fig.4 Speed Gears](image)

Optimal face width, quality and module range for gear pairs were determined via graphics like Fig.5 which contain the results of all gear pairs calculated by KISSsoft according to module, minimum root safety and minimum flank safety .

![Fig.5 Module, \( S_F \), \( S_H \)](image)

Then, proper centre distance was specified for speed gears group. After determining of face width, quality and module range of gears, all results of gear pairs which were calculated by KISSsoft for different centre distance values were placed in graphics like Fig.6 according to tip diameters of gear pairs and centre distance in order to specify the optimal centre distance.

![Fig.6 Tip diameter of gear pairs, centre distance values](image)

After determining of centre distance from in graphics like Fig.6 and module from module range which was defined in graphics like Fig.5, then optimisation of number of teeth of gear pairs was applied. Proper number of teeth of gear pairs were determined considering maximum specific sliding and contact ratio of gear pairs.

After determining of face width, quality, module, centre distance and number of teeth, optimisation of helix angle was applied. Helix gears create additional axial forces in system according to spur gears. Therefore, contact ratio and axial forces were considered during determining of helix angle.
Finally, addendum modification coefficient and pressure angle of gears were specified via KISSsoft. Addendum modification coefficient and pressure angle have effect on gear profile so contact ratio, specific sliding and safety factors were considered during optimisation.

Optimisation results of face width, quality, module, centre distance, number of teeth, helix angle, addendum modification coefficient and pressure angle for four speed gears groups are like Table 2 below.

Table 2 Optimisation results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of teeth ( z_1 )</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>57</td>
</tr>
<tr>
<td>Number of teeth ( z_2 )</td>
<td>64</td>
<td>55</td>
<td>45</td>
<td>41</td>
</tr>
<tr>
<td>Module [mm]</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1,75</td>
</tr>
<tr>
<td>Pressure angle [°]</td>
<td>20°</td>
<td>20°</td>
<td>20°</td>
<td>20°</td>
</tr>
<tr>
<td>Helix angle [°]</td>
<td>13°</td>
<td>15°</td>
<td>17°</td>
<td>15°</td>
</tr>
<tr>
<td>Addendum modification coefficient ( x_1 )</td>
<td>0,6</td>
<td>0,3</td>
<td>0,1</td>
<td>0</td>
</tr>
<tr>
<td>Addendum modification coefficient ( x_2 )</td>
<td>0,9419</td>
<td>0,2201</td>
<td>-0,0416</td>
<td>0,1297</td>
</tr>
<tr>
<td>Facewidth [mm]</td>
<td>40</td>
<td>25</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Quality</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Optimal four speed gears group which were defined all geometrical parameters like Table 2 was placed in volume as Fig.9. According to Fig.9, it seems that there is no any problem about volume constraint. All gears can be assembled properly in volume.

4. Results and discussion

Tooth bending stress, tooth contact stress and safety factor of pinion gears for each speed which were optimized via KISSsoft were also calculated according to mathematical model in ISO 6336. The results of pinion gears for both KISSsoft and mathematical model are like Table 3 below.

Table 3 Results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth-root stress ( \sigma_R ) from KISSsoft [N/mm(^2)]</td>
<td>543,96</td>
<td>569,46</td>
<td>576,47</td>
<td>570,03</td>
</tr>
<tr>
<td>Tooth-root stress ( \sigma_R ) from mat. Model [N/mm(^2)]</td>
<td>546,97</td>
<td>607,52</td>
<td>625,93</td>
<td>561,37</td>
</tr>
<tr>
<td>Safety factor for bending stress ( S_R ) from KISSsoft</td>
<td>1,41</td>
<td>1,34</td>
<td>1,32</td>
<td>1,34</td>
</tr>
<tr>
<td>Safety factor for bending stress ( S_R ) from mat. Model</td>
<td>1,46</td>
<td>1,32</td>
<td>1,28</td>
<td>1,43</td>
</tr>
<tr>
<td>Contact stress ( \sigma_H ) from KISSsoft [N/mm(^2)]</td>
<td>1363,60</td>
<td>1286,05</td>
<td>1292,8</td>
<td>1197,23</td>
</tr>
<tr>
<td>Contact stress ( \sigma_H ) from mat. Model [N/mm(^2)]</td>
<td>1345,09</td>
<td>1264,66</td>
<td>1239,2</td>
<td>1226,15</td>
</tr>
<tr>
<td>Safety factor for contact stress ( S_H ) from KISSsoft</td>
<td>1,10</td>
<td>1,13</td>
<td>1,13</td>
<td>1,22</td>
</tr>
<tr>
<td>Safety factor for contact stress ( S_H ) from mat. model</td>
<td>1,12</td>
<td>1,19</td>
<td>1,21</td>
<td>1,22</td>
</tr>
</tbody>
</table>

Regarding to results in Table 3, tooth root stress of pinion 1 (546,97 N/mm\(^2\)) according to mathematical model is bigger (%0,5) than KISSsoft result (543,96 N/mm\(^2\)). For root safety factor, results of mathematical model (1,46) is bigger (%3,5) than the results of KISSsoft (1,41). Tooth contact stress of pinion 1(1345,09 N/mm\(^2\)) according to mathematical model is smaller (%1,4) than the results of KISSsoft (1363,60 N/mm\(^2\)). For flank safety factor, mathematical model result(1,12) is bigger (%1,8) than KISSsoft result (1,1).

Regarding to results for pinion 2, mathematical model result is bigger (%6,7) than KISSsoft result for tooth root stress. Tooth contact stress according to mathematical model is smaller (%1,7) than KISSsoft result. For root safety factor, mathematical model result is smaller (%1,5) than KISSsoft result and flank safety factor of mathematical model is bigger (%5,3) than KISSsoft result.

Regarding to results for pinion 3, tooth root stress according to mathematical model is bigger (%8,5) and tooth contact stress according to mathematical model is smaller (%4,1). For root safety factor, result of mathematical model is smaller (%3) and flank safety factor of KISSsoft result is smaller (%7) than mathematical model.
Regarding to results for pinion 4, tooth root stress according to mathematical model is smaller (%1.5) and tooth contact stress is bigger (%2.4) than KISSsoft result. The root safety factor of mathematical model is bigger (%6.7) than KISSsoft result. For flank safety factor, results are same.

According to results, it seems that there are maximum %8 differences between KISSsoft and mathematical results. There are some reasons for these differences. KISSsoft considers the tolerances and deformation of gears during calculation. Besides, KISSsoft specifies some correction coefficients according to own experiences. Although there are some differences between results, it seems that safety factors for both method are suitable according to target values. Therefore, KISSsoft can be used reliably for strength calculation of gears.

5. Conclusion

Four speed gears of a tractor transmission were optimized by KISSsoft software. During optimisation, input power-torque, ratios and maximum volume were considered as constraint. Facewidth, centre distance, module, quality, number of teeth, helix angle, addendum modification coefficient and pressure angle of gear pairs were specified with optimisation. Then, tooth root stress, tooth contact stress and safety factors were also calculated according to mathematical model in ISO 6336. After calculations, the results were compared. Regarding to tooth root stresses, maximum differences is %8.5 for pinion 3. Regarding to tooth contact stresses, maximum differences is %4.1 for pinion 3. Regarding to root safety factors, maximum differences is %6.7 for pinion 4. Regarding to flank safety factors, maximum differences is %7 for pinion 3. According to this study, both KISSsoft results and mathematical model results are within the range of target value.

Also, the results below were determined during optimisation:

i. Increasing the module has a positive effectiveness on root safety factor and negative effectiveness on flank safety factor.
ii. Increasing the face width of gears has a positive effectiveness on flank safety factor.
iii. Increasing the centre distance results decreased tooth contact stress.
iv. Increasing the number of teeth results increased contact ratio.
v. Increasing the helix angle results increased both contact ratio and axial forces.
vi. Increasing the addendum modification coefficient has a positive effectiveness on root safety factor.

Acknowledgements

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6. Literature


Fig.10 Concept design
FINITE ELEMENTS METHOD MODELLING OF ROLLING BEARINGS

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Abstract: This study presents to determine the contact stress in rolling bearings by using analytical and numerical method. Analytical solution is obtained by using Hertzian contact theory. Obtained analytical solution by this theory require comparison with the numerical calculations to obtain more accurate results for contact problems. Because of that the same problems are also examined by using finite element method. The geometry of the model being studied gives different type of contact configurations such as a point or line of contact. In cylindrical roller bearing the contact form is line contact and for the ball bearing the contact characteristic is point contact. High stress occurs on both of these two contact areas. Contact stress causes elastic or plastic deformation and the contact area will change depending on the magnitude of the contact stress. Therefore, it is really important to calculate more accurate stress at the contact area.

KEYWORDS: HERTZ CONTACT, NON-LINEAR CONTACT, ROLLER BEARING, FINITE ELEMENT METHOD, ANSYS.

1. Introduction

Bearings, having a crucial role in the machine design, are the components to provide smooth rotation by reducing friction between the rotating machine parts.

The general structure of bearing are shown in Fig 1, consists of inner and outer rings and the roller elements which vary depending on the application. The cage prevents the roller elements rubbing against each other.

There are two main functions of roller bearings: First is to reduce frictional forces between moving parts by giving a surface to roll on instead of sliding. The secondary function of bearings is to transmit the force. The roller bearings are classified according to the direction in which the load is applied. Generally bearings carry two kinds of force: radial and axial and some bearings can also carry both radial and axial load at the same time.

In this study a ball bearing and a cylindrical roller bearing are examined.

2. Theoretical Aspects

The force and motion are transferred between machine parts by means of contact phenomena. A contact problem occurs when at least two bodies not mechanically joined touch each other without becoming rigidly attached.

When there are non-conforming surfaces come into mate the contact form can be point or line. The localized stress value on this area is very high. Since the stress is the force over the area, any load on a point contact would be infinite stress as mathematical view.

The original analysis of elastic contact stresses was published in1881 by H. Hertz. In his honour, the stresses at the mating surfaces of curvature bodies in compression are called Hertz contact stresses.

Hertzian contact stress is one of the major reasons of surface failures especially for bearings, cams, gear teeth, locomotive wheels, valve tappets and pin joints linkages [1].

Hertz calculations are limited to case of contact of elastic bodies with simple quadratic shapes and when he was developing his theory Hertz made some important assumptions which are written below [1]:

i. Contacting bodies are isotropic, homogeneous and elastic.
ii. The contact areas are essentially flat and small relative to the radii of curvature of the undeflected bodies in the vicinity of the interface.
iii. The strains are small and within the elastic limits.
iv. The contacting bodies are perfectly smooth; therefore, friction forces between mated parts need not to be taken into account.

Boussinesq developed Hertz’s theory by using theory of elasticity. Boussinesq improved the equations for the state of stress within an isotropic, homogeneous and linearly elastic space, under a concentrated load, which will act perpendicular to the surface. He studied the deformation of semi-infinite solid due to pressure exerted on a small area of its plane surface [2].

Ludenberg in 1939 developed a general theory of elastic contact between two semi-in finite bodies, in which the effect on the stress of the presence of tangential load is taken into consideration.

Midlin investigated the distribution of the tangential forced across the area of contact when one elastic body slides over another.

Lure presented a general three-dimensional punch contact problems.

The stress examined in two contacting bodies at a rolling interface is highly dependent on the geometry of the mate surfaces as well as on the loading material properties.

In this study ball and cylindrical roller bearings are examined. In a ball roller bearing, a ball passes over the raceway surface, the theoretical contact form is assumed as a point in this application. A cylindrical roller bearing, cylinders passes over the raceway, the theoretical contact shape is assumed as line contact for this application.

In order to examine contact stresses for cylindrical and ball bearing, traditional Hertzian contact theory is used. According to the theory

Fig. 1 Roller bearing structure. a)Cylindrical roller bearing b)Ball bearing
sphere to sphere contact presents ball bearing and cylinder to cylinder contact presents cylindrical roller bearing

Hertz contact theory equations for point and line contact types, used in analytical solutions, are shown below:

2.1. Point contact:

Two spheres in contact are shown in Fig 2. The theoretical contact form is assumed as hemisphere with circular contact shape shown in Fig 3.

Total applied load $F$ on the contact patch is written as follows [4]:

$$ F = \frac{2}{3} p a^2 p_{\text{max}} $$

(1)

Where $a$ is radius of contact patch. Maximum pressure is written as follows:

$$ p_{\text{max}} = \frac{3}{2 \pi a^2} \frac{F}{a} $$

(2)

Average pressure is written as follows:

$$ p_{\text{avg}} = \frac{F}{\pi a^2} $$

(3)

Maximum pressure is written depending on average pressure

$$ p_{\text{max}} = \frac{3}{2} p_{\text{avg}} $$

(4)

Material constant can be written as follows:

$$ E_1, E_2 \text{ are elasticity modulus and } \nu_1, \nu_2 \text{ are Poisson’s ratios of mated materials.} $$

$$ m_1 = \frac{1 - \nu_1^2}{E_1}, \quad m_2 = \frac{1 - \nu_2^2}{E_2} $$

(5)

2.2. Line contact:

Geometry constant can be written as follows:

$$ B = \frac{1}{2} \left( \frac{1}{R_1} + \frac{1}{R_2} \right) $$

(6)

The contact-patch radius $a$ is written as follows:

$$ a = \frac{p}{4} p_{\text{max}} \frac{m_1 + m_2}{B} $$

(7)

$$ a = \frac{1}{2} \sqrt{0.375 m_1 + m_2} \frac{F}{B} $$

(8)

The pressure distribution within the hemisphere is written as follows:

$$ P = p_{\text{max}} = \sqrt{\frac{x^2}{a^2} + \frac{y^2}{a^2}} $$

(9)

Static stress distributions in spherical contact:

$$ \sigma_z = -p_{\text{max}} $$

(10)

$$ \sigma_{xy} = \sigma_{yz} = \left( \frac{1 + 2 \nu}{2} \right) p_{\text{max}} $$

(11)

$$ \tau_{yz} = \left( \frac{1 - 2 \nu}{3} \right) p_{\text{max}} $$

(12)

Von Misses equivalent stress is written as follows:

$$ \sigma_{eq} = \sqrt{\sigma_z - \sigma_x^2 + \sigma_y - \sigma_y^2 + (\sigma_z - \sigma_y)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)} $$

(13)

Two cylinders in contact are shown in Fig 4. The theoretical contact form is assumed as rectangular as shown in Fig 4.

Total applied load $F$ on the contact patch is written as follows [5]:

$$ F = \frac{1}{2} p a L p_{\text{max}} $$

(14)

where $L$ is the length of contact along the cylinder axis.

$$ p_{\text{max}} = \frac{2F}{paL} $$

(15)
\[ P_{\text{avg}} = \frac{F}{2aL} \]  
\[ P_{\text{max}} = 1.273P_{\text{avg}} \]

Geometry constant can be written as follows:
\[ B = \frac{1}{2} \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \]

Radius of contact patch \( a \) is written as follows:

\[ a = \frac{2}{p_{\text{avg}}} \sqrt{\frac{m_1 + m_2 F}{B L}} \]

The pressure distribution within the semi-elliptical prism:
\[ P = p_{\text{max}} \left( 1 - \frac{x^2}{a^2} \right) \]

Static stress distributions in cylindrical contact:
\[ \sigma_{xx} = -p_{\text{max}} \left( 1 - \frac{x^2}{a^2} \right) \]
\[ \sigma_{yy} = -p_{\text{max}} \left( 1 - \frac{x^2}{a^2} \right) \]
\[ \tau_{xx} = 0 \]

Von Misses equivalent stress is written as follows:
\[ \sigma_{\text{vm}} = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 + 3\tau_{xx}^2} \]

3. Finite Element Model

All of these theories discuss the contact problem with in the analytical methods and use highly idealised model. Unfortunately these approaches have limited application in engineering.

The more accurate results are examined for rolling bearing such as ball and cylindrical roller bearings contact problem with numerical method. Therefore same problem is also modelled in ANSYS-18.1 workbench environment.

4. Numerical example

4.1. 6208 Ball Bearing Analytical Solution

Firstly 6208 ball bearing shown in Fig5 is analyzed according to Hertizan contact theory. Applied load is \( F=5000 \text{N} \).

According to Hertizian theory, the analytical results for 6208 ball bearings are shown in Table 1.

<table>
<thead>
<tr>
<th>( \tau_{\text{max}} ) [MPa]</th>
<th>( P_{\text{max}} ) [MPa]</th>
<th>( \sigma_{\text{vm}} ) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2570</td>
<td>5474</td>
<td>2744</td>
</tr>
</tbody>
</table>

4.2. 6208 Ball Bearing FEA Analysis

Modelling and the analysis of the problem are completed in ANSYS 19-1 Workbench software.

In terms of accuracy and simplicity the problem is modeled for one ball by using cyclic symmetry.

In order to obtain more accurate results, the mesh density over the contact area is increased as shown in Fig6.

The obtained maximum Von Misses stress is 3174 [MPa].
4.3. NU210 Cylindrical roller bearing analytical Solution

Firstly NU210 cylindrical roller bearing as shown in Fig.8 is analyzed according to Hertzian contact theory. Applied load is F=5000N.

![Fig.8 NU210 Cylindrical roller bearing dimensions](image)

According to Hertzian theory, the analytical results for NU210 cylindrical roller bearings are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>50 mm</td>
</tr>
<tr>
<td>D</td>
<td>90 mm</td>
</tr>
<tr>
<td>B</td>
<td>20 mm</td>
</tr>
<tr>
<td>F</td>
<td>59.5 mm</td>
</tr>
<tr>
<td>D₁</td>
<td>77.4 mm</td>
</tr>
</tbody>
</table>

Table 2 NU210 cylindrical bearing analytical solution results.

<table>
<thead>
<tr>
<th>τ max [MPa]</th>
<th>P max [MPa]</th>
<th>σ vM [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>1464</td>
<td>3000</td>
</tr>
</tbody>
</table>

4.4. NU210 Cylindrical roller bearing FEA Solution

In order to obtain more accurate results, the mesh density over the contact area is increased shown in Fig.9.

![Fig.9 NU210 Cylindrical roller bearing Solid-FEM model.](image)

The obtained maximum Von Mises stress is 3781 [MPa].

5. Results and discussion

Comparison of obtained Von Mises stress results for ball and cylindrical roller bearings are presented in Table 3.

<table>
<thead>
<tr>
<th>Bearing type</th>
<th>Analytical σ vM [MPa]</th>
<th>FEM σ vM [MPa]</th>
<th>% Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball</td>
<td>2744</td>
<td>3174</td>
<td>13.5</td>
</tr>
<tr>
<td>Roller</td>
<td>3000</td>
<td>3781</td>
<td>20.6</td>
</tr>
</tbody>
</table>

All obtained results are acceptable for required Von Mises stress calculation for ball and cylindrical roller bearings.

6. Conclusion

Numerical analysis of rolling bearing contact problem is simulated by using ANSYS workbench environment. Thus the contact stresses are analysed for point and line contact types with 3D model. For ball bearing applications the contact area is actually an elliptical geometry and the contact form depends on the applied force which means, both of these problems are non-linear and analytical theory has lots of assumptions.

Bearings load capacity and reliability are so important. Therefore the rolling bearings play such a prominent machine elements. Calculation the life of a bearing with considerable accuracy become even more important. Thus making it possible to match the bearing life with the service life of the machine involved.

In this study FEM is used to examine the contact analysis of rolling bearing. Specifically, the normal and tangential forces as well as the rolling friction between mated parts are analysed in order to more accurate results. Numerical analysis of contact problems by computer programs gives more accurate results.

Acknowledgements

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7. Literature


SUBSTITUTION OF GEAR-BAR MECHANISM WITH BAR MECHANISM ON THE INFEED MECHANISM OD BOTTLE WASHER

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Abstract: In this paper we will consider substitution of special mechanism, part of bottle washer, which carries bottles to special „baskets”. These mechanism are mostly gear- bar mechanism and their construction is very expensive and overhauls last too long because of complexity of mechanisms.
Mechanisms synthesis based on highly developed analytical / numerical procedures will be considered in this thesis. This means that we will develop procedure for constructing bar mechanism which will be able to fulfill our task to transfer bottles into „baskets”, and to return into start position. The mechanism should also meet requirements in terms of main dimensions, which should be the same as for the old mechanism so the substitution can be performed. Special attention will be paid to analyze the singular positions of the mechanism when it loses mobility. These positions it is necessary to solve in a way so that mechanism continues to move and perform its function.

Key words: BAR MECHANISM, PLANETARY MECHANISM, MECHANISM SYNTESES, ANALYTICAL MECHANISM SYNTESES, MECHANISM ANALYSIS.

1. Introduction

In every beverage filling line there are many mechanisms which in combination with high automation level, provides efficient work of beverage filling lines with almost no hand manipulation. All glass bottle filling lines must include bottle washer that is, because of washing standards, large and in it there is many bottles located in special baskets. These baskets are fixed on chain mechanism which transports them trough baths with cleaning fluids, and above spray nozzles. Because of this it is necessary to insert many bottles into baskets at the same time. Bottle should be transferred from vertical into horizontal position and transported in baskets. This type of movement should be also synchronized with movement of baskets. Special gear-bar mechanism does this task. Production of these mechanisms is very expensive, also maintenance is very difficult and it requires very long time. Breakdowns are not often but when it happens it is very difficult to repair the mechanism. Because of these problems, possibility of replacement of gear-bar mechanism with bar mechanism, whose connection link makes full rotation, will be shown in this paper. Mechanisms synthesis based on highly developed analytical / numerical procedures will be considered in this paper. This means that the geometric parameters should be defined, on the basis of set tasks, which mechanism should complete. The main task to be achieved is the positioning of the element for transferring the bottle into the basket from the initial (catching the bottle) into the final position (delivery of the bottle to the "basket") and after realization of this task, mechanism should return to the starting position so the operation can be repeated. The mechanism should also meet requirements in terms of main dimensions, which should be the same as for the bevel-lever mechanism so the substitution can be performed.

2. Short analysis of gear-bar mechanism and main task short introduction

Bottle washer infeed mechanism main task is to transfer bottles from nearly vertical position (≈10° between bottle and vertical axis) into baskets in horizontal position across special made guides (Fig 1).

This task fulfills special gear-bar mechanism which is expensive for production and complicated for maintenance and adjustment. Draft of this mechanism is shown on figure 2.

Mechanism on figure 2 generates special cam movement necessary to fulfill the task transferring bottle from vertical into horizontal position. This mechanism also returns into start position, and it is ready to repeat this action.
Special cam path through multiple positions is shown on figure 3. We can clearly see the path of cam peak and specially the part of this path that matches with task demanded movement. Also we see that during comeback movement cam peak makes longer path, and this fact made us to consider optimization of this movement. Attention should be paid on static strength of this mechanism because during task fulfill there are many blockages and high torsion loads. Also we should mention that mechanism should follow movements of other machine parts and mechanism, and it should have possibilities for adjustment, that is not case with mechanism shown on figure 2. Because of deficiencies of gear-bar mechanism, mentioned before, and due to set tasks in further paper paragraphs we will consider possibility of replacing this mechanism with bar mechanism, whose connection link performs full rotation and replaces a gear with a special cam.

3. Procedure for forming of bar-planetary mechanism

Because of task that bar mechanism needs to fulfill (five specific positions), it is necessary that the connection link makes full rotation. This means that this connection link is the shortest bar in mechanism.

On figure 4 we can see four bar mechanism that does the demanded tasks. Connection link AB does planar movement and full 360 degrees angular rotation.

Bar AB makes planar movement and we can see that it rotates around point A so we can substitute bar 3 with a gear (figure 5).

Because gear 3 makes planar movement during point A rotates on circular arc which center is in point O2, this mechanism can be planetary mechanism shown on figure 6.

Planetary mechanism shown on figure 6 has two degrees of freedom if the gear 5 is movable. Gear 3 is called satellite (planate), gear 5 is central gear (the sun) and the bar 2 is called satellite carrier. If we want that the rotation courses of gear 3 and 5 is the same than we can enter gear 4 between them. Satellite carrier 2 now has triangle form O2CA (figure 7). This bar can change its form and be even more complex depending on mechanism purpose.

If we install gears 7 and 8 on shafts A and C in parallel plain (gear 7 is located on shaft C and gear 8 is located on shaft A) and rotation velocity of gears 4 and 7 are the same (fix connection), rotation velocity of gears 3 and 8 are different. This planetary mechanism is shown on figure 8.

If the teeth number of individual gears of mechanism are: \( z_3, z_4, z_5, z_7, z_8 \) than the transmission ratio relative to bar 2 is:\[ i_{5 \rightarrow 3} = \frac{\dot{\theta}_5 - \dot{\theta}_2}{\dot{\theta}_3 - \dot{\theta}_2} = \left( \frac{z_4}{z_5} \right) \left( \frac{-z_3}{z_4} \right) = \frac{z_3}{z_5} > 0 \]

\( \dot{\theta}_3 \) – absolute rotation velocity of gear 3 relative to stationary point;

\( \dot{\theta}_5 \) – absolute rotation velocity of gear 5 relative to stationary point.

When we bring together bar mechanism shown on figure 5 and planetary mechanism shown on figure 8 we get bar-planetary mechanism-figure 9.

This bar-planetary mechanism has further characteristics:

- it has one degree of freedom;
- connection link AB i.e. gear 3 makes full rotation during planar movement;
- rotation courses of gears 3 and 5 are the same;
- drive electric motor can be connected with gear 5 and connected on shaft O2;
- if necessary on satellite carrier (on triangle bar 2) can be installed other gear pairs on parallel plains (figure 7).

So now we see that we can get movement on the shortest bar in mechanism that we got using mechanism synthesis. Analysis of bar-planetary mechanism is giving mathematical procedure for determination positions and velocities of all mechanism members. This will give us many qualitative and quantitative mechanism characteristics.
4. Bar mechanism synthesis

Using bar mechanism synthesis procedure we should create mechanism whose connection link would make full rotation and during that movement it would take five specified positions. Applying procedures from [1], [2] and [3] this task is coming down to determine zeros of a fourth degree polynomial.

5. Bar-planetary mechanism analysis

5.1 Bar mechanism position analysis

On figure 10 we can see bar mechanism which bar 3 is the shortest bar and it makes complete rotation. Due to that fact mechanism can be transformed into mechanism shown with dashed lines. Its shortest part is connected to ground pivot and rotates 360 degrees.

If we apply position presentation using complex numbers [5] figure 11 can be presented like this:

\[
Z_{AB} = Z_B - Z_A; \quad Z_B = l_3 e^{i\theta_1}; \quad Z_A = x_A + iy_A; \quad A(x_A,y_A); \quad l_{AB} = |Z_{AB}|; \quad \theta_{AB} = \arg Z_{AB} \]

\[
l_4 e^{i\theta_1} = Z_{AB} + l_4 e^{i\theta_2} \]

\[
l_4 e^{-i\theta_1} = Z_{AB} + l_4 e^{-i\theta_2} \]

Eliminating \( \theta_2 \) we get:

\[
\theta_{21,2}^* = \pm 2 \arctan (\sqrt{1-c} / (1+c)) = \theta_\gamma (\theta_3) \]

\( c = \cos \theta_2^* = (l_2^2 - l_{AB}^2 - l_4^2) / 2l_{AB}l_2 = (1 - x^2)/(1 - x^2) ; \)

\( x = \tan \frac{l_2}{l_2^2} \)

Now:

\[
\theta_{21,2}^* = 2 \arctan \frac{l_2 \sin \theta_2^*}{l_{AB} + l_2 \cos \theta_2^*} \]

\[
\theta_{21,2}^* = \theta_{21,2} + \theta_{AB} \]

Solutions with prefix “+” in equation (1) determines closed loop presented with continuous line on figure 11 (left from \( \xi \)-axis), and solutions with prefix “-” in equation (1) determines closed loop presented with dashed line on figure 11 (right from \( \xi \)-axis).

Equation (1) presents relation between angles \( \theta_2 \) and \( \theta_\gamma \), so if we know geometrical characteristics of mechanism: \( (x_A,y_A), l_2, l_3, l_4 \) and if \( \theta_2 \) is known we can calculate \( \theta_\gamma \) and after that \( \theta_\gamma \). When we determine these parameters mechanism is completely determined.

5.2 Planetary mechanism position analysis

On figure 12 we can see planetary mechanism that is part of bar-planetary mechanism.

For planetary mechanism we can determine position like this:

\[
i_5 - 3 = \frac{\theta_3 - \theta_2}{\theta_3} = \left( -\frac{z_A}{z_5} \right) \left( -\frac{z_3}{z_4} \right) = \frac{z_3}{z_5} \]

\[
\theta_5 - \theta_2 = \frac{z_A}{z_5} (\theta_3 - \theta_2) \]

From this equation we get:

\[
\theta_2 \left( \frac{z_A}{z_5} - 1 \right) + \theta_3 = \theta \left( \frac{z_A}{z_5} + C \right) \]

\( C \)- integral constant

5.3 Bar-planetary mechanism position analysis

If we consider equations (1) and (2) and due to the fact that mechanism has one degree of freedom, determination positions of bar-planetary mechanism should be done just by solving equations (1) and (2). So if \( \theta_3 \) is given, than equations (1) and (2) are not related. First from equation (1) \( \theta_2 \) should be calculated (than \( \theta_\gamma \)), and after that from (2) \( \theta_5 \) should be calculated. If \( \theta_5 \) is given than calculating \( \theta_3 \) (and after that from equation (1) \( \theta_2 \) and \( \theta_\gamma \) are calculated) should be done by solving nonlinear equation:

\[
\theta_2 (\theta_3) = \frac{z_3}{z_5} \theta_5 \theta_3 + C = 0 \]

Specially if \( z_5 = z_3 \) than \( \theta_3 = \theta_5 + C \)

5.4 Bar mechanism velocity analysis

By derivation of equation \( l_4 e^{i\theta_1} = Z_{AB} + l_4 e^{i\theta_2} \) in respect to time we get \( l_4 e^{i\theta_1} \cdot i \dot{\theta_1} = Z_{AB} + l_4 e^{i\theta_2} \cdot i \dot{\theta_2} \), than multiplication this equation with \( e^{i\theta_1} \) we get \( l_4 \cdot i \dot{\theta_1} = Z_{AB} e^{-i\theta_1} + l_4 e^{i(\theta_3 - \theta_1)} \cdot i \theta_2 \). By separation of real part of equation we get:

\[
\dot{\theta}_2 = \frac{\Re \left( Z_{AB} e^{-i\theta_1} \right)}{l_2 \sin (\theta_2 - \theta_3)} = \frac{l_2 \sin (\theta_2 - \theta_3) \dot{\theta}_2}{l_2 \sin (\theta_2 - \theta_3)} \]

On same way we get:

\[
\dot{\theta}_3 = \frac{\Re \left( Z_{AB} e^{-i\theta_1} \right)}{l_2 \sin (\theta_2 - \theta_3)} = \frac{l_2 \sin (\theta_2 - \theta_3) \dot{\theta}_3}{l_2 \sin (\theta_2 - \theta_3)} \]

where:

\( Z_{AB} = Z_A - Z_B = l_4 e^{i\theta_1} \cdot (i \theta_3 - (x_A - iy_A)) \)

5.5 Planetary mechanism velocity analysis

\[
\frac{\dot{\theta}_5 - \dot{\theta}_2}{\dot{\theta}_3 - \dot{\theta}_2} = \frac{z_3}{z_5} \]

\[
\dot{\theta}_5 - \dot{\theta}_2 = \frac{z_2}{z_5} (\dot{\theta}_3 - \dot{\theta}_2) \]
5.6 Bar-planetary mechanism velocity analysis

Considering equations (4), (5) and (6) and fact that mechanism has one degree of freedom it can be concluded that velocity analysis equation is linear. It is a system of three equations with three variables when one of four rotation velocities $\theta_2, \theta_3, \theta_4, \theta_5$ is given.

From equations (4) and (5) we can see that there are special mechanism positions when $\theta_3 = \theta_4 \pm \pi$ and when $\theta_2 \neq \theta_4$. These are trivial positions when $\theta_2 = 0$ and $\theta_3 = 0$, while $\theta_3 \neq 0$. Singular positions appear when $\theta_2 = \theta_4 \pm \pi ; \theta_3 = \theta_2 \pm \pi$. In this case two bars are placed on one straight line (figure 13).

6. Mechanism synthesis-example with specific parameters for bottle washer

Mechanism synthesis should give us positions of special cam while making work path and during return path (figure 3). For five positions from table 1 we applied mechanism synthesis mentioned earlier.

Table 1: Five positions of special cam that mechanism should generate

<table>
<thead>
<tr>
<th></th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>665</td>
<td>-287</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>95</td>
<td>-245</td>
<td>-109°</td>
</tr>
<tr>
<td>3</td>
<td>-78</td>
<td>-293</td>
<td>-176°</td>
</tr>
<tr>
<td>4</td>
<td>95</td>
<td>-245</td>
<td>-241°</td>
</tr>
<tr>
<td>5</td>
<td>383</td>
<td>-228</td>
<td>-289°</td>
</tr>
</tbody>
</table>

For these 5 specific positions we get two solutions and one of them is acceptable (figure 14). On figure 14 also we can see path comparison of old special cam peak path (green line) and new mechanism (purple line) point of connection link paths.

We can conclude that the point of connection link of a four-bar mechanism, which represents also a peak of a new special cam, matches with path of the old mechanism. Connection link of this mechanism makes full rotation and we can say that this is a good solution for the task that was set on the beginning of this paper.

7. Conclusion

On machines that do bottle washing gear-bar mechanism should be replaced with bar mechanism because they are cheaper, easier to maintenance and adjustment. To get mechanism with this type of movement it is necessary to connection link makes planar movement and full rotation. Planetary mechanism is added to four-bar mechanism to perform this movement. This mechanism has one degree of freedom.

In this paper is shown that using analytical mechanism synthesis (5 specific positions given) we can define mechanism which has connection link that makes full rotation. Planetary mechanism can be different due to the movement that we want to achieve.

Position and velocity analysis gives us possibility to determine mechanism movement during whole movement cycle. Determination of mechanism position is solving nonlinear equation (3) which can be solved numerically. In this analysis possibility of determination of specific positions is given. Also in this analysis influence of geometrical parameters on output parameters (especially on rotation velocity) is shown.

7. References

NUMERICAL ANALYSIS OF TURBO-GENERATOR STEAM TURBINE ENERGY EFFICIENCY AND ENERGY POWER LOSSES CHANGE DURING THE VARIATION IN DEVELOPED POWER

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Abstract: Developed power variation of turbo-generator (TG) steam turbine allows insight into the change of turbine energy efficiency and energy power losses. Measurements were performed in five different TG steam turbine operating points and analysis is presented in three randomly selected operating points. Turbine developed power was varied from 500 kW until the maximum power of 3850 kW in steps of 100 kW. Turbine energy efficiency increases from 500 kW to 2700 kW and maximum energy efficiency was obtained at 70.13 % of maximum turbine power (at 2700 kW) in each operating point. From 2700 kW until the maximum of 3850 kW, TG turbine energy efficiency decreases. Change in TG turbine energy efficiency is caused by an uneven intensity of increase in turbine power and steam mass flow. For all observed operating points, energy efficiency during turbine exploitation is approximately 10 % or more lower than the maximum obtained one. A continuous increase in turbine energy power losses during the developed turbine power increase are the most influenced by the continuous increase in steam mass flow through the turbine.

KEYWORDS: STEAM TURBINE, ENERGY EFFICIENCY, ENERGY POWER LOSSES, POWER VARIATION

1. Introduction

Steam turbine propulsion plants are not a rarity for a number of LNG carriers [1]. Such steam propulsion plants have many essential components, not only for ship propulsion, but also for electricity and heat production. Each component from the steam propulsion plant can and should be investigated and optimized to achieve the optimal operating parameters. One of the constituent components of such marine steam propulsion plant is turbo-generator (TG) which steam turbine is analyzed in this paper from the energy aspect [2].

Measurements of required TG steam turbine operating parameters were performed on conventional LNG carrier. Every LNG carrier with steam propulsion system has at disposals at least two or more turbo-generator sets which are designed to cover all ship requirements for electrical power.

On the analyzed LNG carrier is mounted two identical TG operating sets. Each TG turbine has identical operating parameters (inlet and outlet temperatures, pressures and mass flows). For the analysis in this paper is selected one TG steam turbine. Steam turbine, which drives an electric generator on the analyzed LNG carrier comprises of nine Rateau stages. Steam turbines with Rateau stages, analysis of their operation and its characteristics is presented in [3]. Usual and specific designs of marine steam turbines along with their auxiliary systems are presented in [4].

The main goal of the TG steam turbine analysis in this paper was to present change in steam turbine energy efficiency and energy power losses during the change in turbine developed power. Measurements of necessary operating parameters were provided in five different turbine operating points, at five different loads. In each turbine operating point was varied turbine developed power from the lowest to the highest one. During the power variation was calculated turbine energy efficiency and energy power losses. The results of the analysis were presented for three selected turbine operating points, but presented conclusions are valid also for all the other operating points. Steam turbine developed power variation allows detecting optimal turbine loads with the highest energy efficiency, for each operating point. It was compared turbine energy efficiency and energy power losses from the real exploitation (measured operating parameters) with achieved optimal operating conditions when the turbine has the highest energy efficiency. TG steam turbine load depends on ship electrical consumers and their current needs for the electrical power. From the aspect of energy efficiency, for the analyzed TG steam turbine will be better to be more loaded to achieve maximal energy efficiency in each operating point.

Main characteristics and specifications of the LNG carrier in which steam propulsion system is mounted analyzed TG steam turbine are presented in Table 1.

Table 1. Main characteristics of the analyzed LNG carrier

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead weight tonnage</td>
<td>84,812 DWT</td>
</tr>
<tr>
<td>Overall length</td>
<td>288 m</td>
</tr>
<tr>
<td>Max breadth</td>
<td>44 m</td>
</tr>
<tr>
<td>Design draft</td>
<td>9.3 m</td>
</tr>
<tr>
<td>Propulsion turbine</td>
<td>Mitsubishi MS40-2 (max. power 29.420 kW)</td>
</tr>
<tr>
<td>Turbo-generators</td>
<td>2 x Shinko RGA 92-2 (max. power 3.850 kW each)</td>
</tr>
</tbody>
</table>

2. Low power steam turbine energy analysis

2.1. Steam turbine energy analysis equations

The first law of thermodynamics defined energy analysis of any steam system component [5]. Mass and energy balance equations for a standard volume in steady state disregarding potential and kinetic energy can be expressed according to [6]:

\[ \sum \dot{m}_{IN} = \sum \dot{m}_{OUT} \]  
\[ \dot{Q} = \dot{m}_{OUT} \cdot h_{OUT} - \dot{m}_{IN} \cdot h_{IN} \]  
\[ \dot{E}_{in} = \dot{m} \cdot h \]  
\[ \eta_{en} = \frac{\text{Energy output}}{\text{Energy input}} \]

2.2. Energy efficiency and energy power losses for the TG steam turbine

Steam turbine for a turbo-generator drive is a condensing type [9]. Schematic view of steam turbine connected to an electric generator (the whole set of steam turbine and electric generator is usually called turbo-generator) is presented in Fig. 1. Superheated steam mass flow, specific steam enthalpies and specific steam entropies at the TG steam turbine can also be seen in Fig. 1. All variables important for TG turbine numerical analysis were marked with 1 for inlet variables and with 2 for outlet variables.

According to producer specifications [9], TG turbine power can be expressed with the following third degree polynomial:

\[ P_{TG} = -4.354 \cdot 10^{-10} \cdot m_{TG}^3 + 6.7683 \cdot 10^{-6} \cdot m_{TG}^2 + 0.251318 \cdot m_{TG} - 256.863 \]
where \( P_{\text{TG}} \) was obtained in (kW) when \( \dot{m}_{\text{TG}} \) in (kg/h) was placed in the equation (5). Steam mass flow through the TG turbine (\( \dot{m}_{\text{TG}} \)) was measured component, while the developed TG turbine power was calculated according to equation (5).

\[
\eta_{\text{TG, en}} = \frac{(h_1 - h_2)}{(h_1 - h_{2S})}
\]  

(9)

2.3. The principle of the TG developed power variation

TG steam turbine real developed power can be calculated according to Fig. 2 by an equation:

\[
P_{\text{TG}} = \dot{m}_{\text{TG}} \cdot (h_1 - h_2)
\]  

(10)

Three different methods can be used for the power change of TG turbine (if it is assumed always the same inlet pressure and temperature and the same outlet pressure):

1) Change in steam mass flow through the TG steam turbine
2) Change in the value of steam specific enthalpy at the steam turbine outlet (\( h_2 \))
3) Combination of method 1 and 2

To present the change of TG steam turbine energy efficiency and energy power losses in this paper is selected combined method (method 3) for each operating point.

Turbine developed power was varied from 500 kW up to a maximum of 3850 kW in steps of 100 kW. Power change requires a change in steam mass flow through the turbine, so the adequate steam mass flow for any turbine power was calculated by using the reversed equation (5). In each operating point, steam pressure and temperature at the turbine inlet and steam pressure at the turbine outlet remain identical to the measured data. Steam enthalpy at the turbine outlet (\( h_2 \)) was calculated for each turbine power and mass flow by using equation (7). Change in steam enthalpy at the turbine outlet (\( h_2 \)) along with the change of steam mass flow causes the change of TG steam turbine energy efficiency and energy power losses, equations (8) and (9).

3. Measurement results of the analyzed TG

Measurement results for TG steam turbine at different loads are presented in Table 2. Measured operating parameters were: steam pressure at the TG turbine inlet and outlet, steam temperature at the TG turbine inlet and the steam mass flow through TG turbine.

![Fig. 1. Inlet and outlet variables for the TG steam turbine](image)

During measurements, no steam leakage on the analyzed TG turbine was observed, so the mass balance for the TG steam turbine inlet and outlet is:

\[
\dot{m}_{\text{TG,1}} = \dot{m}_{\text{TG,2}} = \dot{m}_{\text{TG}}
\]  

(6)

According to Fig. 1 and Fig. 2, \( h_1 \) is steam specific enthalpy at the turbine inlet, and \( h_2 \) is steam specific enthalpy at the turbine outlet after real (polytropic) expansion. Steam specific enthalpy at the turbine inlet was calculated from the measured pressure and temperature at each operating point. Steam specific entropy at the turbine inlet, and steam specific enthalpy at the turbine outlet was calculated from measured steam pressure at the turbine outlet (\( s_1 = s_{2S} \)), Fig. 2.

Steam specific enthalpy at the turbine inlet, steam specific enthalpy at the end of isentropic expansion and steam specific entropy at the turbine inlet were calculated by using NIST REFPROP 8.0 software [11].

\[
h_2 = h_1 - \frac{P_{\text{TG}}}{\dot{m}_{\text{TG}}}
\]  

(7)

Steam specific enthalpy after isentropic expansion \( h_{2S} \) was calculated from the measured steam pressure at the turbine outlet \( p_2 \) and from known steam specific entropy at the turbine inlet \( s_1 \). Ideal isentropic expansion assumes no change in steam specific entropy (\( s_1 = s_{2S} \)), Fig. 2.

Steam specific enthalpy at the turbine inlet, steam specific enthalpy at the end of isentropic expansion and steam specific entropy at the turbine inlet were calculated by using NIST REFPROP 8.0 software [11].

![Fig. 2. TG real (polytropic) and ideal (isentropic) expansion](image)

TG steam turbine energy power losses in each operating point can be calculated according to Fig. 2 as:

\[
L_{\text{TG,en,PL}} = \dot{m}_{\text{TG}} \cdot (h_2 - h_{2S}) = \dot{m}_{\text{TG}} \cdot (h_1 - h_{2S})
\]  

(8)

Energy efficiency of TG steam turbine can be calculated according to [12] by using the following equation:

\[
\eta_{\text{TG}} = \frac{P_{\text{TG}} - L_{\text{TG,en,PL}}}{P_{\text{TG}}}
\]  

(11)

![Used measuring equipment](image)

All the measurement results were obtained from the existing measuring equipment mounted on the TG steam turbine inlet and outlet. All measuring equipment is calibrated by producers. List of all used measuring equipment was presented in Table 3.

![Table 3. Used measuring equipment for the TG turbine analysis](image)

### Table 2. Measurement results for TG steam turbine at several loads

<table>
<thead>
<tr>
<th>Operating point</th>
<th>Steam pressure at the TG turbine inlet (MPa)</th>
<th>Steam temperature at the TG turbine outlet (°C)</th>
<th>Steam pressure at the TG turbine outlet (MPa)</th>
<th>Steam mass flow through TG turbine (kg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00425</td>
<td>4000.58</td>
<td>5.97</td>
<td>490.5</td>
</tr>
<tr>
<td>2</td>
<td>0.00392</td>
<td>3838.78</td>
<td>6.07</td>
<td>502.5</td>
</tr>
<tr>
<td>3</td>
<td>0.00397</td>
<td>3778.91</td>
<td>6.07</td>
<td>502.5</td>
</tr>
<tr>
<td>4</td>
<td>0.00412</td>
<td>3951.37</td>
<td>6.02</td>
<td>504.0</td>
</tr>
<tr>
<td>5</td>
<td>0.00557</td>
<td>4428.43</td>
<td>5.80</td>
<td>493.0</td>
</tr>
</tbody>
</table>

### Table 3. Used measuring equipment for the TG turbine analysis

<table>
<thead>
<tr>
<th>Steam temperature (TG inlet)</th>
<th>Greisinger GTF 601-Pt100 - Immersion probe [13]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam pressure (TG inlet)</td>
<td>Yamatake JTG980A - Pressure Transmitter [14]</td>
</tr>
<tr>
<td>Steam pressure (TG outlet)</td>
<td>Yamatake JTD910A - Differential Pressure Transmitter [15]</td>
</tr>
<tr>
<td>Steam mass flow (TG inlet)</td>
<td>Yamatake JTD960A - Differential Pressure Transmitter [15]</td>
</tr>
</tbody>
</table>
5. Energy efficiency and energy power losses during TG turbine developed power variation

Change in TG steam turbine energy efficiency and energy power losses during the turbine developed power variation was presented in three operating points from Table 2 – operating points 1, 3 and 5. Obtained conclusions and trends are also valid for the other TG steam turbine operating points.

5.1. Developed power variation for operating point 1

Change in energy efficiency for TG turbine in operating point 1 (Table 2), during the developed power variation is shown in Fig. 3. Increase in turbine developed power causes an increase in energy efficiency until the maximum value, after which follows a decrease in turbine energy efficiency. Maximum turbine energy efficiency is obtained at power of 2700 kW (70.13 % of maximum turbine power) and amounts 67.82 %. At the highest turbine load of 3850 kW, energy efficiency amounts 65.72 % in this operating point.

Turbine energy efficiency in each operating point, as well as in operating point 1, is calculated by using equation (9). For each operating point, energy efficiency change is affected only with the change in steam specific enthalpy after real polytropic expansion \(h_2\) which is calculated according to equation (7). Steam mass flow through the TG turbine in equation (7) is calculated by using the reversed equation (5) where the turbine power is known, and steam mass flow is an unknown variable. Values of steam specific enthalpy after real polytropic expansion \(h_2\) decreases in the turbine power range from 500 kW until the 2700 kW, because the intensity of increase in turbine power is higher in comparison with an increase in steam mass flow through the turbine. In the turbine power range from 2700 kW until the highest turbine load of 3850 kW, steam specific enthalpy after real polytropic expansion \(h_2\) increases because the intensity of increase in turbine power is lower in comparison to an increase in steam mass flow through a turbine in that operating area.

TG steam turbine load depends on ship electrical consumers and their current needs for the electrical power. In operating point 1, TG steam turbine energy efficiency during LNG carrier exploitation amounts only 56.13 % which is much lower energy efficiency than possible maximum one for this operating point. To obtain better energy efficiencies of TG steam turbine in exploitation, it can be recommended that TG turbine should be more loaded, but not more than 2700 kW.

![Fig. 3. Steam turbine energy efficiency change during the developed power variation for operating point 1](image)

Continuous increase in steam mass flow during the TG turbine power increase from 500 kW to 3850 kW causes a continuous increase in turbine energy power loss, as presented in Fig. 6, also in TG turbine operating point 3.

5.2. Developed power variation for operating point 3

Change in energy efficiency for TG turbine in operating point 3 (Table 2), during the developed power variation is shown in Fig. 5. As in observed operating point 1, an increase in turbine developed power causes an increase in energy efficiency until the maximum value, after which follows decrease in turbine energy efficiency.

In operating point 3, maximum energy efficiency is obtained also at turbine developed power of 2700 kW and amounts 66.50 %. For this operating point, at the highest turbine load of 3850 kW, energy efficiency amounts 65.44 %, while during LNG carrier exploitation turbine energy efficiency amounts only 53.84 %. The reasons for such TG turbine energy efficiency change are identical as in operating point 1 described earlier.

![Fig. 5. Steam turbine energy efficiency change during the developed power variation for operating point 3](image)

Continuous increase in steam mass flow during the TG turbine power increase from 500 kW to 3850 kW causes a continuous increase in turbine energy power loss, as presented in Fig. 6, also in TG turbine operating point 3.

![Fig. 6. Steam turbine energy power loss change during the developed power variation for operating point 3](image)

TG steam turbine developed power variation showed that energy power losses are proportional to turbine load - higher load results with the higher energy power losses and vice versa. Energy power losses are not proportional to the energy efficiency of the TG steam turbine.
operating point. As in TG turbine operating point 1, energy power losses are proportional to turbine load - higher load results with the higher energy power losses and vice versa.

5.3. Developed power variation for operating point 5

The same trends and conclusions obtained from TG steam turbine operating points 1 and 3 are also valid for operating point 5 (Table 2). In operating point 5 maximum turbine energy efficiency amounts 69.37 % and as before, is obtained at turbine developed power of 2700 kW. At the highest turbine load (3850 kW) in this operating point energy efficiency is 67.22 %, while during LNG carrier exploitation TG turbine energy efficiency is 59.50 %, Fig. 7. TG turbine operating point 5 also confirmed conclusion that energy power losses are proportional to turbine load - higher load results with the higher energy power losses and vice versa, Fig. 8.

6. Conclusions

The paper presents numerical analysis of TG steam turbine energy efficiency and energy power losses change during the variation in turbine developed power. Measurements were performed in five different TG steam turbine operating points and analysis is presented in three randomly selected operating points, but major conclusions are valid in each of them.

Analyzed TG steam turbine energy efficiency increases from 500 kW to 2700 kW of developed power and maximum energy efficiency was obtained at 70.13 % of maximum turbine power (at 2700 kW) in each operating point. From 2700 kW until the maximum of 3850 kW, TG turbine energy efficiency decreases. Increase and decrease in TG turbine energy efficiency is caused by an uneven intensity of increase in turbine power and steam mass flow. For all observed operating points, turbine energy efficiency in LNG carrier exploitation is approximately 10 % or more lower than the maximum obtained ones.

TG steam turbine energy power losses are proportional to turbine load - higher load results with the higher energy power losses and vice versa. The main reason for continuous increase in turbine energy power losses during the developed power increase are found in continuous increase in steam mass flow through the turbine.

7. Acknowledgment

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8. References

INFLUENCE OF THE AMBIENT TEMPERATURE CHANGE ON STEAM PRESSURE REDUCTION VALVE EXERGY DESTRUCTION AND EXERGY EFFICIENCY

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Abstract: The paper presents an exergy analysis of pressure reduction valve mounted in the steam propulsion system on conventional LNG carrier. From exploitation are obtained that the valve pressure and temperature decrease becomes as higher as steam system load increases. Valve exergy power input and output decreases during the increase in steam system load, mostly because of the steam mass flow decrease. Steam system load increase in exploitation also causes a decrease in valve exergy destruction with a simultaneous decrease in valve exergy efficiency (from 68.42 % to 68.09 %). The ambient temperature variation showed that the valve exergy destruction is the lowest for the lowest observed ambient temperature, in any steam system load. The exergy efficiency of the pressure reduction valve is reverse proportional to valve exergy destruction. An increase in the ambient temperature for 10 °C causes a decrease in analyzed valve exergy efficiency for between 2.5 % and 3 %.

KEYWORDS: AMBIENT TEMPERATURE, STEAM PRESSURE REDUCTION VALVE, EXERGY DESTRUCTION, EXERGY EFFICIENCY

I. Introduction

The main function of pressure reduction valves is reducing pressure of operating medium (in steam plants that operating medium is usually superheated steam). If the operating medium is superheated steam, along with the pressure reduction through the pressure reduction valve was also reduced steam temperature while steam specific entropy increases [1]. In such way the steam system maintained desired operating parameters [2] in all of its parts.

The basic rule for pressure reduction valve operation is that before and after valve specific enthalpy of operating medium remains constant [3]. It is irrelevant to investigate steam pressure reduction valves from the viewpoint of energy, because without any mass flow leakage, steam pressure reduction valves have energy efficiency of 100 % and energy power losses equal to zero, in any observed operating point.

In the land-based steam power plants pressure reduction valves are very rare [4], because in that kind of steam power plants is not necessary to reduce the masses of plant components. In order to remain the walls of every component from the marine steam plant as thick as possible and thus reduce their mass, pressure reduction valves are necessary on ship steam systems [5].

A detailed analysis of any valve type can be rarely found in the scientific literature. If some were found, mostly it is investigations of control valves for steam turbines [6], in some cases along with its actuation systems [7]. Investigations of steam pressure reduction valves are rare, especially for several steam system loads [8].

In this paper was analyzed steam pressure reduction valve, mounted on the main condenser “dump” line, through a several steam system loads. For each load is presented a decrease in steam temperature and pressure on the analyzed valve from the ship exploitation. Based on the measurements of valve operation parameters are presented valve exergy power inputs and outputs, as well as exergy destruction and exergy efficiency in each observed system load. Exergy power inputs and outputs, as well as exergy efficiency and exergy destruction of any steam system component are changeable when the ambient temperature increases or decreases. Engine room temperature variation is performed from 10 °C to 50 °C in steps of 10 °C what is usually expected change of engine room temperature. For observed ambient temperature variation is calculated and presented pressure reduction valve exergy destruction and exergy efficiency in each observed steam system load.

2. Analyzed pressure reduction valve elements and operation characteristics

Analyzed pressure reduction valve is mounted in LNG carrier steam propulsion plant near steam generators. Main characteristics of the LNG carrier which steam propulsion system includes the analyzed pressure reduction valve are presented in Table 1:

<table>
<thead>
<tr>
<th>Table 1. LNG carrier characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead weight tonnage</td>
</tr>
<tr>
<td>Overall length</td>
</tr>
<tr>
<td>Max breadth</td>
</tr>
<tr>
<td>Design draft</td>
</tr>
<tr>
<td>Propulsion turbine</td>
</tr>
<tr>
<td>Steam generators</td>
</tr>
</tbody>
</table>

The position of the analyzed pressure reduction valve in the LNG carrier steam system is near the steam generators. The pressure reduction valve is mounted on steam generators “dump” pipeline. This pressure reduction valve is involved in steam system operation during the system startup. During system startup, steam generators produce much more superheated steam than is necessary for system operation. These facts occur because from the ecological point of view, it is more appropriate to burn LNG surplus in steam generators, than release it into the atmosphere. The superheated steam amount which is not used in steam system was directed to the main condenser. Before entering the main condenser, it is necessary to reduce superheated steam pressure after which follows steam cooling by water spray injection. For pressure reduction of superheated steam before its entrance into the main condenser is responsible analyzed valve. So, the measurements of necessary steam operating parameters before and after pressure reduction valve are and can be performed only during the steam system startup period. General pressure reduction operating range of the analyzed valve is reduction from 6.13 MPa to 0.4 MPa.

Analyzed steam pressure reduction valve intersection, along with all main components can be seen in Fig. 1. This type of pressure reduction valve has two valves (main and auxiliary) for pressure pulsation compensation and for ensuring accurate outlet pressure.

![Fig. 1. Analyzed steam pressure reduction valve intersection [9]](image-url)
3. Exergy analysis equations

3.1. Governing exergy analysis equations

Mass balance equation for a volume in steady state disregarding potential and kinetic energy can be expressed as [10]:

\[ \sum m_{\text{IN}} = \sum m_{\text{OUT}} \]  

(1)

Exergy analysis is based on the second law of thermodynamics [11]. The main exergy balance equation for a volume in steady state is [12]:

\[ \dot{X}_{\text{heat}} = P = \sum \dot{m}_{\text{OUT}} \cdot e_{\text{OUT}} = \sum \dot{m}_{\text{IN}} \cdot e_{\text{IN}} + \dot{E}_{\text{ex,D}} \]  

(2)

where the net exergy transfer by heat (\( \dot{X}_{\text{heat}} \)) at the temperature \( T \) is equal to [13]:

\[ \dot{X}_{\text{heat}} = (1 - T_0 / T) \cdot \dot{Q} \]  

(3)

Specific exergy can be defined according to [14] by an equation:

\[ \varepsilon = (h - h_0) - T_0 \cdot (s - s_0) \]  

(4)

The exergy power of a flow can be calculated according to [15]:

\[ \dot{E}_{\text{ex}} = \dot{m} \cdot \varepsilon = \dot{m} \cdot [(h - h_0) - T_0 \cdot (s - s_0)] \]  

(5)

Exergy efficiency [16] is usually defined as:

\[ \eta_{\text{ex}} = \frac{\dot{E}_{\text{ex,OUT}}}{\dot{E}_{\text{ex,IN}}} \]  

(6)

3.2. Steam pressure reduction valve exergy analysis

For the analyzed pressure reduction valve, all necessary operating points were presented in Fig. 2. The specific enthalpies and specific entropies were calculated from measured steam pressures and temperatures by using NIST REFPROP software [17].

![Steam pressure reduction valve scheme with a general operating range](image)

**Fig. 2. Steam pressure reduction valve scheme with a general operating range**

Mass and exergy balances for the analyzed steam pressure reduction valve are:

**Mass balance:**

\[ m_1 = m_2 \]  

(7)

**Exergy balance:**

- Exergy power input:
  \[ \dot{E}_{\text{ex,IN}} = \dot{m}_1 \cdot \varepsilon_1 \]  

(8)

- Exergy power output:
  \[ \dot{E}_{\text{ex,OUT}} = \dot{m}_2 \cdot \varepsilon_2 \]  

(9)

- Exergy destruction:
  \[ \dot{E}_{\text{ex,D}} = \dot{E}_{\text{ex,IN}} - \dot{E}_{\text{ex,OUT}} = \dot{m}_1 \cdot \varepsilon_1 - \dot{m}_2 \cdot \varepsilon_2 \]  

(10)

- Exergy efficiency:
  \[ \eta_{\text{ex}} = \frac{\dot{E}_{\text{ex,OUT}}}{\dot{E}_{\text{ex,IN}}} = \frac{\dot{m}_2 \cdot \varepsilon_2}{\dot{m}_1 \cdot \varepsilon_1} \]  

(11)

The ambient state in the LNG carrier engine room during the provided measurements was:

- pressure: \( p_0 = 0.1 \text{ MPa} = 1 \text{ bar}, \)
- temperature: \( T_0 = 25 \text{ °C} = 298.15 \text{ K}. \)

4. Measuring equipment and measurement results of pressure reduction valve

Measurements were performed in three different LNG carrier steam system operation points during the system startup. After system startup, all produced superheated steam is used in steam system and “dump” line is not in operation from that moment on. Required operating parameters (pressures, temperatures and mass flows) for each steam pressure reduction valve operating point are presented in Table 2 in relation to the main propulsion propeller speed. Main propulsion propeller speed is directly proportional to steam system load.

In Table 2 can be seen that as propulsion propeller speed increases, the steam mass flow, which is sent directly to the main condenser decreases. This fact presents that steam system uses more and more produced superheated steam as propulsion propeller speed (steam system load) increases. After 41.78 rpm, steam system uses all of produced superheated steam and steam “dump” line is closed.

![Table 2. Steam pressure reduction valve inlet and outlet - measurement results](image)

**Table 2. Steam pressure reduction valve inlet and outlet - measurement results**

<table>
<thead>
<tr>
<th>Propulsion propeller speed (rpm)</th>
<th>Pressure reduction valve - steam inlet (1*)</th>
<th>Pressure reduction valve - steam outlet (2*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>Pressure (kPa)</td>
<td>Mass flow (kg/h)</td>
</tr>
<tr>
<td>25.58</td>
<td>312.5</td>
<td>6.010</td>
</tr>
<tr>
<td>34.33</td>
<td>309.0</td>
<td>6.080</td>
</tr>
<tr>
<td>41.78</td>
<td>304.0</td>
<td>6.110</td>
</tr>
</tbody>
</table>

Streams numeration refers to Fig. 2.

Measurement results presented in Table 2 were obtained by using the existing measuring equipment mounted before and after analyzed pressure reduction valve. List of used measuring equipment is presented in Table 3. From Table 3 only the Shaft Power Meter used for propulsion propeller speed measuring is not mounted at the analyzed pressure reduction valve inlet or outlet, it is mounted directly on propulsion propeller shaft.

![Table 3. List of used measurement equipment](image)

**Table 3. List of used measurement equipment**

<table>
<thead>
<tr>
<th>Measurement equipment</th>
<th>Steam temperature (valve inlet and outlet)</th>
<th>Steam pressure (valve inlet)</th>
<th>Steam pressure (valve outlet)</th>
<th>Steam mass flow (valve inlet and outlet)</th>
<th>Propulsion propeller speed</th>
</tr>
</thead>
</table>

5. Pressure reduction valve exergy analysis results with the discussion

5.1. Pressure reduction valve exergy analysis - exploitation

Decrease in pressure and temperature on the analyzed pressure reduction valve is presented on Fig. 3. During the increase in steam system load, steam pressure at the analyzed pressure reduction valve inlet increases, Table 2, and this occurrence causes simultaneous increase in pressure reduction. At the propulsion propeller speed of 25.58 rpm, analyzed valve reduces steam pressure for 5.61 MPa, at 34.33 rpm steam pressure reduction amounts 5.68 MPa, while at the highest observed propulsion propeller speed of 41.78 rpm, right before the closing of “dump” line, pressure reduction amounts 5.71 MPa.

Increase in steam pressure reduction resulted also with the increase in steam temperature reduction. During the increase in steam system load, the steam temperature reduction increases from 79.9 °C (at 25.58 rpm) to 87.5 °C (at 41.78 rpm).
Exergy power input and output of the analyzed pressure reduction valve continuously decreases during the increase in steam system load, Fig. 4. According to the equations (8) and (9) the main reason for such decrease in the exergy power input and output can be found in the decrease in steam mass flow, Table 2. After 41.78 rpm, steam system uses all of the produced steam, so amount of steam, which passes directly from steam generators to main condenser is equal to zero.

Increase in steam system load causes decrease in valve exergy power input from 4823.8 kW (at 25.58 rpm) to 1115.7 kW (at 41.78 rpm) while exergy power output simultaneously decreases from 3300.3 kW to 759.7 kW between the same propulsion propeller speeds.

Exergy destruction (exergy power losses) of the pressure reduction valve decreases from 1523.5 kW at 25.58 rpm to 356 kW at 41.78 rpm.

The same decrease trend during the increase in propulsion propeller speed can also be seen in pressure reduction valve exergy efficiency, Fig. 5, which decreases from 68.42 % at 25.58 rpm to 68.09 % at 41.78 rpm.

At any observed pressure reduction valve operating point, exergy destruction (exergy power loss) is the lowest for the lowest observed ambient temperature. An increase in the ambient temperature causes an increase in valve exergy destruction, Fig. 6.

Valve exergy destruction is also related to steam mass flow through the valve; higher steam mass flow resulted in the higher exergy destruction at any steam system load and at any temperature. Increase in the ambient temperature causes an increase in valve exergy destruction. Between propulsion propeller speeds of 25.58 rpm and 41.78 rpm, valve exergy destruction amounts from 1446.62 kW to 338.05 kW for the ambient temperature of 10 °C, while for the ambient temperature of 50 °C valve exergy destruction amounts from 1651.16 kW to 385.86 kW in the same operation range.

During the ambient temperature variation, exergy efficiency of the analyzed pressure reduction valve is reverse proportional to valve exergy destruction. The highest valve exergy efficiency is obtained for the lowest ambient temperature of 10 °C (and for the lowest exergy destruction), while the lowest valve exergy efficiency is obtained for the highest ambient temperature of 50 °C (and for the highest exergy destruction), Fig. 7.

At each observed ambient temperature, pressure reduction valve exergy efficiency slowly decreases during the increase in steam system load. Increase in the ambient temperature for a 10 °C causes decrease in valve exergy efficiency for between 2.5 % and 3 %.

When compared analyzed pressure reduction valve exergy efficiency with steam turbines, it can be concluded that valve exergy efficiency are much more affected by the change in the ambient temperature than steam turbines in general, because an increase in the ambient temperature for 10 °C causes decrease in steam turbine exergy efficiency for 1 % or less [5].
6. Conclusion

This paper presented an exergy analysis of pressure reduction valve mounted in the steam propulsion system on conventional LNG carrier. The pressure reduction valve is analyzed in two different ways: based on measurement data from exploitation and based on the ambient temperature variation. Analyzed valve is mounted on the steam generators “dump” line, which led superheated steam surplus direct to the main condenser.

From LNG carrier exploitation data are obtained that the valve pressure and temperature decrease become as higher as steam system load increases. Valve exergy power input and output decreases during the increase in steam system load, mostly because of the steam mass flow decrease (superheated steam surplus is as lower as the system load increases). Steam system load increase in exploitation also causes a decrease in valve exergy destruction (from 1523.5 kW at 25.58 rpm to 356 kW at 41.78 rpm) with a simultaneous decrease in valve exergy efficiency (from 68.42 % at 25.58 rpm to 68.09 % at 41.78 rpm).

Pressure reduction valve exergy destruction is the lowest for the lowest observed ambient temperature, in any steam system load. An increase in the ambient temperature causes an increase in valve exergy destruction. Valve exergy destruction is related to steam mass flow through the valve; higher steam mass flow resulted in the higher exergy destruction at any steam system load and at any temperature.

The exergy efficiency of the pressure reduction valve is reverse proportional to valve exergy destruction - the highest exergy efficiency is obtained for the lowest observed ambient temperature (and for the lowest exergy destruction), while the lowest valve exergy efficiency is obtained for the highest observed ambient temperature (and for the highest exergy destruction). An increase in the ambient temperature for 10 °C causes a decrease in analyzed valve exergy efficiency for between 2.5 % and 3 %.

7. Acknowledgment

The authors would like to extend their appreciations to the main ship-owner office for conceding measuring equipment and for all help during the exploitation measurements. This work has been fully supported by the Croatian Science Foundation under the project IP-2018-01-3739.

8. References

[18] https://www.greisinger.de (accessed: 25.10.18.)
**Abstract:** Comparison of numerical methods for modeling the impact of an explosion on a metal plate such as LOAD_BLAST; LOAD_BLAST_ENHANCED; Arbitrary Lagrangian-Eulerian; Particle Blast Method; Smooth Particle Hydrodynamics which are implemented in the program LS-DYNA. The adequacy and accuracy of these methods are evaluated depending on the distance ratio to the explosive charge. The advantages and disadvantages of each method and recommendations for their use based on the results of this modeling and the experience of the authors of this article are presented.

**Keywords:** EXPLOSION, MINE RESISTANCE, MODELING, LS-DYNA

1. **Introduction**

The results of the combat losses analysis in armed conflicts over the past decades have shown that a large number of damages to armored combat vehicles (ACV) and their crews are caused by mines and improvised explosive devices[1]. Therefore, a topical solution to the problem of determining the effectiveness of protective structures during explosive loading is to improve the anti-mine protection of ACV. Nowadays, numerical methods are used for solving physical problems on high-speed processes. This is quite effective tool for modeling processes occurring in conditions of explosive load of the protective structure. Modern software with integrated numerical methods allows us to estimate the influence of design parameters and physical and mechanical characteristics of the material and its elements on the operation of the structure as a whole during impulse influence. Numerical modeling can’t replace traditional experimental research methods, but can significantly reduce their number and make the whole process more efficient and improve the anti-mine protection of ACV.

Currently, one of the most popular programs that allows to model the impact of explosion on protective structures is LS-DYNA [2]. Usually researchers choose one of the methods of numerical modeling that is implemented in this software package without substantiation of their choice. Each of these methods has errors for specific modeling conditions, so we must compare its accuracy and adequacy for determining the explosive loads and deflections of armored shell of ACV.

2. ** Preconditions and means for resolving the problem**

2.1. **Theoretical Model**

The main criterion for assessing the impact of explosion on protective structures is the coefficient of distance Z (Table 1) to the explosive charge, which is determined in such a manner [3]:

\[
Z = \frac{R}{3W}\]

where: \(Z\) – coefficient of distance to the explosive charge; \(R\) – distance from center of charge; \(W\) – charge weight in TNT.

<table>
<thead>
<tr>
<th><strong>Classification</strong></th>
<th><strong>Z, kg/m</strong></th>
<th><strong>LOAD_BLAST</strong></th>
<th><strong>LOAD_BLAST_ENHANCED</strong></th>
<th><strong>ALE</strong></th>
<th><strong>PBM</strong></th>
<th><strong>SPH</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Far field</td>
<td>&gt;4 - ≤40</td>
<td>Yes</td>
<td>Yes*</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Average field</td>
<td>0.4-4</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes???</td>
<td>Possibly</td>
<td>No</td>
</tr>
<tr>
<td>Near field</td>
<td>0.053-0.4</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes?</td>
</tr>
<tr>
<td>Contact explosion</td>
<td>≈0.053</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The general view of the experimental setup for the explosive load of the armor plate is shown in Fig. 1. [4, 5]. When performing research, the armor plate was clamped between two plates (Fig. 1). The explosive charge of trinitrotoluene (TNT) in the form of a sphere was placed at different distances (R) from the target plate. The value of the charge weight also varied. The scheme of conducting an experiment is shown in Fig. 1b.

Cowper-Symonds model (2) for the material of plate was used in the course of numerical modeling [2].

\[
\sigma_T = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/3}\right] \sigma_0 + \beta E_p \varepsilon_{eff}^p
\]

\[
E_p = E_{iy}E_f \left(E - E_{iy}\right)
\]

\[
\varepsilon_{eff}^p = \int_0^{1/2} \left(\frac{2}{3} \dot{\varepsilon}_p^0\right) dt,
\]

where: \(C\) – parameters of strain rate; \(\dot{\varepsilon}\) – equivalent strain rate; \(\sigma_0, \sigma_T\) – Static and dynamic yield stress; \(E\) – Young’s modulus; \(E_{iy}\) - hardening modulus.

The equation of the state of explosive detonation products[2]:

**Table 1:** Conditional classification of the explosion depending on the value of Z

**Table 2:** Possibility of application of calculation methods depending on [6]. *Note: in conjunction with the LOAD_BLAST_ENHANCED method

**Contact explosion**

**LOAD_Blast**

**LOAD_Blast_ENHANCED**

**ALE**

**PBM**

**SPH**
\begin{align*}
p = A(1 - \frac{\omega}{V}) \exp \{ -R V \} + B(1 - \frac{\omega}{R V}) \exp \{ -R V \} + \frac{\omega}{V} E. \tag{3}
\end{align*}

where: \( V = \frac{\rho}{\rho_0} - \frac{\rho}{\rho_0} \) – relative specific volume; \( A, B, C, R_1, R_2, \omega \) – empirical constants; \( E \) – internal energy.

The equation of state of air [2]:

\[ p = e \cdot (\gamma - 1) \rho / \rho_0 \tag{4} \]

where: \( \gamma = 1.4 \) – indicator of air adiabatic.

The mechanical characteristics of the armor plate are summarized in Table 3. Characteristics for the equation of state of explosive detonation products are given in Table 4.

**Table 3:** Characteristics of the plate material [4, 5]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, GPa</td>
<td>210</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
</tr>
<tr>
<td>Static yield stress, MPa</td>
<td>950</td>
</tr>
<tr>
<td>Dynamic yield stress, MPa</td>
<td>1250</td>
</tr>
<tr>
<td>Relative elongation, %</td>
<td>9</td>
</tr>
<tr>
<td>Density, kg/m³</td>
<td>7838</td>
</tr>
</tbody>
</table>

**Table 4:** Characteristics of the equation of state of detonation products [7]

<table>
<thead>
<tr>
<th>Explosive index</th>
<th>Chapman-Jouget Parameters, MAT_HIGH_EXPLOSIVE_BURN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \rho_0 )</td>
</tr>
<tr>
<td>TNT</td>
<td>kg/m³</td>
</tr>
<tr>
<td>1630</td>
<td>21,0</td>
</tr>
</tbody>
</table>

The coefficients of the state equation of detonation products in the form Jones-Wilkens-Lee, *EOS_JWL*

<table>
<thead>
<tr>
<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( \omega )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPa</td>
<td>GPa</td>
<td>m³/kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>371,2</td>
<td>3,231</td>
<td>1,045</td>
<td>4,15</td>
<td>0,95</td>
<td>0,30</td>
</tr>
</tbody>
</table>

2.3. Numerical modeling

The plate on which the explosion acts, is modeled as three-dimensional, four-node, shell finite elements (Shell) and three-dimensional, eight-node, solid elements (Solid) in all variants. Accordingly, in each calculation scheme, the weight of the explosive varied and the distance to it varied.

2.2. Experimental stand

Fig. 1: The general view of the experimental setup (a) and the scheme of conducting an experiment (b) [4, 5]: \( R \) – distance from center of charge, \( t \) – plate thickness; \( D \) – plate diameter; \( \delta_t \) – maximal mid-point transient deflection; \( \delta_r \) – residual mid-point deflection.

Fig. 2: Different methods of numerical modeling of explosive loading of a plate: \( a \) – LOAD_BLAST ma LOAD_BLAST_ENHANCED; \( b \) – ALE 2D; \( c \) – PBM; \( d \) – SPH; under each of the figures - maximum deflections of the plate with the application of the appropriate method.

Fig. 3: Graphs of the displacement of the central node of a plate during the simulation of the explosion of charge with the use of various calculation methods: \( a \) – \( W=8,75 \) kg, \( R=0,2 \) m; \( b \) – \( W=15 \) kg, \( R=0,4 \) m; \( c \) – \( W=15 \) kg, \( R=0,7 \) m; \( d \) – \( W=15 \) kg, \( R=1 \) m.
Table 5: Results of numerical modeling of the impact of explosion on a plate using various calculation methods

<table>
<thead>
<tr>
<th>Calculation method</th>
<th>W, kg</th>
<th>R, m</th>
<th>$\delta_1$, mm</th>
<th>$\delta_2$, mm</th>
<th>$\Delta$, %</th>
<th>Time of calculation, s</th>
<th>Data volume, MB</th>
<th>Dimensions of a finite element, mm</th>
<th>Number of finite elements, units</th>
<th>$Z$, kg/m$^{1/3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOAD_BLAST (Shell)</td>
<td>8,75</td>
<td>0.13</td>
<td>165.0</td>
<td>109.7</td>
<td>33.5</td>
<td>81</td>
<td>41.8</td>
<td>12x12</td>
<td>4380</td>
<td>0.063</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.2</td>
<td>107.0</td>
<td>109.9</td>
<td>5.7</td>
<td>78</td>
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</tr>
<tr>
<td></td>
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<td>0.7</td>
<td>43.0</td>
<td>47.7</td>
<td>19.9</td>
<td>80</td>
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<td></td>
<td></td>
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<td>0.455</td>
</tr>
<tr>
<td>LOAD_BLAST (Solid)</td>
<td>8,75</td>
<td>0.13</td>
<td>165.0</td>
<td>105.2</td>
<td>36.2</td>
<td>377</td>
<td>128</td>
<td>14x14</td>
<td>18150</td>
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<td>107.0</td>
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<tr>
<td>LOAD_BLAST (ENHANCED) (Shell)</td>
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<td>0.13</td>
<td>165.0</td>
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<td>98</td>
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<td>SPH (Shell)</td>
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<td>Particle Blast (with air) (Shell)</td>
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<td>136</td>
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<td>23.8</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
<td>0.405</td>
</tr>
</tbody>
</table>
3. Result and Discussion.

The obtained simulation results using the considered calculation methods showed high accuracy in comparison with the experimental data, which were selected as reference ones. An additional point is that obtained results correlate with results of other works. [8-10].

The use of Solid or Shell elements in the numerical model has approximately the same level of precision while solving tasks. However, the amount of data needed to store the solution of the same task for Solid elements will be on average three times more than Shell. It is clear that the time of solving the problem with the use of Solid elements will be significantly higher compared with the use of Shell elements. Such conclusions aren't new and completely logically proceed from the mathematical content of both elements. For the majority of tasks regarding the assessment of the impact of explosions on protective structures, it is quite sufficient to use Shell elements except for the presence of significant plastic deformations and the destruction of structural elements. In this case, the use of Solid elements will be expedient.

Application of the LOAD_BLAST and LOAD_BLAST_ENHANCED method has significant advantages over other methods because of their ease of use, relative simplicity of the preparation of the finite element model, the smallest volumes of data compared with other methods, the smallest hardware requirements for computers. The disadvantages of such calculation methods are the impossibility of taking into account "shading" by one design of another, the absence of reflection and overlay of shock waves, which leads to an increase of measure of inaccuracy in the evaluation of the protective properties of complex structures. By the way, there is a fairly small choice of charge explosive form. The effect of a spherical charge in the air or on the surface of the soil is integrated in this calculation method. This requires a recalculation of the charge value of the charge, taking into account the soil and coefficients taking into account the shape of the charge. LOAD_BLAST_ENHANCED further allows us to estimate the pressure acting on the protective structure on its surface and the effect of the negative phase of the shock wave (this isn't counted in LOAD_BLAST).

Using the SPH method allows us to take into account processes of reflection and overlay of shock waves, but requires considerable hardware resources. In addition, this method is very sensitive to grid density, the number of SPH elements, and the correct choice of contact between the elements of the SPH and the elements of the Lagrange.

The ALE method requires a lot of hardware resources, requires considerable hardware resources. In addition, this method is very sensitive to grid density, the number of SPH elements, and the correct choice of contact between the elements of the SPH and the elements of the Lagrange.

The Particle Blast method has the advantage because of the lack of a mesh, needs a relatively small amount of data to note, has a fairly high accuracy and high speed of problem solution. The application of this method is quite promising at the present time.

4. Conclusion

The obtained results show that for the conditions of charge demolition under the bottom or chassis of the ACV, all the methods of modeling the impact of the explosion described in this article have high adequacy and accuracy. The use of each method is expedient in view of their disadvantages and advantages at the discretion of the researcher. Taking into account the authors' experience, it is expedient to carry out the research of the protective structure in the initial stages using the methods LOAD_BLAST and LOAD_BLAST_ENHANCED. We should use one of the methods such as Arbitrary Lagrangian-Eulerian, Corpuscular Particle Method, Smooth Particle Hydrodynamics in order to receive more detailed information about the protective structure.

5. Literature

МОДЕЛИРОВАНИЕ РАДИАЛЬНО-СДВИГОВОЙ ПРОКАТКИ АУСТЕНИТНОЙ НЕРЖАВЕЮЩЕЙ СТАЛИ AISI-321 С ЦЕЛЬЮ ОПРЕДЕЛЕНИЯ ОПТИМАЛЬНЫХ ТЕХНОЛОГИЧЕСКИХ ПАРАМЕТРОВ ДЛЯ ПОЛУЧЕНИЯ УМЗ-СТРУКТУРЫ

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Аннотация: В статье рассматриваются результаты компьютерного моделирования процесса радиально-сдвиговой прокатки аустенитной нержавеющей стали AISI-321, в ходе которого было проведено варьирование основными технологическими параметрами - температурой нагрева заготовки и скоростью вращения валков. Установлено, что с понижением начальной температуры нагрева заготовки изменение начального размера зерна происходит более интенсивно, причем наименьшие измельчение зерна наблюдается в поверхностной зоне. В то же время, снижение скорости вращения валков является малоэффективным способом для интенсификации процесса измельчения зерна.

Ключевые слова: РАДИАЛЬНО-СДВИГОВАЯ ПРОКАТКА, МОДЕЛИРОВАНИЕ, РАЗМЕР ЗЕРНА, АУСТЕНИТНАЯ НЕРЖАВЕЮЩАЯ СТАЛЬ

1. Введение

Несмотря на современный уровень развития технологий виртуальных вычислений, основным методом исследования какого-либо технологического процесса остается физический эксперимент. Поскольку только в натурном опыте, имеется возможность учесть все параметры, оказывающие влияние на исследуемый процесс. В то же время, проведение только физических экспериментов – задача весьма нерациональная, требующая больших затрат сил, времени и материальных средств.

Идеальным компромиссом является использование программных комплексов виртуального моделирования, которые позволяют провести симуляцию изучаемого процесса, учесть практически все параметры, влияющие на него, а также провести оптимизацию исследуемого процесса, т.е. определить значения всех зависимых параметров, при которых исследуемый процесс будет протекать наиболее стабильно.

После этого, при проведении физического эксперимента с оптимальными значениями, результат будет наиболее успешным, без отбраковки заготовки или поломки оборудования.

Для проведения компьютерного моделирования была выбрана программа Simufact Forming, которая наравне с традиционно используемой программой Deform позволяет моделировать процессы обработки давлением любой сложности. Однако Simufact Forming имеет определенные преимущества перед Deform: в ней имеют более гибкие возможности для построения сетки конечных элементов, в том числе и разные построители сеток; также в ней имеется дополнительная база материалов Matilda, с помощью которой имеется возможность моделирования эволюции микроструктуры.

Ранее уже была рассмотрена модель процесса радиально-сдвиговой прокатки (РСП) заготовки из стали AISI-321 [1]. В ходе тех исследований были рассмотрены такие параметры направленно-деформированного состояния, как эквивалентные напряжения и деформации, усилие деформирования, среднее гидростатическое давление, а также изменение размера зерна. Помимо этого, данные параметры были рассмотрены в контексте многопроходного деформирования (7 проходов).

Было установлено, что после семи проходов в заготовке развивается уровень деформации, достаточный для формирования УМЗ-структуры. Настоящая работа посвящена исследованию влияния на процесс РСП основных технологических параметров, таких как температура нагрева заготовки и скорость вращения валков.

2. Параметры моделирования

В качестве модели для исследования использовалась модель, описанная в работе [1]. Исходная заготовка диаметром 30 мм и длиной 150 мм прокатывалась на стане с обжатием 3 мм (рис. 1).

Материал заготовки – нержавеющая аустенитная сталь AISI-321 (0,08% C, 17-19% Cr; 9-11% Ni; 2% Mn; 0,8% Si; 0,5-0,7% Ti). Поскольку для выбранной марки стали начальная температура рекристаллизации или диффузионного отжига равна 1020 °C [2], то температура нагрева стали была равна 1000 °C, как максимально возможная для исключения процесса рекристаллизации; скорость прокатки была равна 50 об/мин, как номинальное значение на стане СВП-08. Коэффициент трения на контакте заготовки и валков был принят равным 0,3, как рекомендуемое значение для горячей прокатки [3].

При создании многопроходной модели были использованы следующие параметры (таблица 1).

Рис 1 Модель радиально-сдвиговой прокатки

<table>
<thead>
<tr>
<th>№</th>
<th>Режим обжатий по проходам</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Начальный диаметр, мм</td>
</tr>
<tr>
<td>2</td>
<td>Конечный диаметр, мм</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>№ проход</th>
<th>Начальный диаметр, мм</th>
<th>Конечный диаметр, мм</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>27</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>9</td>
</tr>
</tbody>
</table>

Помимо изменения уровня обжатия, также было проведено варьирование двумя технологическими параметрами - температурой нагрева и скоростью вращения валков. Дополнительные значения начальной температуры нагрева были заданы равными 900 и 800 °C, поскольку повышение температуры является нерациональным решением - нагрев стали AISI-321 выше 1000 °C приведет к началу процесса рекристаллизации в ходе деформирования.

Учитывая тот факт, что во многих работах [4], которые посвящены многократной интенсивной пластической...
деформации, было установлено незначительное влияние скорости деформации на параметры деформирования, было решено провоанализировать лишь одно дополнительное значение скорости – 40 об/мин. Также данное решение связано с тем, что базовое значение скорости 50 об/мин является максимально возможным для стана СВП-08, расположенного в Рудненском индустриальном институте. И понижен скорость в любом случае приведет к более интенсивному охлаждению заготовки, что приведет к повышению силовых нагрузок на стан.

Для определения значений напряжения необходимо находить значения компонентов соответствующих тензоров, что для трехмерного течения металла является очень сложной задачей. Поэтому обычно используют простой показатель интенсивности напряжения, или так называемое эквивалентное напряжение. Также необходимо исследовать не только эквивалентное напряжение, но и параметры, которые позволяют оценить долю растягивающих и сжимающих напряжений в очаге деформации. Таковыми являются главные напряжения \( \sigma_1, \sigma_2 \) и \( \sigma_3 \). Все три главных напряжения в совокупности представляют собой среднее гидростатическое давление.

3. Изучение моделей с пониженными температурами нагрева

При анализе моделей с температурами нагрева 900°С и 800°С проводилось изучение энергосиловых параметров (напряжения и усилие), а также эволюции микроструктуры. Исследование деформированного состояния не проводилось, т.к. от данного параметра эквивалентная деформация не зависит.

При понижен начальной температуры нагрева заготовка имеет меньший уровень пластичности. Это вызывает повышение энергосиловых параметров, что является негативным фактором с точки зрения стойкости инструмента. В то же время, понижение уровня сжимающих напряжений и преобладание их значений над растягивающими напряжениями является наиболее благоприятной картиной НЖС. В этом случае происходит залечивание возможных внутренних дефектов (пустот, пор, несплошностей) в обрабатываемом металле. Результаты анализа энергосиловых параметров в моделях с пониженными температурами нагрева приведены в таблицах 2-4.

Таблица 2 – Значения напряжений по проходам в модели с температурой нагрева 900°С

<table>
<thead>
<tr>
<th>Проход</th>
<th>1-й проход</th>
<th>2-й проход</th>
<th>3-й проход</th>
<th>4-й проход</th>
<th>5-й проход</th>
<th>6-й проход</th>
<th>7-й проход</th>
</tr>
</thead>
<tbody>
<tr>
<td>Поверхность</td>
<td>Эквивалентное напряжение, МПа</td>
<td>155</td>
<td>163</td>
<td>176</td>
<td>193</td>
<td>209</td>
<td>226</td>
</tr>
<tr>
<td>Периферия</td>
<td>103</td>
<td>114</td>
<td>127</td>
<td>144</td>
<td>162</td>
<td>181</td>
<td>197</td>
</tr>
<tr>
<td>Центр</td>
<td>78</td>
<td>84</td>
<td>92</td>
<td>106</td>
<td>122</td>
<td>148</td>
<td>160</td>
</tr>
<tr>
<td>Поверхность</td>
<td>Среднее гидростатическое давление, МПа</td>
<td>-312</td>
<td>-323</td>
<td>-336</td>
<td>-357</td>
<td>-374</td>
<td>-392</td>
</tr>
<tr>
<td>Периферия</td>
<td>-127</td>
<td>-134</td>
<td>-144</td>
<td>-167</td>
<td>-182</td>
<td>-205</td>
<td>-227</td>
</tr>
<tr>
<td>Центр</td>
<td>-62</td>
<td>-74</td>
<td>-82</td>
<td>-102</td>
<td>-121</td>
<td>-138</td>
<td>-156</td>
</tr>
</tbody>
</table>

Таблица 3 – Значения напряжений по проходам в модели с температурой нагрева 800°С

<table>
<thead>
<tr>
<th>Проход</th>
<th>1-й проход</th>
<th>2-й проход</th>
<th>3-й проход</th>
<th>4-й проход</th>
<th>5-й проход</th>
<th>6-й проход</th>
<th>7-й проход</th>
</tr>
</thead>
<tbody>
<tr>
<td>Поверхность</td>
<td>Эквивалентное напряжение, МПа</td>
<td>164</td>
<td>176</td>
<td>188</td>
<td>205</td>
<td>219</td>
<td>244</td>
</tr>
<tr>
<td>Периферия</td>
<td>108</td>
<td>123</td>
<td>144</td>
<td>164</td>
<td>182</td>
<td>208</td>
<td>237</td>
</tr>
<tr>
<td>Центр</td>
<td>83</td>
<td>94</td>
<td>105</td>
<td>129</td>
<td>142</td>
<td>167</td>
<td>184</td>
</tr>
<tr>
<td>Периферия</td>
<td>-134</td>
<td>-152</td>
<td>-169</td>
<td>-184</td>
<td>-202</td>
<td>-228</td>
<td>-255</td>
</tr>
<tr>
<td>Центр</td>
<td>-73</td>
<td>-84</td>
<td>-97</td>
<td>-118</td>
<td>-133</td>
<td>-154</td>
<td>-172</td>
</tr>
</tbody>
</table>

Анализ таблиц 2-4 показал, что понижен начальной температуры нагрева является эффективным способом повышения уровня как сжимающих, так и эквивалентных напряжений. Так, по сравнению с базовой моделью, при снижении нагрева на 100°С уровень эквивалентных напряжений после 7 прохода повышается на 23% в осевой зоне, на 34% в периферийной зоне и на 9% в поверхностной зоне. При снижении нагрева на 200°С уровень эквивалентных напряжений после 7 прохода повышается на 42% в осевой зоне, на 62% в периферийной зоне и на 24% в поверхностной зоне. Резкое снижение процентной разницы эквивалентных напряжений в поверхностной зоне связано с тем, что после 7 прохода потенциальная температура заготовки имеет более низкую температуру, чем внутренние слои. Это, в свою очередь, вызывает значительный рост сжимающих напряжений в этой зоне.

Отчетливо видно, что после каждого прохода значения сжимающих напряжений на поверхностях превышают значения в центре в несколько раз – в 5,5 раз после 1 прохода и в 2,7 раз после 7 прохода. Снижение разницы значений напряжений связано с двумя факторами – с понижением температуры заготовки в ходе деформирования, за счет чего идет общий рост сжимающих напряжений; и с уменьшением диаметра заготовки, за счет чего осевая зона подвергается сжимающему действию со стороны вала более интенсивно.

При изучении усилий деформирования было отмечено, что данный параметр, как и напряжения, находится в обратной зависимости от температуры нагрева, т.e. при понижении температуры заготовки усилия прокатки увеличиваются.

Анализ значений усилий показал, что снижение начальной температуры нагрева заготовки вплоть до 800°С позволит осуществить все 7 циклов деформирования на стане СВП-08 без перегрузок двигателей. В обоих случаях ни средние, ни пиковые значения не превышают допустимой величины (100 кН).

Анализ эволюции микроструктуры показал, что снижение температуры нагрева заготовки является весьма эффективным методом для интенсификации процесса измельчения зерна. Несмотря на то, что во всех трех рассмотренных моделях уровень динамической рекристаллизации остается постоянным (за счет неизменности уровня обжатия), доля статической рекристаллизации при снижении температуры нагрева также снижается. Это приводит к большему повышению степени измельчения исходного зерна в металле, особенно в поверхностной зоне. Также, для наглядности были построены диаграммы, отражающие значения среднего размера зерна для трех температур (рисунок 2).

При анализе данных диаграмм было установлено, что с понижением начальной температуры измельчение начального размера зерна происходит более интенсивно во всех трех зонах, но наибольшее измельчение зерна наблюдается в поверхностной зоне, где после 7 прохода при температуре нагрева 900°С был зафиксирован размер зерна 5 мкм, что в 1,4 раза меньше значения в базовой модели. А в случае нагрева заготовки до 800°С в поверхностной зоне был зафиксирован размер зерна 2 мкм, что в 3,5 раза меньше значения в базовой модели.
4. Изучение модели с пониженной скоростью деформации

При рассмотрении модели со скоростью вращения валков 40 об/мин было отмечено значительно меньшее влияние (по сравнению с температурой нагрева) данного фактора на энергосиловые параметры радиально-сдвиговой прокатки и эволюцию микроструктуры. Это напрямую связано с природой влияния основных параметров деформации на уровень пластичности – скорость деформации имеет наименьшее влияние, что подтверждается многочисленными данными, в частности, значениями термомеханических коэффициентов.

Для наглядности, вместо таблиц, были построены диаграммы (рисунки 3-5), отражающие значения напряжений во всех зонах для обеих скоростей: 40 об/мин и для базового значения скорости 50 об/мин.

Анализ диаграмм на рисунках 2-4 показал, что понижение скорости вращения валков при радиально-сдвиговой прокатке имеет весьма незначительное влияние на формирование напряженного состояния. При этом отмечена обратная зависимость этих параметров, т.е. при снижении скорости вращения валков, значения эквивалентного напряжения и среднего гидростатического давления возрастают.

Так, по сравнению с базовой моделью, при снижении скорости вращения валков на 10 об/мин уровень эквивалентных напряжений после 7 прохода повышается на 6% в осевой зоне, на 4% в периферийной зоне и на 3,5% в поверхностной зоне. Уровень сжимающих напряжений при...
снижении скорости вращения валков на 10 об/мин после 7 прохода повышается на 9% в осевой зоне, на 5% в периферийной зоне и на 3% в поверхностной зоне.

Анализ возникающих усилий показал, что пониженная скорость вращения валков позволяет осуществить все 7 циклов деформирования на стане СВП-08 без превышения нагрузок на электродвигатели, т.к. в этом случае ни средние, ни пиковые значения не превышают допустимой величины (100 кН). Так, после 7 прохода среднее значение усилия составило 67 кН. Это больше базового значения на 7%. Пиковое значение усилия составило 78 кН, что больше базового значения на 8%.

Анализ эволюции микроструктуры показал, что снижение скорости вращения валков является неэффективным методом для процесса измельчения зерна. Несмотря на то, что с увеличением числа проходов размер зерна в рассматриваемой модели меньше, чем в базовой – это объясняется несколько большей степенью охлаждения заготовки за счет увеличения времени деформирования.

Анализ диаграмм на рисунке 6 показал, что снижение скорости вращения валков, как единственного варьируемого параметра, является малоэффективным способом для усиления процесса измельчения зерна. После 7 прохода наибольшее измельчение зерна наблюдается в поверхностной зоне, где был зафиксирован размер зерна 6 мкм, что в 1,2 раза меньше значения в базовой модели. В остальных двух зонах размеры зерна в 1,1 раза меньше базовых значений.

5. Определение оптимальных параметров обжатия, температуры нагрева и скорости вращения валков

При установлении оптимальных параметров любого технологического процесса необходимо сначала определить с параметрами оптимизации. В случае процессов обработки металлов давлением это, в первую очередь, возможность осуществления деформирования, т.е. возможно ли провести деформирование на существующем оборудовании или нет. Здесь анализируется возникающее усилие деформирования и сравнивается с допускаемыми значениями. В результате были определены оптимальные параметры деформирования нержавеющей аустенитной стали AISI-321 на стане СВП-08:
- уровень обжатия: 21 мм (7 проходов);
- температура нагрева заготовки: 900 °С или 800 °С;
- скорость вращения валков: 50 об/мин или 40 об/мин.

Здесь необходимо пояснить наличие двух значений температуры и скорости. При варьировании каким-то одним из этих параметров все модели получались удачными в плане отсутствия перегрузки электродвигателей. Однако, при выборе температуры нагрева заготовки 800 °С и скорости вращения валков 40 об/мин в дополнительно построенной модели уже в 5 проходе было зафиксировано превышение допустимого уровня усилия (108,5 кН). Поэтому, для удобства использования результатов моделирования была составлена итоговая таблица варьируемых параметров (таблица 5).

Таблица 5 — Варианты использования варьируемых параметров

<table>
<thead>
<tr>
<th>1 проход</th>
<th>2 проход</th>
<th>3 проход</th>
<th>4 проход</th>
<th>5 проход</th>
<th>6 проход</th>
<th>7 проход</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 °С</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
</tr>
<tr>
<td>900 °С</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
</tr>
<tr>
<td>800 °С</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
</tr>
<tr>
<td>50 об/мин</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
</tr>
<tr>
<td>40 об/мин</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
<td>да</td>
</tr>
</tbody>
</table>

Значение температуры равное 1000 °С не рекомендуется как оптимальное, поскольку при нагреве до 900 °С имеется возможность провести 7 циклов данного процесса и получить более высокий уровень проработки металла.

6. Заключение

Представлены результаты моделирования процесса радиально-сдвиговой прокатки аустенитной нержавеющей стали AISI-321, в ходе которого было проведено варирование основными технологическими параметрами - температурой нагрева заготовки и скоростью вращения валков. Установлено, что с понижением начальной температуры нагрева заготовки измельчение начального размера зерна происходит более интенсивно, причем наибольшее измельчение зерна наблюдается в поверхностной зоне. В то же время, снижение скорости вращения валков является малоэффективным способом для интенсификации процесса измельчения зерна.

7. Сведения о грантовой программе

Данная работа выполнена в рамках выполнения темы №AP05131382 «Разработка и исследование технологии получения ультрамелкозернистых материалов с улучшенными механическими свойствами и повышенной радиационной стойкостью для использования их в качестве материалов первой стенки термоядерных реакторов и в ядерной энергетике» по программе грантового финансирования по научным и (или) научно-техническим проектам на 2018-2020 годы в Республике Казахстан.

8. Литература

1. Introduction

Stainless steels are most important for their corrosion resistance. Stainless steels have a chromium content of at least 10.5 % [1,2]. The high degree of chromium activity is the principal basis for utilizing it as an alloying element in corrosion resisting alloys. As a result of reactions of chromium with the oxygen from the air, a protective oxide film forms and prevents further rapid oxidation. Additions of Mo increase corrosion resistance in reducing acids and against pitting attack in chloride solutions. Varying additions of Ni, N, Cu, Mn, W, Ti, Ni and other elements may also be present [1-7]. Thus, there are numerous grades of stainless steel alloys with varying contents of chemical elements to suit the environment the alloy must endure. Stainless steels are classified on the basis of their microstructures as ferritic, martensitic and austenitic stainless steels. The soft austenitic steels have exceptional ductility, elongation exceeding 50 %. The ferritic stainless steels offer good strength and ductility, but without the outstanding formability of the austenitic varieties. Duplex stainless steel (DSS) with austenitic and ferritic grains possess beneficial combinations of these two phases. The ferrite/austenite ratio in DSS must be close to 50:50. According to the standard HRN EN 10088-1:2015 different DSS can have 22 – 28 % of Cr, 6 – 22 % of Ni, less than 2.00 % of Mn and less than 2.5 % of Mo. DSS exhibit greater toughness and better weldability than ferritic stainless steel [6]. Compared with austenitic grades, DSS have higher resistance to pitting and stress corrosion cracking. Accordingly, they are widely used in various chemical, petrochemical, food, power, transportation, paper and oil industries.

Most of these applications require welding as a joining method. DSSs undergo microstructural changes during heat treatment or welding process [6]. During welding of DSS, it is essential to maintain a ferrite–austenite ratio close to 50:50. This phase balance, may however, be upset due to rapid cooling involved in most weld thermal cycles resulting in weld metal ferrite contents in excess of 50 %. The resultant phase ratio is dependent on the energy input during welding, as this determines the cooling rate and the extent of the phase transformation which is diffusion based. If high heat inputs are used, coarse grains are produced in the weld region, wide heat-affected zones and possibly, precipitation of brittle intermetallic phases may develop [7].

Fig. 1. Joint preparation for TIG welding of steels according to the ISO 9692-1:2013 [10].

In this research the intention was to clarify the improvements in productivity when TIG welding is applied with activation flux on X2CrNiMoN22-5-3 7 mm thick stainless steel. This material is austenitic-ferritic stainless steel with high resistance to general corrosion, pitting and crevice corrosion and high resistance to stress corrosion cracking (SCC) in chloride-bearing environments and environments containing hydrogen sulphide. It has also high resistance to erosion corrosion and corrosion fatigue. The tensile strength and weldability of this material are suitable for various applications.
General objective was to produce a sound weld without consumption of nickel and manganese by omitting the edge preparation and additional filler material. Direct substitution of expensive alloying elements, as it is nickel and manganese in the filler materials for welding is not easy to achieve. However, development of welding technology without filler materials can generate welds that can be acceptable for some specific applications.

2. Experimental

2.1. Material

Standard duplex stainless steel with designation X2CrNiMoN22-5-3 has been used in this experiment. Mechanical properties of this material according to the standard HRN EN 10088-2:2015 [11] are presented in table 1. Chemical composition has been analysed with Energy-dispersive X-ray spectroscopy (EDS) on scanning electron microscope Tescan Vega TS5136 [12]. The chemical composition is 0,014 % C, 1,903 % Mn, 0,026 % P, 0,002 % S, 0,278 % Si, 5,005 % Ni, 22,421 % Cr, 2,559 % Mo and 0,169 % N.

Activation flux has been prepared from powders SiO$_2$ and Cr$_2$O$_3$ in proportion 1:1. In order to prepare highly concentrated powder suspensions 96 % ethyl alcohol has been added in proportion 1:2 to this mixture.

Table 1: Mechanical properties of duplex stainless steel X2CrNiMoN22-5-3 [11]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>460</td>
<td>640 to 840</td>
<td>25</td>
</tr>
</tbody>
</table>

2.2. Penetration of the electric arc

Penetration of the electric arc has been tested on the test coupons in dimensions 200 × 200 × 7 mm. Plates were cleaned with acetone prior deposition of the activation flux. One thin layer of activation flux was laid on the surface of the work-piece using a paintbrush prior each A-TIG bead on plate welding. Welding was performed with FRONIUS MagicWave 2200 Job G/F TIG welding machine. Tungsten electrode with diameter 2,4 mm and designation WT20 has been used for welding. In order to have a linear motion of the electric arc with accurate speed of moving a TIG welding torch has been installed on the “BUG-O Systems” Modular Drive Systems automatic machine used for guidance in welding. Two types of welding gas have been used with the same flow of 9 l/min. Table 2 presents welding parameters for all weld runs in the first part of the experiment. Four samples 1A, 2A, 3A and 4A have been welded with 100 % Ar shielding gas. Other samples 1B, 2B, 3B and 4B have been welded with welding gas composed of 97,5 % Ar and 2,5 % N$_2$. Nitrogen has been added to stimulate occurrence of austenitic phase and prevent ferritization.

Table 2: Welding parameters in bead on plate welding

<table>
<thead>
<tr>
<th>Sample</th>
<th>Activation flux</th>
<th>Welding speed [cm/min]</th>
<th>Current [A]</th>
<th>Heat input [kJ/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>NO</td>
<td>10,2</td>
<td>160</td>
<td>0,666</td>
</tr>
<tr>
<td>2A</td>
<td>NO</td>
<td>7,8</td>
<td>200</td>
<td>1,209</td>
</tr>
<tr>
<td>3A</td>
<td>YES</td>
<td>10,2</td>
<td>200</td>
<td>0,762</td>
</tr>
<tr>
<td>4A</td>
<td>YES</td>
<td>7,8</td>
<td>200</td>
<td>1,310</td>
</tr>
<tr>
<td>1B</td>
<td>NO</td>
<td>10,2</td>
<td>160</td>
<td>0,768</td>
</tr>
<tr>
<td>2B</td>
<td>NO</td>
<td>7,8</td>
<td>160</td>
<td>1,320</td>
</tr>
<tr>
<td>3B</td>
<td>YES</td>
<td>10,2</td>
<td>160</td>
<td>0,774</td>
</tr>
<tr>
<td>4B</td>
<td>YES</td>
<td>7,8</td>
<td>200</td>
<td>1,366</td>
</tr>
</tbody>
</table>

2.3. A-TIG welding parameters

After welding and examination of bead on plate welds, parameters for welded joint have been determined. The constant parameters were:
- welding speed 9,1 cm/min;
- shielding gas flow 9 l/min;
- electrode tip workpiece distance 3 mm;
- tungsten electrode diameter 2,4 mm;
- welding torch inclination 90°.

Two welded joints have been produced without any filler material, first one with 100 % Ar shielding gas (marked as Z1) and the other one with Ar + 2,5 % N$_2$ shielding gas (marked as Z2). Plates in dimensions 200 × 100 × 7 mm were placed on a 10 mm thick cooper backling plate. Plates had single square edge preparation without any spacing between. Samples have been welded with application of the same activation flux in width of 20 mm on the upper surface. Table 3. Presents welding parameters used for producing welded joints.

Table 3: Welding parameters used for producing welded joints [12]

<table>
<thead>
<tr>
<th>Sample</th>
<th>Welding speed [cm/min]</th>
<th>Current [A]</th>
<th>Voltage [V]</th>
<th>Heat input [kJ/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1</td>
<td>9,1</td>
<td>200</td>
<td>14,7</td>
<td>1,163</td>
</tr>
<tr>
<td>Z2</td>
<td>9,1</td>
<td>200</td>
<td>15,4</td>
<td>1,218</td>
</tr>
</tbody>
</table>

2.3. Preparation of samples for analysis

From the produced welds specimens for tensile strength testing, and macrostructure analysis have been sectioned perpendicular to the welding direction using a circular band saw. Specimens for tensile strength test have been machined to required dimensions using a universal milling machine according to the requirements of the standard HRN EN ISO 4136:2013.

Specimens for analysis of macrostructure have been ground and polished using sandpapers: 1) P320, 2) P500, 3) P1000, 4) P2000 and 5) P4000. After polishing the specimens were etched for 40 s in reagent composed of NaOH and H$_2$O in proportion 2:3 and using DC current with voltage 2 V.

Specimens for corrosion resistance analysis according to standard ASTM G48-03 (method – A) have been plasma cut in dimensions 100 × 45 mm and washed with hot water to eliminate grease and impurities from the surface.

3. Results

3.1. Visual control

During welding with active flux, the weld pool was calm as it is characteristic for the TIG welding process. There were no spatters on the surface of the material around the produced welds. Sample 1A has a wider bead on the plate weld in comparison with sample 3A. Heat affected zone and the root of the weld are wider on the sample 3A in comparison with sample 1A. Welds produced with higher current (samples 2A and 4A) have the same influence of the A-TIG welding on the width of the bead on the plate weld. Sample 4A has sufficient penetration on the root side and narrower bead on plate width in comparison with sample 2A that is without root penetration. The difference between samples made with the second shielding gas (Ar + 2,5 % N$_2$) is the same as with 100 % Ar.

Figure 2 presents weld face and weld root on Z1 specimen. Figure 3 presents weld face and weld root on Z2 specimen. Appearance of the weld on the face side on both samples is very similar and depends only on the guidance of the electric arc. At the root side of the specimen Z1 lack of fusion can be observed after a few centimetres of a correct joint. The reason can be in the incorrect guidance of the electric arc after half of the path. At the root side of the specimen Z2 full penetration can be observed.
3.2 Macrostructure analysis

Macrostructure has been examined on a LEICA MZ6 stereomicroscope. Figure 4 presents a comparison of geometrical features in the produced bead on plate welds in the first part of the experiment. Samples made with 100 % Ar shielding gas are located on the left and samples made with Ar + 2,5 % N₂ are located on the right side of the figure 4. The difference of the geometrical features in dependence on the shielding gas type is clearly seen.

When Ar + 2,5 % N₂ has been used, the produced bead on plate welds have wider and shallower penetration in comparison with 100 % Ar shielding gas. Sufficient penetration through the whole thickness has only been achieved when welding current was 200 A and welding speed was 7,8 cm/min.

Figure 5 presents geometrical features of the produced welds Z1 and Z2. Both welds have a minimal face and root reinforcement but have proper shape. Specimen Z1 has a face width 8,1 mm and root reinforcement 0,3 mm. Specimen Z2 made with Ar + 2,5 % N₂ has a smaller face width, 7,6 mm and the root reinforcement 0,4 mm. Transition from an elongated base metal microstructure (obtained with forming of the sheets) to the weld metal microstructure is clearly seen on both welds. It is also possible to see molten metal flow contours from the outside to the inside. This feature is a clear footprint of the Marangoni's effect.

3.3. Tensile strength testing

The uniaxial tensile testing of the specimens has been conducted according to HRN EN ISO 4136:2013 standard [13]. Sample Z1 welded with 100 % Ar shielding gas has a fracture in the heat affected zone. Sample Z2 welded with mixture shielding gas 2,5 % N₂ and 97,5 % Ar has a fracture in the base material approx. 40 mm far from the weld centre. Table 3 presents results of the transversal tensile strength testing of the produced welds. Both welds have similar mechanical properties. Measured mechanical properties of the produced weld Z2 also fulfill requirements of the HRN EN 10088-2:2015 standard for the base material.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$R_m$ [N/mm²]</th>
<th>$R_{p0,2}$[N/mm²]</th>
<th>$S_0$[mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1</td>
<td>773,23</td>
<td>679,12</td>
<td>176,70</td>
</tr>
<tr>
<td>Z2</td>
<td>776,45</td>
<td>683,21</td>
<td>178,57</td>
</tr>
</tbody>
</table>

3.4. Corrosion resistance analysis

Corrosion resistance analysis of the produced welds has been conducted according to the standard ASTM G48 - 03 - method A - Ferric chloride pitting test) [14]. Samples were immersed in 10% solution of FeCl₃ in H₂O with a temperature of 50°C for a period of 48 h. Figure 6 presents samples after corrosion analysis. It can be observed that most of the pits have been developed in the weld metal on samples 1A, 3A and 4A. Weld metal on sample 2A is free of any pits. Samples welded with mixture shielding gas 2,5% N₂ and 97,5% Ar (1B, 2B, 3B and 4B) are free of pits in the weld metal and the heat affected zone. However, some pits occurred in the base material a few millimeters away from the heat affected zone. A-TIG welding resulted with less pits (3B and 4B) in comparison with conventional TIG welding (1B and 2B).
4. Conclusions

From the obtained results in this investigation the following conclusions can be summarized:

a) When comparing bead on plate width A-TIG welding produces narrower welds in comparison with conventional TIG. The same influence is observed when welding with current 160 A and with 200 A.

b) Appearance of the weld on the face side of samples welded with A-TIG and conventional TIG welding is almost the same and depends only on the guidance of the electric arc.

c) Macrostructure analysis of geometrical features of the produced bead on plate welds has confirmed that A-TIG welding intensifies the penetration and produces narrower and deeper welds. Shielding gasses used in this experiment have small influence on the geometrical features of the produced welded joints. Full penetration has been achieved only in A-TIG welding with 200 A and with welding speed 7.8 cm/min.

d) Transversal tensile testing of the produced welds has confirmed that both shielding gases influence similar on the tensile strength. Measured mechanical properties of the produced welds fulfill requirements of the standard EN 10088-2:2015 for the base material.

e) Corrosion resistance analysis of the produced welds has confirmed a positive effect of mixture shielding gas 2.5 % N₂ and 97.5 % Ar, welding speed and current and other constant parameters according to this experiment.

References

1. Introduction

In the production process of manufacturing of tubing stocks, the most time-consuming operation is scalping of openings from surface defects. When choosing effective ways of scalping, there are taken into account the defect depth and the nature of technological defects, as well as techno-economic study of the costs of production and waste convertibility. The methods of edge cutting scalping increasingly meet the above requirements [1]. Increase in performance when scalping the openings of tubing stocks from surface defects can be achieved by increasing the width of the cutaway layer, which is restricted only by the rigidity of technological system and does not have a significant impact on durability of the cutting tools [2].

The essence of the method of scalping the openings by a contour tool is that the work-piece 4 (Fig. 1) is fixed immovably on a special machine by means of the specific device and the contour tool 1 with a pusher 2 is moving along the axis of a processing opening. For centering the pusher with a contour tool on a processed surface of opening, the pusher design has the guiding bars 3. A significant feature of this method is that with appropriate selection of processing parameters (section thickness, cutting speed, cutting tool geometry), there are formed the pipe-like chips (flow chips) 5, which are supplied to the front of the cutting tool and can be easily removed from the cutting zone. When doing so, the stress state of the contour tool on nature is approaching the scheme of all-round compression, which is a positive factor in terms of increasing its durability.

Testing of this method on various processing materials (a work-piece with a length up to 1000 mm and diameters 60≤70 mm) showed that it is most effective use in the processing of tubing stocks from titanium alloys BT 0-0, BT 1-0, PT7M, by a high speed steel tool, at a cutting speed \( v = 10 \text{ m/min}, t = 1 \text{ mm} \). Besides, compared with a serial boring technology, the scalping performance increases by 3-5 times.

Removal of the defective surface layer to the desired depth is directly related to the processing accuracy of diametrical dimensions of a contouring tool.

Considering that machining accuracy is influenced by such complex interrelated factors as temperature and cutting force, wear bit, accuracy of machine and so on, then even the slightest increase in machining accuracy poses major difficulties. Therefore, in the manufacture of parts, in technological process there are sought to foresee such operations and cutting modes, in which the negative impact of the above factors on machining accuracy is minimal. And when for technical reasons, it is not possible to eliminate the negative influence of one or another factor on machining accuracy, then the correction enters accounting its influence. Hence, it is impossible to reduce the considerable power loads and the resulting elastic deformations in a technological system when processing the openings of tubing stocks by the contour tool (Fig. 1). It has been established that in this technological operation the contour tool is elastically deformed both in axial and radial directions, while machining accuracy of diametrical dimensions of the openings is affected by radial deformation.

Under radial deformation of the contour tool, its active diameter is getting smaller than the original one, and the cutting depth becomes less than the planned one. Therefore, the diametrical size of the machined opening is always smaller than the size of the contour tool by the magnitude of. In this regard, in the manufacture of the contour tool, it is necessary to make the appropriate correction on the diametrical size of its cutting edge depending on its elastic radial deformation.

Wear bit has a marked impact on machining accuracy of diametrical sizes. An essential factor influencing on tool wear is a cutting temperature, which should not exceed the red-hardness of tooling material. Therefore, to predict the effective application of the contour tool material by a cutting temperature when processing the tubing stocks from various materials, it is necessary to know the pattern of temperature distribution on the cutting part of the contour tool.

On the basis of the foregoing, there is a need for a methodology of calculation of the stress-strain state of the contour tool during the process of cutting.

Determination of the executing size of the contour tool's cutting edge and the areas of application of tooling material by a cutting temperature with a view to achieving machining accuracy of diametrical sizes, is a practical value of the proposed methodology.
2. Basic Part

2.1 Problem Statement

Consider processing of the inner surface of the tubing stock by the contour tool, which moves at a constant speed using the pusher, and cuts a thin layer (Fig. 1). We assume that, when cutting, the shear stresses reach the limit value, which is specific to the process material, and the pressure is set in the radial and axial directions at the point of contact.

The article [3] describes the basic differential equations of two-dimensional nonstationary thermoelasticity problem for calculating the contour tool:

\[
\frac{\partial U}{\partial r} = \sigma_r \left(1 + \mu \right) \left(1 - 2\mu \right) - \frac{\mu}{E} \left(\frac{\partial W}{\partial Z} + \frac{U}{r} \right) + \frac{1 + \mu}{E} \alpha T;
\]

where \( z = l, \sigma_z = P_{b1}, z = 0, \sigma_z = P_{b2} \)

\[
\frac{\partial U}{\partial Z} = \sigma_z \left(1 + \mu \right) \left(1 - 2\mu \right) - \frac{\mu}{E} \left(\frac{\partial W}{\partial r} + \frac{U}{r} \right) + \frac{1 + \mu}{E} \alpha T
\]

at the point of contact

\[
r = \frac{D}{2}; \quad Z = l;
\]

\[
\frac{\partial U}{\partial r} = \frac{1 - \mu}{E} \left( P_{b1} - \mu \right) \frac{U}{r} \mu (1 + \mu) \alpha T;
\]

\[
\frac{\partial U}{\partial Z} = \frac{2(1 + \mu) \sigma_a}{E} - \frac{\partial W}{\partial r} \left( \tau = \tau_a \right).
\]

With a continuous contour tool on the axis symmetry:

\[
r = 0; \quad \frac{\partial U}{\partial r} = 0; \quad \frac{\partial W}{\partial r} = 0; \quad \frac{\partial T}{\partial r} = 0,
\]

stress tensor component; \( \varepsilon_{ij}, \dot{\varepsilon}_{ij} \) - strain and strain-rate tensor components; \( P_{b1}, P_{b2} \) - tool surface pressures; \( \tau_a \) - shear stress on the external surface; \( d, D \) - internal and external diameters of the tool, respectively; \( l \) - the width of the tool.

The stress and strain tensor components are determined by the thermoelasticity dependences \([4]\) :

\[
\sigma_{r} = \frac{E}{(1 + \mu)(1 - 2\mu)} \left[ (1 - \mu) \frac{\partial U}{\partial r} + \mu \left( \frac{\partial W}{\partial Z} + \frac{U}{r} \right) - (1 + \mu) \alpha T \right];
\]

\[
\sigma_{Z} = \frac{E}{(1 + \mu)(1 - 2\mu)} \left[ (1 - \mu) \frac{\partial W}{\partial Z} + \mu \left( \frac{\partial U}{\partial r} + \frac{U}{r} \right) - (1 + \mu) \alpha T \right];
\]

\[
\varepsilon_{r} = \frac{\partial U}{\partial r}; \quad \varepsilon_{z} = \frac{\partial W}{\partial Z}; \quad \varepsilon_{\Theta} = \frac{U}{r}; \quad \gamma = \frac{\partial U}{\partial Z} + \frac{\partial W}{\partial r}.
\]
2.2 Solution to the Problem

Integration of a systems of differential equations (1) with initial and boundary conditions (2) and (3) is carried out by finite difference method. The finite difference mesh is shown in Fig. 2.

For the numerical solution, we shall introduce the dimensionless quantities:

\[
\begin{align*}
\bar{T} &= T/T_0; \quad \bar{Z} = Z/l; \quad \bar{\tau} = \tau (D/2); \quad \bar{t} = t/t_0; \\
\bar{P}_a &= P_a/E; \quad \bar{P}_b = P_b/E; \quad \bar{\tau}_a = \tau_a/E; \quad 0 \leq \bar{Z} \leq 1; \\
d/\bar{D} &\leq \bar{\tau} \leq 1; \quad 0 \leq \bar{t} \leq l_0/l,
\end{align*}
\]

where \(l_0\) — the length of work material; \(E\) — modulus of material elasticity.

In terms of the dimensionless quantities, the above stated equations will take the following form:

For the numerical solution, we use the finite difference schemes [5]:

\[
\begin{align*}
\frac{\partial \bar{T}}{\partial \bar{\tau}} &= \frac{\bar{U}_{i,j+1} - \bar{U}_{i,j-1}}{2\bar{\tau}}; \\
\frac{\partial \bar{U}}{\partial \bar{Z}} &= \frac{\bar{U}_{i+1,j} - \bar{U}_{i-1,j}}{2}\bar{D}; \\
\bar{U} &= \frac{\partial \bar{T}}{\partial \bar{Z}} - \frac{\bar{U}}{\bar{\tau}}; \\
\frac{\partial^2 \bar{U}}{\partial \bar{\tau}^2} &= \frac{\bar{U}_{i+1,j+1} - 2\bar{U}_{i,j+1} + \bar{U}_{i-1,j+1}}{\Delta \bar{\tau}^2};
\end{align*}
\]

Similar schemes are also used for the functions \(\bar{T}\) and \(\bar{W}\).

In the finite differences, the differential equations (6) will be written down as follows:

\[
\begin{align*}
\frac{\partial \bar{T}}{\partial \bar{\tau}} &= \frac{1}{\Delta \bar{\tau}} \left[ \bar{T}_{i,j+1} - \bar{T}_{i,j-1} \right] - \frac{1}{\Delta \bar{\tau}^2} \left[ \bar{T}_{i+1,j+1} - 2\bar{T}_{i,j+1} + \bar{T}_{i-1,j+1} \right] + \frac{4al}{V_c^2} \frac{\partial^2 \bar{U}}{\partial \bar{\tau}^2} \\
\frac{\partial \bar{U}}{\partial \bar{Z}} &= -\frac{\alpha_0 D}{\Delta \bar{\tau}} \left( \bar{P}_a \bar{r} - 1 \right); \\
\frac{\partial \bar{T}}{\partial \bar{Z}} &= -\frac{\alpha_0 D}{\Delta \bar{Z}} \left( \bar{T}_{i,j} - 1 \right); \quad \bar{Z} = 0:1;
\end{align*}
\]
\[ U_{i,j} = \left( \frac{U_{i,j+1} + U_{i,j-1}}{2} \right) + \frac{1 - 2\mu}{2(1 - \mu)} \left( \frac{D}{2l} \right) \frac{U_{i,j+1} + U_{i,j-1}}{\Delta Z^2} + \frac{1}{2(1 - \mu)} \left( \frac{D}{2l} \right) \frac{l}{D} \frac{1 - \mu}{2\DeltaZ} \times \]
\[ \times (\bar{W}_{i,j+1} + \bar{W}_{i,j} + \bar{W}_{i,j-1} - \bar{W}_{i,j+1}) + \frac{1 + \mu}{1 - \mu} \frac{\alpha_0}{l} \cdot \frac{\Delta Z}{l} \]
\[ \Delta \left( \frac{2}{\Delta Z^2} + \frac{1}{(1 - \mu)\Delta Z^2} \right) \]
\[ \{ 2 \Delta \left( \frac{2}{\Delta Z^2} + \frac{1}{(1 - \mu)\Delta Z^2} \right) \} \]

Initial and boundary conditions in the finite differences:
\[ T_{i,j}(0) = \text{1}; \]
\[ r = 0; \quad T_{i,j} = T_{i,j+1}; \quad \bar{W}_{i,j} = \bar{W}_{i,j+1}; \]
\[ \bar{W}_{i,j} = \bar{W}_{i,j+1}; \]
\[ r = 1; \quad T_{i,j+1} = T_{i,j} - \frac{\alpha_0}{l} \Delta t \left( T_{i,j} - 1 \right); \]
\[ Z = 0; \quad \bar{U}_{i,j} = \bar{U}_{i,j+1}; \]
\[ Z = 1; \quad \bar{W}_{i,j} = \bar{W}_{i,j+1}; \]
\[ r = 1; \quad \bar{U}_{i,j+1} = \bar{U}_{i,j} + 2\Delta Z \]
\[ \left( \frac{1 + \mu}{1 - \mu} \right) \frac{l}{D} \frac{1}{2(1 - \mu)} \left( \frac{\bar{W}_{i,j+1} - \bar{W}_{i,j-1}}{D} \right) + \frac{1}{2(1 - \mu)} \left( \frac{\bar{U}_{i,j+1} - \bar{U}_{i,j-1}}{\Delta Z} \right) \]

At the beginning of time integration, as a zero approximation by the coordinates of the functions \( U \) and \( \bar{W} \), we shall take the linear dependences, and for the temperature, we shall take adopt a uniform distribution. At each time step, the system of algebraic equations is solved by an iterative method, the strain rates deformation on the right side of the first equation (9) is determined as \( \dot{e}_{ij} = \frac{e_{ij} - e_{ij}}{\Delta t} \), where the values \( e_{ij} \) are taken from previous time step.

The stress-strain state and the temperature field of the contour tool were calculated during machining the openings of the tubing stocks from titanium alloy BT1-0, by means of the contour tool made of high-speed steel P6M5, for which the values are as follows:

\[ \alpha = 0.14 \text{ J/kg/K}; \quad \rho = 8.0 \times 10^3 \text{ kg/m}^3; \quad \lambda = 0.065 \text{ J/m.sec.K}; \]
\[ \mu = 0.32; \quad E = 22400 \text{ n/mm}^2; \quad \alpha_0 = 17 \text{ W/(m}^2 \text{ K}); \quad \text{cutting speed} \ V_c = 3.5 \text{ m/min}; \quad \text{machining diameter} \ D = 50 \text{ mm}; \quad \text{cutting depth} \ t = 1 \text{ mm}; \quad \text{the width of the tool} \ l = 20 \text{ mm}; \quad \text{the length of work material} \ l_0 = 400 \text{ mm}; \quad \text{radial component of cutting force} \ P_a = 900 \text{ n/mm}; \quad \text{axial component of cutting force} \ P_b = 1500 \text{ n/mm}; \quad \text{front clearance angle of the tool} \ \gamma = -15^0, \text{ back clearance angle} \ \alpha = 2^0. \]
3. Analysis of the Results

Calculation results (Fig. 3) demonstrate that the temperature of the cutting tool near the contact surface reaches a maximum value of about 300°C, i.e. is below the red-hardness of tooling material under consideration (620°C) and decreases slowly until \( \varphi = 0.85 \).

![Graph](image)

Fig.3. The results of the calculated temperature field \((T)\) and radial displacement \((U)\times10^3\)

Within \( \varphi = 0.5 – 0.85 \), temperature delivers more intensively by the linear principle. The above stated circumstance allows using effectively this tooling material for the given technological operation. The reliability of the obtained results of the temperature study the machining process with the contour tool, is proved by identical values of theoretical calculations \((300^0C)\) and experimental data \((285^0C)\). The radial displacements are mostly negative and accordingly, the point are moved toward the center of the tool. However, near the contact surface, there are also produced the slightly positive displacements.

In this example (Fig. 3), the value of a diametric correction \(\Delta K = 2U\), the radial displacements of the cutting edge of the contour tool \(U = 0.001\)mm. Therefore, with a machining diameter \(D = 50\) mm, the executing size of the contour tool’s cutting edge is \(D_K = D + \Delta K = 50 + 0.002 = 50.002\) mm.

4. Conclusion

1. When machining the openings of the tubing stocks by the contouring tool, to study the stress-strain state of the tool, it is advisable to consider the associated thermoelasticity problem, which is solved by a finite difference method.

2. The application of the proposed methodology in practice, the known variables (the geometry of the cutting tool \((\gamma, \alpha)\), components of cutting forces \((P_a, P_b)\), cutting mode elements \((V, t)\), as well as physical-mechanical properties of tooling material), will provide an opportunity for determining the executing size of the contour tool for a specific size machining and the area of application of tooling material, by the above mentioned algorithm.

5. Literature

1. Introduction

Due to the limited energy resources and ever-increasing energy demand, systems with high energy efficiency are gaining importance. It is also known that miniaturized manufacturing, which show a trend of continuous decrease in the dimensions of devices (such as shell and tube heat exchanger and plate heat exchanger) that exchange thermal energy have been popular in recent years. In other words, interest in small sized and high efficiency heat exchangers is increasing day by day. The importance of heat transfer enhancement techniques can be better understood by considering the coercive conditions for satisfying energy demands at the same thermal powers using thermal energy sources of the same and/or lower temperature by heat exchangers produced with less material and operating with less working fluid. Some of these heat transfer enhancement techniques are passive methods not requiring external power such as increasing the heat transfer area (corrugated and finned surfaces), roughening of surfaces, solid additives for liquids (e.g. addition of nano-material), while others are active methods requiring external power such as producing turbulence and/or promoting turbulence intensity, vibrating the surface, and vibrating the fluid [1,2].

The heat transfer area per unit volume in heat exchangers is referred to compactness. In other words, when smaller hydraulic diameter channels are used in a heat exchanger, the surface area that can be used for heat transfer is also increased. The main goal in terms of thermally and hydraulically in compact heat exchangers is to minimize the total cost by reducing physical dimensions of the heat exchanger for a given thermal power under defined temperature limitations, and to make the heat exchange between the two fluids more efficient. If the hydraulic diameter of tube used in shell and tube heat exchangers is below 5 mm, such heat exchangers are considered as compact. Depending on the application, the total heat transfer coefficient is increased, while the required surface area can be reduced by using flat or augmented heat transfer surfaces in heat exchangers. Thus, higher thermal power transmissions are obtained without changing the defined thermal conditions. Heat exchangers have been used in many industrial plants and applications such as oil refineries, thermal and geothermal power plants, and chemical industry etc. Although there are variously designed heat exchangers, the shell and tube heat exchangers are the most preferred type because they are cheap, easy to manufacture and to maintain [3-7].

One of the passive heat transfer enhancement techniques is the addition of solid materials (micro- and nano-sized particles) in a certain proportion to commonly used working fluids (such as water, oil, ethylene glycol). Thus, the working fluids commonly used in heat exchangers are converted into suspensions with improved thermophysical properties. These suspensions, referred to as nanofluids, find new applications every day. High thermal conductivity, which is important in terms of heat transfer from the changing thermophysical properties (specific heat, density, heat conduction coefficient and viscosity) of the fluid and the other mechanisms specific to nanofluids that facilitate the diffusion of heat in the fluid, increase the convective heat transfer coefficient. With the developing technology, production of solid materials (particles) with small dimensions in the nanometer range is becoming widespread and their costs are constantly decreasing.

Micro materials have disadvantages when compared to nano materials, such as faster sedimentation, 1000 times smaller surface/volume ratios, lower thermal conductivity when added to liquids at the same concentration, clogging of very small diameter (micro) channels, more mechanical wear on contact surfaces and more increase in pumping power. When using with very small solid material sizes and small volume fractions, the importance of problems such as clogging and increased pumping power are less for nanofluids prepared from nano-materials. Furthermore, the large surface area of nanoparticles increases their stability in the fluids and slows down the sedimentation. Colloids mixture formed by the addition of nano-sized solid materials into the fluid are referred to as nanofluids. The higher heat transfer rates are obtained with nanofluids compared to commonly used working fluids. These fluids are becoming increasingly popular in many applications, such as nuclear reactors, engines of vehicles, air conditioning systems, processors of mobile phones and computers (smart liquids) and even to the cooling of equipment with high thermal density such as medical devices. The enhancement effects of nanofluids on heat transfer coefficients can be summarized as follows [8-11].
The high surface area/volume ratio of suspended nano-materials in the fluid increases the thermal capacity and the effective thermal conductivity of the fluid.

The collisions of nano-materials with each other and with the contact surfaces also increases the intensity of interactions for the working fluid molecules with each other and with the contact surfaces.

The turbulence intensity and irregular fluctuations in the flow are increasing.

Random scattering of nano-materials in the fluid contributes to the flattening of the temperature gradient in the direction perpendicular to the flow.

Large hydraulic diameter tubes commonly used in the shell and tube heat exchangers also increase the amount of fluid needed for operation. The use of working fluid can be reduced by decreasing the hydraulic diameters of the tubes. However, nanofluids increase the risk of clogging by clumping and/or agglomerating in micro and nano channels and this makes mini channels the most suitable alternative for nanofluids applications. In addition, the use of mini channels in the shell and tube heat exchangers has additional advantages, such as reduction of the dimensions, minimizing space and reduction in weight, as well as increasing thermal efficiency and compactness. The thermal efficiency of the heat exchanger can be further increased if these factors are supported by the use of nanofluids as a working fluid. Mini channels, both reduce dimensions of heat exchangers and the amount of working fluid used and so energy, material and cost savings can be achieved. Depending on the hydraulic diameter used in the flow channels, the mini channel definition range is 3 mm ≥D ≥ 200 μm according to Kandlikar and Grande, whereas it is 6 mm ≥D ≥ 1 mm according to Mehendale et al. Some of the advantages of using nanofluids in the shell and tube heat exchangers were summarized below.

Arunachala et al. investigated experimentally heat transfer on the shell and tube sides by using water and 4 different concentrations (0.5%, 1%, 1.5%, 2%) of Al₂O₃/water nanofluids (average material diameter of 40 nm) in the shell and tube heat exchanger. The tube length of the heat exchanger is 1000 mm, the outer diameter of tube is 13 mm, the wall thickness is 1 mm and the tube arrangement (tube pitch ratio 1.5) is square. The shell of the heat exchanger made of PVC has a length of 1100 mm, an outer diameter of 63 mm and a wall thickness of 5 mm and the baffle cut ratio is 25%. In the experiments where nanofluids for 2% volumetric concentration and tube-side flow rates were kept constant at 1-2, 2-3 and 3-4 L/m, heat transfer enhancement compared to water was reported to be 34%, 44.8% and 57.6% respectively, in the laminar flow (695 < Re < 1396) conditions [15].

Ramesh and Vivekananthan studied the heat transfer in a shell and tube heat exchanger using γ-Al₂O₃/water (average material diameter of 20 nm) nanofluids and ethylene glycol. In the experiments performed at 6 different volumetric concentrations (0.2%, 0.5%, 1%, 1.5%, 2% and 2.5%), it was stated that there was an enhancement in the convective heat transfer coefficient as the nanofluids concentration increases. But a decrease in the convective heat transfer coefficient was reported after 2.5% volumetric concentration, compared to ethylene glycol and water [16].

Farajollahi et. al. investigated experimentally tube side thermal performance of γ-Al₂O₃/water (average material diameter of 25 nm and 0.3%, 0.5%, 0.75%, 1%, 2% volume concentrations) and Ti₃O₇/water (average material diameter of 10 nm and 0.15%, 0.3%, 0.5%, 0.75% volume concentrations) nanofluids in a shell and tube heat exchanger made of stainless steel under turbulent flow (20,000 < Re < 70,000) conditions. They used a single tube-pass heat exchanger with 16-tubes and a tube pitch of 8 mm. The wall thickness of stainless steel tubes was 1 mm with an outer diameter of 6.1 mm and a length of 815 mm. The shell inner diameter is 55.6 mm, the distance between the baffles is 50.8 mm and cut of baffles is 25%. The researchers found that the overall heat transfer coefficients in the water to water experiments were consistent with Dittus-Boelter correlation with a ±9.2% difference. In addition when used nanofluids instead of water, convective heat transfer coefficient was augmented 9.2%, 10.87% and 12.4% for 0.01%, 0.03% and 0.04% volume fractions respectively and also they stated that pumping power increased with increase in the volume fraction and viscosity of the nanofluids [17].

Godson et al. studied experimentally tube side heat transfer from 3 different volumetric fractions (0.01%, 0.03% and 0.04%) of hot silver/water (average material diameter of 54 nm) nanofluids to cold water in a single pass shell and tube heat exchanger with counter flow, in the range of Reynolds 5000-25,000. In the heat exchanger where 25 copper tubes are used, inner diameter of the tubes is 4 mm, while the outer diameter is 6 mm and the length (L/D=175) is 700 mm. The shell made of stainless steel had an inner diameter of 150 mm and an outer diameter of 200 mm. The researchers found that Nusselt numbers obtained from water to water experiments were consistent with the Dittus-Boelter correlation with a ±9.2% difference. In addition when used nanofluids instead of water, convective heat transfer coefficient was augmented 9.2%, 10.87% and 12.4% for 0.01%, 0.03% and 0.04% volume fractions respectively and also they stated that pumping power increased with increase in the volume fraction and viscosity of the nanofluids [18].

Mapa and Mazhar experimentally investigated tube side heat transfer of a MC-STHE with an inner diameter of 2.4 mm, wall thickness of 0.25 mm, and length of 248 mm (L/D=103) and manufactured from 37 stainless steel tubes. They studied heat transfer from the hot water and hot copper-oxide/water nanofluid at two different volume fractions of 0.01% and 0.02% (average material diameter of 29 nm) passing through the tube (50<Re<450) to the cold water on the shell side. Researchers stated that the nanofluids enhanced heat transfer and the presence of nanomaterials in the fluid thinned the thermal boundary layer, but the thermal power did not increase after Reynolds 200 [19].

In this study, the tube side thermal and hydraulic performances of water and two different low volume fractions Al₂O₃/water (0.02% and 0.2%) nanofluids were investigated experimentally in a MC-STHE designed based on Kern method and Kandlikar and Grande mini channel approach. The experiments were carried out with hot water on the shell side and cold water and cold nanofluids on the tube side in the MC-STHE. The average particle diameter of the Al₂O₃ nanomaterial used in the preparation of the nanofluids is 50 nm. During the experiments, shell side flow rate was kept constant at 180 L/h, while the tube side flow rate was changed between 60-600 L/h. The enhancement and deterioration effects in convective heat transfer and hydraulic performance for the use of nanofluids instead of water on the tube side of MC-STHE were experimentally investigated and discussed.

### 2. Experimental setup

The inner and the outer diameters of the tubes used in MC-STHE which thermal and hydraulic performance investigated experimentally were 2 mm and 3 mm respectively. The rotated equilateral triangular tube arrangement (p = 1.5 Dₜ) having a higher heat transfer coefficient on the shell side was preferred in the design of tube bundle. A total of 13 tubes were used in the tube bundle and L/D ratio was selected as 120 in determining the tube lengths. 4 baffles with 25% baffle cut were used on the shell side. The material of the shell and baffle plates is cast cestamide, while the material of tubes is copper. The experiments have been carried out under steady state and at the room temperature. A schematic drawing of the experimental setup and photo of the test section were presented in Fig 1. In the experimental setup, there are two cycles that heat removed (hot fluid) and heat absorbed (nanofluids). The flow rates of hot and cold fluids were measured by float type flow meters (rotameters) and measurement accuracy of the flow meters was controlled by weighted vessel method.
\[ \rho_{nf} = (1 - \theta)\rho_w + \theta \rho_{nm} \]  

(1)

Nanofluids specific heat which was analytically obtained and confirmed by experimental studies performed by Zhou and Ni [24] for Al\textsubscript{2}O\textsubscript{3}/water nanofluid at room temperature was

\[ c_{p,nf} = \frac{(1 - \theta)c_{p,w} + \theta c_{p,\text{nm}}}{\rho_{nf}} \]  

(2)

There are many different expressions for thermal conductivity and viscosity of nanofluids in the literature. In this study, the simplest and most commonly used expressions suitable for Al\textsubscript{2}O\textsubscript{3}/water nanofluids and low volume fractions (<0.5%) were preferred.

Thermal conductivity expression for Al\textsubscript{2}O\textsubscript{3}/water nanofluids by Timofieeva et al [25]:

\[ k_{nf} = (1 + 3\theta)k_w \]  

(3)

Nanofluid viscosity, referred Einstein equation [26], used for nanofluids with volume fractions of less than 2%.

\[ \mu_{nf} = (1 + 2.5\theta)\mu_w \]  

(4)

In the above expressions, the subscripts nf, nm, w and \( \theta \) refer to nanofluid, nano material and base fluid water, and a volume fraction of nanofluids, respectively. The thermophysical properties of water are calculated from the expressions given for the temperature range 0-100°C in Ref. [27].

4. Thermal and hydraulic performance calculations

The equations used in the calculation of experimental thermal and hydraulic performance in the MC-STHE prototype designed using Kern method are as follows.

Thermal powers for hot fluid and cold fluid (nanofluid):

\[ Q_h = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o}) \]  

(5)

\[ Q_{nf} = \dot{m}_{nf} c_{p,nf}(T_{nf,i} - T_{nf,o}) \]  

(6)

Here, the subscripts nf and h refer to cold nanofluids on the tube side and hot water on the shell side, respectively, \( \dot{m}_h \) and \( \dot{m}_{nf} \) to mass flow rates, \( c_{p,h} \) and \( c_{p,nf} \) to specific heats, \( T_{h,i} \), \( T_{h,o} \), \( T_{nf,i} \), \( T_{nf,o} \) to outlet temperatures, and \( Q_{nf} \) to inlet temperatures. Average thermal power in the MC-STHE:

\[ Q_{\text{ave}} = (Q_h + Q_{nf}) / 2 \]  

(7)

\[ Q_{\text{ave}} = UAF AT_{nf,in} \]  

(8)
Logarithmic mean temperature difference for counter flow:

$$\Delta T_{lm} = \frac{(T_{s1} - T_{s2}) (T_{w1} - T_{w2})}{\ln\left(\frac{T_{s1} - T_{s2}}{T_{w1} - T_{w2}}\right)}$$ (9)

Convective heat transfer coefficient for shell side (hot water) according to Kern method [29]:

$$h_s = k_s \text{ Re } Pr \frac{D}{\eta |j_s|}$$ (10)

Here, $j_s$ is obtained from graphs proposed by Kern, depending on the baffle cut used on the shell side, tube arrangement and the Reynolds number. Overall heat transfer coefficient ($U$) according to inner surface of tubes with circular cross section:

$$\frac{1}{U} = \frac{1}{h_s} + \frac{D_s}{2k}\ln\frac{D_s}{D} + \frac{D}{D_s h_w}$$ (11)

The tube side convective heat transfer coefficient for nanofluid $h_{nd}$ is calculated by the above equation. The pumping power selected as hydraulic performance criterion [30]:

$$W_p = \frac{\dot{m} \Delta p}{\dot{V}}$$ (12)

Here, $\dot{V}$ is the volume flow rate, and $\Delta p$ is the pressure drop between the inlet and outlet of the tubes. Efficiency index, in which increase in heat transfer and pressure drop compared to water is calculated together, defined in order to evaluate enhancement in heat transfer by using nanofluids at similar Reynolds numbers [1]:

$$\eta = \left(\frac{j_{nf}}{j_w}\right) / \left(\frac{j_{nf}}{j_w}\right)$$ (13)

### 5. Uncertainty analysis

Measurement uncertainties may occur due to sensitivities of measurement equipment used in the experimental study, the accuracy of measurement, reading error of the experimenter, ambient conditions (such as heat, light, humidity and electronic oscillations) and error ratios of the equipment. The uncertainties in the experimental results were calculated using the method proposed by Kline and McClintock [31]. Relative errors of the measuring equipment used in the experimental setup are 4% for the flow meter and 1% for the thermocouples. The results of the average uncertainty calculated were given in Tab. 1.

### 6. Result and discussion

The prototype of a MC-STHE designed for an average thermal power of 1.15 kW using Kern method was manufactured in Gerede Vocational School workshop. Water to water test experiments were carried out to check the accuracy of measurements with experimental setup, before the thermal and hydraulic performance measurements for water and nanofluids in the MC-STHE. While the heat exchanger was very well insulated against the surroundings during the experiments, it was observed that there were heat losses and thermal power differences between the shell side and tube side. In the final experiments with prepared nanofluids and water, the average thermal power differences between the shell and tube sides were approximately 7%. The overall heat transfer coefficient ($U$) for water and nanofluids was obtained from Eq. (8), and the shell side convective heat transfer coefficient was obtained from Eq. (10) and, experimental convective heat transfer coefficients for water and nanofluids on the tube side from Eq. 11 were obtained.

In case of the shell side flow rate is kept constant at 180 L/h, the change of experimental convective heat transfer coefficients, heat transfer enhancement ratios, efficiency indexes and pumping powers obtained in the range of 300-600 L/h flow rates for water and nanofluids on the tube side has been shown in Fig. 2-5 depending on the volume flow rates.

<table>
<thead>
<tr>
<th>Table 1: Uncertainty result.</th>
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<tr>
<td>Water</td>
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<td>Reynolds number</td>
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<td>Tube side thermal power</td>
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<td>Shell side thermal power</td>
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<td>Overall heat transfer</td>
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<td>coefficient</td>
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<td>Logarithmic mean</td>
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As seen in Fig. 2, the experimental convective heat transfer coefficients, which are the thermal performance indicators, showed a similar trend for water and nanofluids in the range of volume flow rates 60 to 125 L/h (in the region where the flow is considered laminar). However, it was found that convective heat transfer coefficients obtained with nanofluids gave results under the convective heat transfer coefficients for water. Therefore, low volume fraction nanofluids have an effect on decreasing the convective heat transfer coefficient compared to water. In other words, the use of nanofluids in the laminar region has been found to have adverse effects on the convective heat transfer coefficient. The average decrease in the convective heat transfer coefficient compared to water was −14% for 0.02% volume fraction while was −5% for 0.2% volume fraction.

Both water and nanofluids showed a similar trend as in the laminar region in the volume flow rate range of 150-350 L/h (where the flow is considered in the transition region). However, it has been observed that the results for nanofluids were above the convective heat transfer coefficient of water in the range of volume flow rates 150-350 L/h and therefore, the use of nanofluids had a positive effect. The use of nanofluids in the transition region was provided an average enhancement of 3.7% for 0.02% volume fraction compared to water in the convective heat transfer coefficient, while providing an average 13% enhancement for 0.2% volume fraction. These results indicate that the random motion of nanoparticles added to water and their interactions with each other slightly increased the fluctuations in the channel through which the flow passes. In addition, the changing thermophysical properties of the fluid were also effective in the increase of the convective heat transfer coefficient.

The similar trend between water and nanofluids was impaired in the range of volume flow rates 350-600 L/h (turbulent region), but the similar trend for different volume fractions of nanofluids has been continued. In other words, the use of nanofluids in this range of volume flow rates delayed the transition to the fully developed turbulent regime and extended the transition region. The average enhancement in convective heat transfer coefficient compared to water was obtained 25% for the 0.02% volume fraction, and 34% for the 0.2% volume fraction. The intensity of fluctuations of the nano materials and their effects on the convective heat transfer have been increased much more with increasing volume flow rate as in the range of 150-350 L/h. Therefore, the use of nanofluids instead of water even in very small volume fractions such as 0.02% significantly augmented the convective heat transfer in the range of 350-600 L/h.
The convective heat transfer enhancement ratios of nanofluids compared to water were given in Fig. 3. The enhancement ratios in the range of volume flow rates 60-125 L/h were lower than one, while the enhancement ratios in the range of 150-600 L/h were higher than one. The lowest and highest enhancement ratios in the flow range of 60-600 L/h were between 0.82 and 1.66 for 0.02% volume fraction, while for 0.2% volume fraction between 0.9 and 1.74%. The results of convective heat transfer coefficient and enhancement ratio were evaluated together, while the use of nanofluid on the tube side of MC-STHE has a negative effect at the volume flow rates up to 125 L/h. It has been found that the negative effects were disappeared and the positive affects of the nanofluids has been become apparent gradually after 125 L/h.

In Fig. 4, the change in pumping power, selected for the hydraulic performance variable of water and nanofluids, was given by volume flow rate. The pumping power of nanofluids at constant volume flow rate is higher than water. The pumping power of the nanofluids is higher than that of water, because the flow induced pressure drop depends on density and viscosity of the fluid. The nano materials added to the water were increased the density and viscosity of the fluid. The average pumping power is 4% higher for 0.02% and 42% higher for 0.2% compared to water in the range of volume flow rate 60-600 L/h. In high volume flow rates, the volume fraction of nanofluids had less effect on pumping power than water, whereas in low volume flow rates, it had a greater effect on pumping power than water. When the heat transfer in a MC-STHE was desired to improve with nano fluids, pumping power and heat transfer results should be evaluated together and the increase in pumping power, depending on the selected volume ratio must be considered.

It is understood that a significant improvement was made when the value of the efficiency index, used to evaluate the effect of the nanofluids on improving the heat transfer, is greater than one. According to this definition and to Fig. 5, upwards 350 L/h for a 0.02% volume fraction and upwards 300 L/h for a 0.2% volume fraction, the use of nanofluids was meaningful in terms of the heat transfer enhancement.

Efficiency indexes were obtained as 1.67 and 1.4 for 0.02% and 0.2% respectively at the highest volume flow rate (600 L/h) in the study. According to Fig. 2, the highest convective heat transfer coefficients in the range of volume flow rates 60-600 L/h were obtained for 0.2% volume fraction. In this volume flow rate range, the Prandtl numbers for the volume fractions of 0.02% and 0.2% are very close to each other.

Due to the changing thermophysical properties of nanofluids, higher Reynolds numbers were obtained for 0.2%. As can be seen from the definition of Colburn factor, increase in the Reynolds number with the use of nanofluids was less than increase in the convective heat transfer coefficient and so the increase in average Colburn factor at 0.2% volume fraction was greater than 0.02% volume fraction. According to the results of $f_{nf}/f_w$ ratio in the numerator of efficiency index, the increase in Colburn factor was obtained higher for 0.2% volume fraction. Also, the $f_{nf}/f_w$ ratio in the denominator of the efficiency index has been found higher at 0.2% volume fraction. Because of the effectiveness index is inversely proportional to $f_{nf}/f_w$ ratio (Eq. 13), better enhancement with 0.02% volume fraction nanofluid has been determined in terms of the efficiency index in the flow rate range of 60-600 L/h. Empirical correlations in the 95% confidence interval have been proposed to correlate the convective heat transfer coefficient results obtained from experimental studies with the Reynolds number, Prandtl number and the volume fraction of nanomaterial. Proposed correlations are given in Tab. 2.
### Table 2: Empirical correlations for water and nanofluids.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Comments and Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Nu = 0.00093 \ Re^{1.183} \ Pr^{1/3} )</td>
<td>Water, ( 1900 &lt; Re &lt; 5100 ), ( Pr=6.7 ), ( R^2 = 0.995 )</td>
</tr>
<tr>
<td>( Nu = 0.43 \ Re^{1.183} \ Pr^{1/3} )</td>
<td>Water, ( 5100 &lt; Re &lt; 10,000 ), ( Pr=6.7 ), ( R^2 = 0.941 )</td>
</tr>
<tr>
<td>( Nu_{0.02%} = 0.000876 \ Re^{1.195} \ Pr^{1/3} )</td>
<td>( Al_2O_3/water ) ( (\theta = 0.02%) ), ( 1000 &lt; Re &lt; 10,000 ), ( Pr=6.67 ), ( R^2 = 0.994 )</td>
</tr>
<tr>
<td>( Nu_{0.2%} = 0.000734 \ Re^{1.219} \ Pr^{1/3} )</td>
<td>( Al_2O_3/water ) ( (\theta = 0.2%) ), ( 1000 &lt; Re &lt; 10,000 ), ( Pr=6.64 ), ( R^2 = 0.983 )</td>
</tr>
<tr>
<td>Alternative correlation for ( Al_2O_3/water ) nanofluids</td>
<td></td>
</tr>
<tr>
<td>( Nu_{0.02%} = 0.0009 \ Re^{1.201} \ Pr^{1/3} \theta^{0.0249} )</td>
<td>( Al_2O_3/water ) ( (\theta &lt; 0.2%) ), ( 1000 &lt; Re &lt; 10,000 ), ( Pr=6.65 ), ( R^2 = 0.988 )</td>
</tr>
</tbody>
</table>

### 7. Conclusions

In this study, a MC-STHE is designed using the proposed relations for macro pipes by Kern. According to the design conditions, average thermal power of 1-1.5 kW, single shell, single tube pass and counter flow heat exchanger is manufactured. The volume flow rate of the shell side was kept constant at 180 L/h during the experiments. The volume flow rate of the tube side was changed from 60 to 600 L/h. In the experimental studies, hot water on the shell side and cold water and \( Al_2O_3/water \) nanofluids, prepared in two different low volume fractions, on the tube side were used. The selected thermal and hydraulic performance criterions, convective heat transfer coefficient and pumping power were obtained depending on the volume flow rate by using the tube side experimental results. In addition, the efficiency index selected for the evaluation of thermal and hydraulic affects together was also calculated for experimental results. The results obtained in this study are as follows:

- It was observed that experimental convection heat transfer coefficients and pumping power increased with increasing Reynolds number and nano material’s volume fraction.
- The use of nanofluids, in the range of volume flow rates 60-125 L/h, adversely affected the convective heat transfer coefficient and deteriorated the convective heat transfer coefficient compared to water.
- In the volume flow rate of 150-350 L/h, the nanofluids positively affected the convective heat transfer coefficient, whereas even in very small volume fractions, the use of nanofluids in the MC-STHE significantly increased the heat transfer compared to water. Average enhancements in the convective heat transfer coefficient for 0.02% and 0.2% volume fractions in the range of volume flow rates 150-350 L/h are 3.7% and 13% respectively.
- While the rate of increase in the convective heat transfer coefficient of water decreased in the 350-600 L/h volume flow rates, the convective heat transfer coefficient of nanofluids has been continued to increase at the same rate by volume flow rate. The nanofluids were delayed the flow to be turbulent and extended the transition region. The obtained average enhancements in the convective heat transfer coefficient for nanofluids with the volume fractions of 0.02% and 0.2% are 25% and 34% respectively in these volume flow rates.
- The pumping power has been higher 66% to 8% and 68% to 24% for 0.02% and 0.2% nanofluids volume fraction compared to water respectively, in the investigated volume flow rate range (60-600 L/h). Therefore, the increase in pumping power should also be taken into account depending on the selected nanofluids volume fraction.
- A better enhancement was obtained for 0.02% volume fraction in terms of the efficiency index where the thermal and hydraulic performances were evaluated together, in the volume flow range 60-600 L/h.
- The use of nanofluids instead of water in MC-STHEs has a positive effect on the tube side convective heat transfer coefficient, especially after the volume flow rate of 125 L/h. While the use of mini channels instead of macro tube reducing the weight and volume of the heat exchanger and increasing the compactness, higher convective heat transfer coefficients can be obtained in the MC-STHE by using nanofluids instead of water.

### 8. Acknowledgments

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This paper was prepared with the contributions of the third author from the continuing PhD study of the first author under the supervision of the second author.

### 9. Nomenclature

- \( A \) - area (m²)
- \( c_p \) - specific heat (J kg⁻¹ K⁻¹)
- \( D_h \) - hydraulic diameter (m)
- \( D_e \) - shell equivalent diameter (m)
- \( D_i \) - inner diameter (m)
- \( D_o \) - outer diameter (m)
- \( F \) - non-dimensional correction factor
- \( f \) - Fanning friction factor \( =\Delta p/(4 (L/D) (\rho u^2))\)
- \( h \) - convective heat transfer coefficient (W m⁻² K⁻¹)
- \( j \) - Colburn factor \( =Nu/Re Pr^{1/3}\)
- \( k \) - thermal conductivity (W m⁻¹ K⁻¹)
- \( L \) - length (m)
- MC-STHE - mini-channel shell and tube heat exchanger
- \( m \) - mass flow rate (kg s⁻¹)
- \( Nu \) - Nusselt number \( =h D/\kappa \)
- \( Pr \) - Prandtl number \( =\mu c_p/\kappa \)
- \( \rho \) - tube pitch (m)
- \( \Delta p \) - pressure drop (Pa)
- \( Q \) - heat transfer rate (W)
- \( Re \) - Reynolds number \( =\rho u D/\mu \)
- \( T \) - temperature (K)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>overall heat transfer coefficient (W m$^{-2}$ K$^{-1}$)</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>volume flow rate (L h$^{-1}$)</td>
</tr>
<tr>
<td>$W$</td>
<td>power (W)</td>
</tr>
<tr>
<td>$\Delta T_{\text{lm}}$</td>
<td>logarithmic mean temperature difference (K)</td>
</tr>
</tbody>
</table>

**Greek Letters**

- $\eta$ - efficiency index ($\equiv (j_{\text{uf}}/j_{\text{uf}})/\left(\dot{f}_{\text{uf}}/\dot{f}_{\text{uf}}\right)$)
- $\theta$ - volume fraction (%)  
- $\mu$ - dynamic viscosity (kg m$^{-1}$ s$^{-1}$)  
- $\rho$ - density (kg m$^{-3}$)  

**Subscripts**

- ave. - average  
- $o$ - outlet  
- $h$ - hot fluid  
- $p$ - pump  
- $i$ - inlet, inner  
- $s$ - shell  
- nf - nanofluid  
- $t$ - tube  
- nm - nanomaterial  
- w - water

## 10. References

DETERMINATION OF GEOMETRIC PARAMETERS OF GRADIENT STRUCTURES FORMED IN OPTICAL GLASS BY THE ELECTRON BEAM METHOD

ВИЗНАЧЕННЯ ГЕОМЕТРИЧНИХ ПАРАМЕТРІВ ГРАДІЄНТНИХ СТРУКТУРИЙ, СФОРМОВАНИХ В ОПТИЧНОМУ ЄРІЛЕННО-ПРОМЕНЕВИМ МЕТОДОМ

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Abstract: The results of experimental studies of the geometry of gradient structures formed in optical glass by the method of electron-beam modification of its surface are presented. The expediency of using the atomic force microscopy method for determining the geometrical parameters of microlayers formed in the surfaces of optical materials by the method of their electron-beam modification is substantiated. A new method for determining the basic geometric parameters (thickness of the gradient layer, topology of the interface “gradient layer - the basis of the material”, surface microrelief, etc.) gradient structures, based on the method of atomic force microscopy is proposed. The proposed method is based on the principle of the complex application of various operating modes of an atomic-force microscope (the results of the instrument operation are considered, both in contact and in non-contact modes) in one measurement cycle. According to the proposed method, the dependencies between the change in the refractive index and the modes of electron-beam modification of the optical glass surface, as well as the dependence between the electron-beam effect modes and the geometric parameters of the gradient structure on the glass (thickness of the gradient structure, surface microrelief and interface between the layers and the base material). The possibility of predicting the development of hidden microdefects at the interface “gradient layer - the basis of the material” is shown. Proved high reliability and adequacy of the proposed method by comparing the results obtained with the results of determining the geometric parameters obtained by other alternative methods.

KEYWORDS: ELECTRON-BEAM METHOD, GRADIENT STRUCTURE, OPTICAL GLASS, GEOMETRIC PARAMETER, ATOMIC-FORCE MICROSCOPY

1. Introduction

In modern instrumentation technology, gradient structures formed in optical glass are widely used. Such coatings have unique properties (high strength, reflective and refractive power, etc.) that can be used as functional elements in various areas of precision instrument making, micro-optics, integrated optics, etc. [1, 2].

As shown in the work [3], the microgeometry of the gradient structures formed in the surface of optical glass determines their performance characteristics depending on the method of preparation. Various methods for obtaining such structures are presented in the work [4, 5], the most popular among them is the electron-beam method [6], which allows forming various layers of the chemical composition and physical properties in the surface layer of the optical glass, which possess, among other things, the property of the gradient change of the refractive index in the thickness of the optical material.

The method of obtaining and the features of the surface microrelief determine the operational characteristics of optical elements (reflection and refraction coefficients, diffusion of the light flux) associated with the instability of their properties through the thickness of the optical material. As it was shown in the work [7], the reasons for such instability are size effects (uneven distribution of material density across the thickness of an optical product, surface structure) and the operating conditions of these elements (aggressiveness of the environment, time and temperature of operation, thermal and mechanical effects in contact with other elements of the product).

The issues of obtaining and studying gradient structures in optical materials were studied by domestic and foreign scientists, including: Dubrovskaya G.N., Kanashevich G.V., Kotelnikov D.I., Lisochenko N.I., Marjan N.I., Yurkovich N.V. and etc. [8-10].

At the same time, among the methods for studying gradient structures, the most promising are analytical methods of scanning probe microscopy. The atomic force microscopy method [11] has significant advantages in studying the microrelief of gradient surfaces modified by electron flow, namely: high accuracy of fixed surface asperities (up to units of angstroms) and sensitivity of the measuring console (≈10⁻⁸ N), and the method itself refers to non-destructive research methods that do not require preliminary preparation of the research material and pretend on the expressivity of the research.

The aim of the work is to study the gradient structures formed by the electron beam effect on the surface of optical glass by atomic force microscopy, which allows determining with sufficient accuracy and reliability the geometric parameters of such structures.

2. Experiment methodology

The objects under study were plane-parallel plates of circular shape (diameter 20 mm and thickness 2; 4; 6 mm) made of K8 optical glass (analog Schott Glass BK7) and a rectangular photographic plate (25×20×1 mm).

Electron-beam modification was carried out on a special laboratory setup (ISTC «Micronanotechnologies and equipment», ChSTU, Cherkasy), containing the Pierce Electron Gun.

A plate made of optical glass (base), preheated to a temperature of 840 K (K8, photographic plate), was rotated in a vacuum chamber above an electron gun with the help of a rotational movement mechanism. The substrate moved nonstop above the electron gun. At the same time, the surface was affected by the low-energy ribbon-shaped electron flow (width 3.0 mm, length 175…200 mm). Electron beam exposure was carried out in the following modes: accelerating voltage 3.5…4.0 kV; electron flow current 175…200 mA; cathode heating current 14.5 A; electron flow rate 4.5…5.0 sm/s; the distance from the anode of the electron gun to the surface being processed is 40 mm; single pass treatment.

Surface microgeometry was studied by atomic force microscopy on an instrument «NT-206» (manufacturer: «Microtestmachines Co.», Belarus) with silicon probes «Ultrasound
The method of determining the characteristics of the surface layer of materials allows determining and controlling the thickness of the gradient layer, the topology of the interface “gradient layer - the basis of the material”, surface microlrelief, etc. and is unique in essence, since it allows to obtain high-precision results of microgeometry values and characteristics of the surface layer with a thickness of 10 nm to 6 μm. To determine the characteristics of a gradient layer that forms on the surface of optical glass, an experimental-calculation technique is used based on a certain degree of probe slippage over the sample (in fact, complex bending and torsional moments occurring in the cantilever) as a result of friction forces [11].

In general, the preparation of AFM and samples for the research of thin surface structures on them, as well as the scanning of the surface in dynamic and static modes, are carried out similarly to the steps carried out for the integrated control of the surface in dynamic and static modes, are carried out similarly to the steps carried out for the integrated control of the characteristics of optical materials [11]. The main difference in the sample preparation procedure is that for gradient structures, the use of chemical-mechanical treatment is unacceptable because of the possibility of significant damage to surfaces [12].

In order to correctly select the parameters of load and delay in determining the mode of monitoring the characteristics at the first stage of research, it is necessary to establish the thickness of the gradient layer as accurately as possible [13].

For this, depending on the type of gradient layer (discrete or solid), you can apply two approaches. Determining the thickness of a discrete layer using the method of AFM is carried out in the following sequence.

After preparing the sample and installing it on the AFM stage, turning on the device and launching the “SurfaceScan” control program on the “Area” panel of the control program, select the scan area with a clearly defined feature of the applied coating;

departing from this boundary in the direction of the gradient at a distance of 1.5 – 2 microns, they automatically lead the probe to the surface in static mode by pressing the “Auto Z Approach” button on the “Main” panel;

after the completion of the automatic summing process on the “Main” panel, pressing the manual up-down buttons with a minimum step of 0.2 nm reaches a value that is half the indications of the “Z” indicator on the “Indicators” panel;

conduction manual removal of the probe from the surface at 1000 steps (that is, at a distance of 0.2 μm);

moving the probe relative to the boundary of the applied coating towards the surface without a gradient layer (as in the previous case - at a distance of 1.5 - 2 microns from this boundary);

in manual mode, the probe is brought to the surface by 1000 steps (0.2 μm) and further, step by step, until the reading of the “Z” indicator on the “Indicators” panel changes its value (will correspond to the distance of the beginning of the action of the intermolecular interaction forces - the distance to the surface of the order of 0.5 – 1 nm);

according to the formula: \( h = m \cdot k \), where \( h \) – thickness of the studied structure, nm; \( m \) – the number of steps taken in manual mode by the operator when leading the AFM probe to the surface; \( k \) – minimum distance at which the probe approaches the surface in one step (\( k = 0.2 \) nm); calculate the probable thickness of the gradient layer.

The absolute error of determining the thickness of the layer by this method does not exceed 1 nm.

In the case of a solid gradient layer, its thickness is determined by the AFM method as follows.

- after preparing the sample and installing it on the AFM stage, turn on the device and run the “SurfaceScan” control program. In the “Area” panel of the control program, an area is selected and a point on it at which the determination of the layer thickness will be carried out;

- the spectroscopy procedure is selected at the point on the “Main” panel;

- the spectroscopy procedure is automatically performed at the point when the “Start” button is pressed on the “Main” panel;

- after completion of the procedure and graphical construction of the static power spectroscopy function in the visualization window of the measured data “View spectroscopy data” (Fig. 1), the AFM device automatically stops working. The data obtained in the graph can be saved on disk in text or graphic format using the file save dialog;

- according to the graph (Fig. 1) determine the possible thickness \( h \) of the researched gradient layer.

![Fig. 1. Visualization window of static power spectroscopy](image)

The thickness of the coatings obtained is checked by the resonant-acoustic method [13] on the «HTITI-1M» instrument, which confirms the high accuracy of the method for determining the thickness of the gradient layer in optical surfaces described in the work.

Determination of geometric parameters of gradient structures.

To determine the geometrical parameters of the gradient structures, after sample preparation and AFM adjustment for operation, the surfaces to be examined are scanned to select the place of the tribological research. Further, by selecting the operation mode of the device “Tribological Line”, the line for conducting the study is determined - a homogeneous surface without inclusions and abrupt differences in relief. At the same time, increasing load should be specified \( (0.3 – 1) \) mN, load time \((1.5 – 6)\) ms and the number of tribological lines (tracks) – from 3 to 5 [15].

According to the dependence of the force on the depth of penetration of the probe, displayed on the screen, the change in the density of the investigated materials is estimated by thickness. After that, the location of the tribological scanning line is scanned. As a result, the volume of the stamped material and the volume of the displaced material in the strain on the boundary of the scanning line are determined. Next, the refractive index is calculated as the ratio of the density change in the gradient layer over its thickness (on the
other hand, this is the ratio of multiplication of the wiping track width \( l \) by the probe load force \( P \) to the multiplication of its height \( h \) by the track surface area \( S \) and the effective Young's modulus of sample \( E \): \( n = (lP) / (hSE) \).

Thus, the above method for determining the geometric parameters of the gradient structures of optical materials using the AFM method allows determining the thickness of such gradient layers, refractive index, etc. with an accuracy of 8–12%.

### 3. Results and discussion

As a result of the experiments conducted and the study of their results, the thickness was determined and the averaged value of the refractive index was calculated on samples of optical glass K8 and photographic plates. The thickness and refractive index of the gradient structure on the optical glass was determined by the sclerometric method under the following conditions: probe load when exposed to K8 glass \( - 6.2 \times 10^{-4} \) N; when acting on a photographic plate \( - 6.4 \times 10^{-4} \) N. The AFM images of the result of sclerometry on the K8 optical glass are shown in Fig.2.

#### Tabl. 1. The results of the study of gradient structures in optical glass K8

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Estimated gradient layer thickness, ( \mu m )</th>
<th>Refractive index (averaged value), ( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated value</td>
<td>The value is obtained by goniometric method (Г-5)</td>
</tr>
<tr>
<td>Sample 1</td>
<td>15.6</td>
<td>1.85</td>
</tr>
<tr>
<td>Sample 2</td>
<td>18.3</td>
<td>1.93</td>
</tr>
<tr>
<td>Sample 3</td>
<td>19.0</td>
<td>2.01</td>
</tr>
<tr>
<td>Sample 4</td>
<td>21.5</td>
<td>2.11</td>
</tr>
<tr>
<td>Sample 5</td>
<td>25.8</td>
<td>1.92</td>
</tr>
<tr>
<td>Reference sample</td>
<td>32.4</td>
<td>2.05</td>
</tr>
</tbody>
</table>

As can be seen from the data presented in table 1, the accuracy of determining the refractive index correlates with the values obtained by the goniometric method (the discrepancy between the calculated and goniometric values does not exceed 8%). Similar results have also taken place for researches carried out for photographic plates.

According to the results of the study, it is clear that the calculated values of the refractive index are somewhat higher than the goniometric ones. This may be due to the fact that for optical glass, the hardness of which is commensurate with the hardness of the indenter, the probe “sticks” on the surface and leads to a slight (about 3-8%) increase in the refractive index compared to goniometric data. However, taking into account the subjectivity of determining the refractive index (determined in arbitrary units), the discrepancy between the calculated and alternative method values of the refractive index can be considered as acceptable, and the data obtained by the proposed sclerometry method correspond to reality.

In parallel with determining the thickness of the gradient layer and calculating the refractive index of the gradient structures in optical glass, a connection was established between the modes of electron-beam modifying (specific power \( P \), kW/m² and the speed of the electron flow \( V \), cm/s) the optical glass surface and the thickness \( h \) (Fig.3) and the refractive index \( n \) of the gradient structure in the glass (Fig.4).

As can be seen from Fig. 2, the intensity of the tracks obtained as a result of the action of the probe and the surface area of the surface increases and is continuous, which indicates the homogeneity of the density distribution of the material over the thickness of the optical glass (i.e., the gradient structure should gradually (not discretely) change the refractive index over its thickness), and, accordingly, the high accuracy of determining the refractive index \( n \), which was confirmed by an alternative method for determining the refractive index, namely, by the goniometric method. (device: Г-5). In general, studies of single-type samples, which were carried out in series, showed a high convergence of the results of determining the refractive index, the value of which for different samples is given in tabl.1.

It has been established (Fig.3, Fig.4) that with an increase in the specific power, a nonlinear increase in the thickness of the gradient structure occurs, whereas the refractive index also increases with the increase in specific power, but almost linearly.
At the same time, an increase in the electron flow rate leads to a nonlinear decrease in both the thickness of the gradient structure and the refractive index.

Such patterns (Fig. 3, Fig. 4), according to the authors, are associated with time and energy flow acting on the surface of optical glass. Thus, with an increase in heat flux, or a decrease in exposure time, the heating of optical glass increases, which leads both to a change in the chemical composition (volatile ions evaporate from the surface, while the concentration of heavy ions increases) and to change its physical characteristics (the melted glass layer, as well as the reduction of microdefects and pores in the surface layer). It should be borne in mind that, unlike metals, the heating of which takes place in a very short time, optical glass, having a relatively small thermal conductivity and a large heat capacity, warms up much slower. The selection of electron beam exposure modes allows you to control the penetration depth, as well as the law of heat distribution (respectively, the optical density of the material) across the thickness of the optical glass, is the basis of the theory of creating gradient structures in an optical material.

4. Conclusion

As a result of the research, the expediency of using the atomic force microscopy method to determine the geometric parameters of gradient microlayers formed in the surfaces of optical materials by the method of their electron-beam modifying was substantiated. To this end, the article presents a method for determining the basic geometric parameters (thickness of the gradient layer and refractive index) of gradient structures based on the atomic force microscopy method. The proposed method is based on the principle of the complex application of various modes of operation of an atomic-force microscope in one measurement cycle.

Regularities between changes in the refractive index and modes of conducting electron-beam modifying the surface of optical glass, as well as between the modes of electron-beam action and the geometric parameters of the structure on glass (thickness and averaged value of the refractive index of the gradient structure) are established.

Comparison of the obtained results with the results of determining the thickness of the gradient layer and the averaged value of the refractive index obtained by the alternative method of goniometry on the 1-5 device showed high accuracy (the relative error between the results obtained by various methods did not exceed 8%) reliability (probability of failure-free determination of values by the method of AFM, not less than 0.95) and the adequacy of the proposed method.

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Fig. 4. The dependence of the change in the averaged value of the refractive index n of the n gradient structure in optical glass on the specific power P (a) and speed V (b) of the electron flow


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UNIVERSAL THERMAL MICROSYSTEMS BASED ON SILICON CARBIDE

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Abstract: The results of modeling the thermal characteristics of microsystems, evaluated mutual thermal influence of the elements depending on the type of construction.


1. Introduction
At present, there is a tendency for development of various types of flowmeters and sensors for measuring the characteristics of gas flows. In general, the changes themselves undergo the design of the probes themselves and select materials with characteristics that exceed traditional values. As shown by the analysis of literature sources, one of several best technologies for investigating the properties of gas flows remains thermal anemometry and the method of television pyrometry. The authors note the high sensitivity of the methods and the considerable accuracy, in comparison with the known methods for measuring the characteristics of gas flows. These methods are widely used in industry, oil and gas, laboratories, military science, etc.

2. Problem discussion
Currently, scientific and production technologies involve the use of high-temperature operations to produce refractory high-strength materials, diagnostics of various technical systems under extreme conditions, etc. For such operations, various energy sources (in particular propane-butane in burners) and their effective use are required. To achieve maximum efficiency, you need to know the speed and temperature of the gas flow. [1,5] At the same time, in the field of thermal anemometry, as has been shown by the analysis of literature data, a thermoanemometric method (TAM) is currently a fairly common method for measuring the volumetric flow rate of gases. As a sensitive element in a thermoanemometric probe, thin electrically conductive wires and films with low thermal inertia are often used. The known disadvantages of TAMs are: a decrease in sensitivity with an increase in the flow rate of the measured gas, low mechanical strength, impossibility of burning (self-cleaning), as well as a change in graduation due to aging and recrystallization of the wire material due to dynamic loads and high heating temperature [1]. The listed disadvantages limit the use of TAM based on traditional probe designs under extreme operating conditions, including high temperatures of the measured gas flow, the presence of radiation, etc.

3. Objective and research methodologies
The paper presents the results of a study of two directions, the method of television pyrometry and the method of thermoanemometric analysis of the characteristics of gas flows.

3.1 Method of television pyrometry for measuring the velocity of a gas stream.
For the experimental study, a technique was developed for measuring the flow velocity from the angle of deviation of the pendulum from the vertical. The option of technical implementation is as follows:

a) The pendulum and the holder are mounted in the positioner, and the gas flame region is placed;
b) The camera connected to the computer registers the image of the pendulum;

c) With the help of special software installed on the computer, the flow velocity along the angle of the pendulum deviation from the vertical is calculated.

Figure 1 - Schematic representation of the technical implementation of the flow velocity measurement technique: 1 - The pendulum; 2 - Holder; 3 - Positioner; 4 - Adjustment device; 5 - Camera; 6 - Computer with special software; 7 - Nozzle; 8 - Gas source; 9 - Rotameter; 10 - Gas flow; 11 - Positioner controller.

To determine the velocity of the gas flame, it was required to obtain the dependence of the velocity of the gas flame on the angle of deviation of the pendulum from the vertical. For this purpose, a simplified physico- mathematical model was used. The obtained dependence is represented by the formula 1:

\[ v = \frac{mg}{\rho S \cos \alpha} \cdot \tan(\alpha) \]

where m - is the mass of the pendulum, g: g - acceleration of gravity, m/s²; ρ - is the density of the gas flame, kg/m³; α - angle of deviation of the pendulum from the vertical, deg The specificity of the flame is such that it has a definite structure [1]:

Figure 2 - Structure of the flame: 1 - core; 2 - recovery area; 3 - area of the torch.

When calculating the flame velocity, it must be taken into account that it consists of zones with different viscosities and temperatures. The values of temperature and viscosity in different zones of the flame are shown in Table 1:

Table 1 – gas flame characteristics
With the help of Matchcad 15, mathematical modeling was performed to obtain the range of possible velocities in different areas of the gas flame:

#### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Core flame</th>
<th>Flame retarding zone</th>
<th>Flame torch area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, °C</td>
<td>300-500</td>
<td>1200-1500</td>
<td>700-1000</td>
</tr>
<tr>
<td>Viscosity, 10^6 m²/s</td>
<td>48-79</td>
<td>233-280</td>
<td>115-177</td>
</tr>
</tbody>
</table>

The purpose of this work is to develop methods that allow the creation of a thermal microsystem with improved characteristics for measuring the velocity (flow rate) and temperature of gas streams, including under conditions of abrasive particles and radiation.

For the first time in work, the thermal micro-system layout in the thermistor probe of the anemometer and the temperature sensor in the form of a Schottky barrier made from a polytypic compound-silicon carbide is theoretically justified. It is shown that the use of single-crystal silicon carbide of certain polytype composition provides the following advantages of TAM:

1) A wide range of measured costs and high sensitivity (due to a controlled change in the electrophysical characteristics of the material);

2) High stability and reproducibility of the operating characteristics of the microsystem under extreme conditions (due to monocrystallinity, high Debye temperature and hardness, wide bandgap and erosion profiling capabilities);

3) The possibility of self-cleaning (due to high chemical and thermal resistance values ). It is also worth mentioning that a patent for the invention of a thermal microsystem has been obtained.

The necessity of step-by-step solution of the problems of designing the SiC-thermal microsystem is pointed out, which, for example, is due, not to the study of the influence of conductive bonds, abrasive and radiation fluxes on the electrical properties of the elements of the microsystem.

### 3.2 Method of thermoanemometric analysis of the characteristics of gas flow.

The method involves determining the flow rate by changing the temperature of a thermistor probe heated by electricity placed in a controlled gas flow. The cooling of the thermistor probe depends on the flow rate, the physical properties of the gas (thermal conductivity, temperature and density) and the temperature difference between the thermistor probe and the gas.

As shown by the analysis of literature data, the thermoanemometric method (TAM) is currently a widely used method for measuring the volumetric flow rate of gases. As a sensitive element in a thermoanemometric probe, thin electrically conductive wires and films with low thermal inertia are often used. The known disadvantages of TAMs are: a decrease in sensitivity with an increase in the flow rate of the measured gas, low mechanical strength, impossibility of burning (self-cleaning), as well as a change in graduation due to aging and re-crystallization of the wire material due to dynamic loads and high heating temperature [1]. The above disadvantages limit the use of TAM based on traditional probe designs under extreme operating conditions, including high temperatures of the measured gas flow, the presence of radiation, etc.

The study of the thermal regime of the microsystem, in which the thermal bonds between the elements are determined mainly by the conduction process, the properties of the material and the design features, is a model analysis of the distribution of the temperature field from a strongly heated element to a slightly heated one. For comparison, 2 variants of the design and the thermal model of the microsystem, presented in Figure. 5, are proposed.

According to the obtained data, curves for the dependence of the electric current on the temperature of the model under study at two point (1), and the coldest point (2) itself, shown in the Fig.7, are plotted. Figure 7 shows that the thermal model this the though hole is preferable, in consequence of the fact that the temperature of the thermo – anemometer in working conditions has less effect on the thermometer located on the foot of the microsystem. In this case, the inverse thermal effect is excluded from the calculation since the working temperature of the thermometer is assumed to be equal to the temperature of medium being measure.
5. Conclusion

In the course of the study, a method for calculating the micro-system was proposed, showing the mutual thermal effect of the elements. According to the data of the study, curves for the dependence of the electric current on temperature are plotted, as shown in Fig. 7. Based on the results of the simulation, it can be judged that the tested versions of the microsystem designs have significant temperature differences >50 °C in the presence of small design solutions.

Reference


DIAGNOSTICS OF THERMAL PIPES WITH SYMMETRIC STRUCTURE THERMAL IMPACT METHOD

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Abstract: On the basis of completed studies, including computer modeling of the morphology of the temperature field of heat pipes and thermal measurements in the framework of the experiment, a method was developed for diagnosing the quality of heat pipes with a symmetrical structure.

KEYWORDS: diagnostics, heat pipe, temperature field, defect, visualization, simulation, thermal imaging system, isotherm.

1. Introduction

It is known that heat pipes (HP) historically belong to the class of special cooling devices and they can carry out high-speed transport of high-intensity heat flows beyond the localization of various heat sources within their own containment. Currently, HP's are widely used in various ground-based, airborne and space-based electronic systems, as well as in nuclear power engineering and, of course, in computer technology [1-5]. Therefore, high demands are made on the reliability of HPs, and the methods and means of diagnosing them are constantly evolving and improving. It should be noted that, along with ultrasound and X-ray methods, a certain scientific and practical interest in the quality control of products in the containment, within which phase transitions take place with absorption and heat release, are thermal methods. The greatest efficiency, reliability and sensitivity among them have thermal imaging, [6,7]. Despite the fact that in the scientific literature there is information about thermal imaging techniques for monitoring various objects, including pipelines, their direct transfer for diagnosing HP is fraught with a number of difficulties. They are caused, for example, by the variety of materials used for the manufacture of shells, wicks, heat transfer fluids, design solutions, etc. The work is devoted to approbation of the developed technique, including the use of field characteristics, for diagnosing HPs.

2. Research methodology

Experimental studies were conducted on a laboratory bench containing an IR - television system (KTP-326Ekh camera based on an uncooled thermal imaging module IR-113, X = 8 thermal receivers: (IR - pyrometer - Mastech MS6530; thermocouple XA ) and PC with software. As the objects of study were selected profile aluminum pipes. The heat carrier in them was acetone or ammonia. Theoretical studies (modeling in the ELCUT and COSMOS environment) were performed using the finite element method [8, 9].

3. Research results and discussion

Analysis of the literature showed that the design of the TT mainly uses approximate engineering methods of thermal calculation, for example,

Figure 1 - Features of the temperature field in an aluminum heat pipe. Method of field characteristics. Payment. (Pulsed Heat Source (PHS) operation time, t = 100 s).

a, c - isotherms and temperature distribution along the selected circuit (1 - PHS; s - HP with defect: 2 - case defect, segment-air);

b, d - the field of temperature gradients and the distribution of the gradient along the selected contour (d-HP with a hull defect, segment-air).

the basis of the theory of thermal circuits, and others. [1]. This is due to the complexity of accounting and descriptions of all phenomena occurring within the operating HP. As the initial thermal model of the profile HP, we have chosen the model of an anisotropic rod (Fig. 1) [1, 10]. A pulsed heat flow source (PHS) with insulated surfaces was located in the center on the surface of the rod. The studies used sources of round and rectangular shapes.

Taking into account the thermal inertia of the system, the maximum time of the PHS operation was x = 120 s. The thermal connection of the PHS with the HP surface was considered ideal. The original equation of heat conduction [10]:

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When constructing a mathematical model, initial and boundary conditions (of the first and third kind) [10], obtained from targeted experiments, were used:

1. At the initial moment of time, for the edges of all bodies included in the model, the temperature was constant:

\[ T_i, \tau = 0 = T_a = \text{const} \]

2. For all PHS edges, taking into account the isothermality of the surface, a condition of the first kind was set:

\[ T = T_p \]

3. On the edges of the HP model, a third kind conditions was specified, which in describes both convective and radiant heat exchange with the environment:

\[ \lambda \frac{\partial T}{\partial n} = -a_k(T-T_a) - \beta(T^4-T_a^4) \]

where: \( a_k \) - a value equal to the product of the Stefan-Boltzmann constant (\( \sigma_0 = 5.7 \times 10^{-8} \text{ W/m}^2/\text{K}^4 \)) and the coefficient of radiation of the surface of the probe material; \( \lambda \) - convection heat transfer coefficient. Heat flow diversion through conductive connections of HP fixture was not considered.

Qualitative analysis of the temperature field by color pictures, the shape and nature of the distribution of isotherms in HP allowed us to identify the following features (Fig. 1). The location of the PHS in the central part of the HP without a defect generates both the left and the right of the source a symmetrical structure of isothermal lines, as well as a symmetrical temperature distribution relative to the selected circuit (Fig. la). The specified value of the anisotropy of the thermal conductivity coefficient \( \lambda / \lambda_x = 40 \) led to the formation of isothermal lines with pointed tops. The nature of the temperature gradient change relative to the selected contour (Fig. lb) also emphasized the symmetric structure of the thermal field.

It is known that the magnitude and speed of transfer of heat flux in the HP depends on many factors, among which a significant role belongs to the defects of the wick structure, the body [1-3]. Most often, these defects may appear due to the imperfection of the HP manufacturing technology, and also be acquired during operation. Pores, cracks in the body of the HP significantly reduce the degree of tightness, and in terms of vibrations, shock can lead to early failure of the HP. Modeling the temperature fields of the HP with defects made it possible to understand the basic laws of change in the field characteristics, and therefore prepare the basis for the development of a diagnostic technique. Defects of regular geometric shape were chosen as the model: round, in the form of a segment, rectangular, triangular. The main variable physical characteristics of the defects were the thermal conductivity coefficient, as well as the density and specific heat capacity. Examples of simulation results of such systems are shown in Fig. lc, d and Fig. 2. It can be seen quite well that along with the change in the shape of isotherms, symmetry breaking with respect to the HP center, a defect with a low thermal conductivity coefficient most strongly changes the field of the temperature gradient.

### 3.2 Experimental studies

To create a pulsed local heating, a film resistive heater was used, which, through heat conductive paste (KPT-8), was attached to the HP strictly in the center. Getting the original brightness contrast (image) was carried out with a horizontal position of the HP (on the edges), and to reduce the methodological errors, heat is removed from the surface of the pipe on both sides of the PHS occurred under conditions of free convection. It should be noted that well-known measures were taken, including shielding to reduce external illumination.
The transition from the image to the quantitative characteristics of the thermal state of the HP was implemented using the method of field characteristics (MFC) in the form of the developed universal software (software) “Parus 5.0” [11]. It allowed to carry out image input (static and dynamic - video) both from a television camera via a video signal input board in a PC, and from a file in the "*.bmp" format. A typical example of visualization is shown in Fig. 3. Considering that the experiment used a commercially available HP, without specially introduced defects, in the framework of this technique we can only talk about the features of the morphology of this temperature slice. The focal nature of its structure, which most likely can be associated with surface defects of the HP body, is quite clearly visible. And the asymmetry is most pronounced in the nature of the temperature distribution, relative to the PHS (it is difficult to transport heat to the left side of the IIP). It is clear that to establish the true causes of the asymmetry effect require additional research.

3. Conclusions
The method of the field characteristics, based on digital thermal imaging processing algorithms, allows you to create criteria for assessing the quality of the heat pipe.

4. Reference
AN EFFICIENT COMBINATION OF WATER TREATMENT AND ELECTRICITY GENERATION BY DIFFERENT MICROORGANISMS

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Abstract: A sample of acid drainage waters generated after rainfall in a dump of low-grade copper ores and mining wastes was tested under laboratory conditions to combine the treatment of such waters with the subsequent generation of electricity. This combination was possible and efficient due to the fact that the same microorganisms participated in both processes, i.e. in the water treatment and in the electricity generation. These microorganisms were heterotrophs related to two main groups: of sulphate-reducing and iron-reducing bacteria. These bacteria were anaerobes, with efficient growth and activity at pH within 3.0 – 3.5 using the organic donors of energy and avoiding the precipitation of the trivalent iron

Key words: WATER TREATMENT, ELECTRICITY GENERATION, BACTERIA

1. Introduction

and precious metals but also uranium, iron and some rare elements) from sulphidic ores, concentrates and even from some mineral wastes by means of different microorganisms, mainly chemolithotrophic bacteria and archaea, is largely and steadily increased in industrial-scale application in several countries located in the five continents. At the same time, most of these activities are connected with the generation of acid drainage waters, which apart from the sulphuric acid, contain several toxic elements, mainly heavy metals, radionuclides and arsenic. Some of these components are recovered and used as useful and valuable products. Apart from this, the treatment of the residual waste waters by adding some biodegradable organic substrates and suitable heterotrophic bacteria, mainly such using sulphates and/or ferric ions as electron acceptors, can be used for generation of electricity by means of constructed fuel cells (Rabaey and Verstraete, 2005; Du et al., 2007; Spasova et al., 2014, 2016; Groudev, 2015).

2. Materials and Methods

In this study drainage waters generated during the bioleaching of a polymetallic sulphide ore were subjected to treatment by means of lab-scale permeable reactive multibarriers. The multibarriers were plastic cylindrical columns 40 cm high, with an internal diameter of 10 cm. The columns were filled with a mixture of limestone (crushed to a particle size of minus 10 mm) and a biodegradable organic matter consisting of a mixture of spent mushroom compost, fresh leaf compost, animal manure and saw dust. The columns were inoculated by means of inocula of three types: of sulphate-reducing bacteria, of iron (III) – reducing bacteria and of mixed cultures of sulphate and iron-reducing bacteria. The microorganisms used in these experiments were preliminary adopted to grow and to be active at relatively low pH levels (within 3.4 – 4.0) to avoid considerably the precipitation of the ferric iron present in the pregnant solutions. These solutions were enriched in soluble organic compounds and portions of them were used separately from each other in the experiments for electricity generation by means of microbial fuel cells. These cells were also Plexiglas cylindrical columns 40 cm high, with an internal diameter of 10 cm. A perforated graphite – Mn⁴⁺ anode and a graphite – Fe³⁺ cathode were located in the bottom and in the top sections of the column, respectively. The two sections were separated by a permeable barrier of 5 cm thickness consisting of a 2.5 cm layer of glass wool and a 2.5 cm layer of glass beads. The feed stream, i.e. the effluents from the multibarrier, was supplied to the bottom anodic sections of the column and effluents passed through the cathodic section and continuously exited at the top. Air was injected during the treatment to the cathodic section.

The quality of the waters treated by means of the permeable reactive multibarriers and by the microbial fuel cells was monitored at the inlet and the outlet of these components of the system for the water cleaning and electricity generation. The parameters measured in situ included: pH, Eh, dissolved oxygen, chemical composition, and temperature. The isolation, identification and enumeration of microorganisms were carried out by the classical physiological and biochemical tests (Karavaiko et al., 1988) and by the molecular PCR genera Desulfromonas, Desulfobulbus and Desulfomicrobium) were able to oxidize the organic substrates only partially to CO₂ and acetate and usually reduced the sulphates at lower rates than the sulphate-reducing bacteria related to the first group. However, some of the strains related to the species of this second group also differ considerably from each other with respect to their ability to oxidize the organic substrates.

The strains of iron (III)-reducing bacteria used in this study also can differ from each other with respect to their ability to degrade the organic sources to energy. These bacteria reduce the ferric iron to the ferrous state and in this way decrease considerably the pollution of their habitats, especially of these containing large amounts of sulphides.
The microbial sulphate reduction in the multibarriers was efficient due to the large amount not only of sulphates but also of soluble biodegradable organic substrates generated from the initial organic matter by the action of the anaerobic heterotrophic bacteria present in this system. The high residual concentrations of such soluble organic substrates and sulphates in the multibarrier effluents, together with the very low residual concentrations of toxic heavy metals, the negative electrochemical potential, the neutral pH and the practical absence of dissolved oxygen, made these effluents very suitable for electricity generation by the microbial fuel cells.

**Conclusion**

Some mixed cultures of sulphate-reducing and iron (III)-reducing bacteria are very efficient for generation electricity by means of microbial fuel cells. The best strains from these bacteria are characterized to and efficient degradation of the organic substrates at relatively low pH (about 3.5 – 4.0) which is usually quite low for these bacteria

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Abstract: The minimum quantity lubrication (MQL) and dry machining operations are two types of environmentally friendly processes that have potentials to replace with conventional cooling methods. In recent years, the studies have been performed on the environmentally friendly lubrication methods such as MQL method in machining operations. These studies have also focused on the usage of vegetable cutting fluids instead of mineral based oils due to increasing awareness to the environment and human health. In this experimental study, Aluminum 6061 was machined under dry and MQL conditions and the cutting force components and surface roughness values were measured. The experiments were carried out by CNC milling machine tool at three different cutting speeds and constant depth of cut and feed. The vegetable cutting fluid was pulverized to the rake face by using single nozzle and double nozzles at two flow rates during MQL milling. Cutting force components and surface roughness values were compared for minimum quantity lubrication and dry milling operations of Aluminum 6061.

Keywords: CUTTING FORCE, SURFACE ROUGHNESS, MQL MACHINING, ALUMINUM 6061

1. Introduction

The challenge of modern machining industry is mainly focused on achievement of high quality in terms of workpiece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy of machining, reducing environmental impact etc. [1]. In machining of ferrous and other high strength materials, the temperature rises with the cutting speed and the tool strength decreases, leading to faster tool wear and failure [2]. In order to reduce the temperature in the cutting zone, traditional flood cooling strategies have been commonly used. However, there are critical needs to reduce the usage of cutting fluids in machining process in order to decrease their environmental and cost effects [3]. As is known, the majority of cutting fluids is based on mineral oils and contains heavy chemicals which are hazardous to the human health and environment [4, 5]. Therefore, the usage of cutting fluids needs to be limited. For this purpose, minimum quantity lubrication (MQL) technique is utilized which is a promising, attractive, efficient and environmentally friendly technique of cooling and lubrication [6].

In MQL technique, a very small amount of lubricant/coolant is mixed with air to form aerosol, which is sprayed at a high pressure in the cutting zone with the help of a nozzle. This system consists of an atomizer, cutting fluid pump, discharge nozzle, etc. The atomizer works as an ejector in which high pressure air is used to atomize the coolant. Atomized coolant is then delivered to the machining zone by the air in a low-pressure distribution system. Due to the venturi effect in the mixing chamber, partial vacuum sucks the cutting fluid from the oil pump where it is maintained at a constant hydraulic load. The air passing through the mixing chamber atomizes the coolant stream into aerosol of micron-sized particles. When this aerosol is sprayed in the cutting zone as mist, it works as coolant as well as lubricant and penetrates deep into the tool-workpiece interface [2]. In MQL method, the cutting fluid can be pulverized in the range between 0.01-2 l/h instead of the 50-1000 l/h in the case of conventional lubrication/cooling systems. Some MQL advantages against other lubrication/cooling systems are: reduction of cutting fluid consumption, cost and tool wear, improvement of surface roughness, diminution decrease of the environmental and worker health hazards and improve lubrication than conventional lubrication/cooling system. The cutting fluid is used in such small quantities that it is practically consumed in the process, eliminating the fluid disposal problems. In addition, chips produced are nearly clean from cutting fluid, which are easily recyclable [7].

In literature, there are several studies on MQL machining. Mulyadi et al. [8] compared to dry, flood, and MQL conditions and pointed that selecting MQL environment can be an intermediate strategy for reducing direct electrical energy requirements, global warming potential, human toxicity, and acidification in machining processes. The MQL method provides a good compromise in terms of tool life, when compared to dry machining. Also it performance was very close to machining under flood coolant environment. Ginting et al. [9] presented an industrial situation in a local small to medium sized enterprise (SME) in Western Australia to determine the technical, economic and environmental benefits of the replacement of traditional flood cooling with MQL. The use of MQL reduced the greenhouse gas emissions and eco-toxicity associated with the disposal of the contaminated liquid. It was found that this alternative cooling method increased the performance of the metal cutting operation. Finally, the replacement of traditional fluid cooling with MQL cooling system can help attain the three pillars of sustainability: economic, environmental, and social. Another implementation example of MQL is that Ford Motor Company began applying MQL to aluminum transmission components in 2005, and by 2008 had over 200 MQL machining centers in operation machining Aluminum transmission cases, torque converter housings, and valve bodies at two plants in North America. MQL machining is Ford’s current standard machining method for these components, and is being implemented in new high-volume machining lines globally. Ford began machining aluminum engine heads and cast iron engine blocks at two plants in Europe in 2011; as in the case of transmissions, MQL is now the primarily standard method for machining cast iron engine blocks and aluminum engine blocks.
and heads, although wet machining is still used for some specialized operations. New engine MQL modules have been installed in Brazil and China [10]. Berzosa et al. [11] reached better surface roughness results in MQL method than that in dry drilling of magnesium alloy. Sun et al. [12] observed better surface roughness in MQL turning of Ti-5553 alloy when compared to flood coolant and cryogenic cooling. Kumar et al. [13] performed turning experiments on AISI 4340 stainless steel under dry, flood cooling, and MQL conditions. Researchers reported that the surface quality improved by 7% to 10% with MQL when compared with flooded supply of lubricants. In Ramana’s study [14], turning of Ti-6Al-4V alloy was performed under dry, flood cooling and MQL conditions. Based on the experimental results, the cutting performance of MQL condition showed better results as compared to dry and flood cooling conditions in reduction of surface roughness. Oliveira et al. [15] compared the influence of cryogenic cooling, MQL method, and flood cooling on end milling of Inconel 718 alloy and it was concluded that the MQL method provided the lowest levels of tool wear at the same cutting conditions and the resulting force levels were similar in both methods flood and MQL using water based cutting fluid. Joshi et al. [16] conducted turning experiments on Inconel 800 under dry, flood cooling, and MQL conditions and compared the surface roughness and flank wear results with each other. The MQL method showed the best performance. Aslantas and Cicek [17] determined that the use of MQL provides important advantages in terms of tool wear, burr formation and surface roughness for micro-milling of Inconel 718 superalloy.

In this experimental study, dry and MQL milling processes were performed on Aluminum 6061 to evaluate and compare the cutting force components and surface roughness values. In MQL milling, the cutting fluid was applied to the rake face through single nozzle and double nozzles at two flow rates.

2. Experimental Study

In experimental studies, slots were machined on Aluminum 6061-T651 parts by a CNC milling machine which chemical composition is given in Table 1. The workpiece parts were prepared in the dimension of 140x170x30 mm.

Table 1. Chemical Composition of Aluminum 6061-T651

<table>
<thead>
<tr>
<th>Element</th>
<th>Si %</th>
<th>Fe %</th>
<th>Cu %</th>
<th>Mn %</th>
<th>Mg %</th>
<th>Cr %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.76</td>
<td>0.63</td>
<td>0.3</td>
<td>0.15</td>
<td>0.99</td>
<td>0.17</td>
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</tbody>
</table>

In milling operations, APHT 100308FR-27P uncoated cutting inserts were used and mounted two inserts on a diameter of 16 mm end mill. The milling experiments were conducted at a constant deep of cut of 1.5 mm, feed of 0.1 mm/rpm and three different cutting speeds as 200 m/min, 250 m/min, and 300 m/min under dry cutting and MQL conditions. In MQL method, milling experiments were performed by applying the cutting fluid to the rake face at total 26 ml/h and 52 ml/h through single nozzle and double nozzles as seen in Table 2 and Fig.1 due to understanding the effects of cutting fluid distribution on surface roughness and cutting force components.

In MQL milling, a micro lubrication system was used and a commercial vegetable cutting fluid was selected. The global lubricant is expected to reach 43.9 million tons in 2022. Cutting fluids represent about 5% of the global lubricant market, with Asia as the largest consumer. Availability of mineral based oils is limited as they are finite source and decreasing steadily whereas vegetable based cutting fluids are sustainable. Vegetable oils are evolving as metalworking fluids due to its higher biodegradability and ability to minimize the waste treatment costs. It also reduces the health risks to operators which were quiet common with petroleum based mineral oils due to their lower toxicity [18].

Table 2. MQL conditions

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Flow rate (ml/h)</th>
<th>MQL pressure (bar)</th>
<th>Nozzle distance (mm)</th>
<th>Nozzle angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MQL with single nozzle</td>
<td>26</td>
<td>5</td>
<td>30</td>
<td>45°</td>
</tr>
<tr>
<td>MQL with double nozzles</td>
<td>13</td>
<td>5</td>
<td>30</td>
<td>45°</td>
</tr>
</tbody>
</table>

Fig.1. Machine tool set-up for MQL milling with a) single nozzle and b) double nozzles
Surface roughness ($R_a$) measurements of milled slots were performed by using Mitutoyo Surftest SJ-210 surface roughness tester. The dimension length was adjusted as 0.8 mm and the resolution of tester is 0.002 µm. During surface roughness measurements, 10 (ten) measurements were done on each surface and arithmetic means were calculated. The cutting forces were measured by Kistler 92578A dynamometer which the workpiece was mounted on.

3. Results and Discussion

3.1 Surface Roughness

Depending on the surface roughness measurement results, the minimum surface roughness was obtained at the cutting speed of 200 m/min in MQL milling with double nozzles at 26 ml/h of flow rate from each nozzle whereas the maximum surface roughness was measured in dry milling at the cutting speed of 300 m/min (Fig.2). The usage of MQL method gave better surface roughness results than that measured in dry milling. Additionally, it can be said that the surface roughness increased with increase of the cutting speed for all selected conditions.

In MQL milling, the utilization of single nozzle or double nozzles affected the surface roughness. When the total flow rate is 26 ml/h, surface roughness decreased as 31%, 29.8% and 7% by using double nozzles at the cutting speed of 200 m/min, 250 m/min and 300 m/min, respectively as comparing with single nozzle. This is because of the reaching cutting fluid effectively to the cutting zone. Similarly, the effect of double nozzles on the surface roughness at the total flow rate of 52 ml/h, surface roughness decreased as 13%, 13.3%, and 31% at the cutting speed of 200 m/min, 250 m/min and 300 m/min, respectively, as comparing with single nozzle.

Additionally, surface roughness measurements showed that the flow rate of aerosol affected the surface roughness. In MQL milling by utilizing single nozzle, surface roughness decreased as 4.1%, 3.9%, and 3.5% and the feed forces decreased as 3.5%, 7%, and 10% at the cutting speeds of 200 m/min, 250 m/min, and 300 m/min, respectively when the flow rate increased from 26 ml/h to 52 ml/h.

Regarding to the effects of aerosol flow rate on the cutting force components in MQL milling with double nozzles, the cutting forces decreased as 2.1%, 1.5%, and 1.7% whereas the feed forces reduced by 10.4%, 9.6%, and 11.6% at the cutting speeds of 200 m/min, 250 m/min, and 300 m/min, respectively when the flow rate increased from 26 ml/h to 52 ml/h.

4. Conclusion

In this experimental study, the effects of cutting conditions on the cutting force components and surface roughness were investigated in milling of Aluminum 6061. In experiments, three
different cutting speeds were selected while the depth of cut and feed rate were kept constant. Depending on the surface roughness and cutting force measurements, the conclusions could be expressed as follows:

- MQL milling gave lower surface roughness values than the dry cutting.
- In MQL milling, the increment of aerosol flow rate caused a reduction on surface roughness values.
- It was observed that lower surface roughness values were obtained by applying same total flow rate through double nozzles instead of single nozzle.
- The cutting force and feed force values were lower in MQL milling than those in dry cutting.
- In MQL milling, the cutting forces and feed forces decreased with increase of aerosol flow rate.
- Lower cutting forces and feed forces were observed by utilizing same total flow rate through double nozzles instead of single nozzle in MQL milling.

References


FLANK WEAR OF SURFACE TEXTURED TOOL IN DRY TURNING OF AISI 4140 STEEL

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Abstract: Surface texturing on a cutting tool is a process which can provide reduction in friction, improved performance of a contact interface and a better tool life. In this paper, influence of surface texturing on tool wear of both textured and non-textured tools were compared. Different textures were applied on coated carbide tools by Femtosecond laser to enhance the wear resistance. Dry cutting experiments on AISI 4140 (32 HRC) were carried out with conventional cutting inserts having parallel and perpendicular textured surfaces to the cutting edge on the flank face. Finally, results showed that surface texturing of cutting insert was found to be beneficial to the decrease of the flank wear.

KEY WORDS: SURFACE TEXTURED TOOL, NON-TEXTURED TOOL, FLANK WEAR, DRY TURNING

1. Introduction

Machining industries will change their processes as dry machining in the next years because of environmental protection laws for occupational safety and health regulations. For this reason, the importance of dry machining increasing day by day. The advantages of dry machining includes non-pollution of the nature, no residue on the swarf which will be rejected in reduced disposal and cleaning costs, no danger to health and is allergy free. Moreover, it offers cost reduction in machining. [1] On the other hand, at dry machining tool wear, adhesion between tool and chip, the friction forces and cutting temperature become more important.

Tool wear is the most important phenomenon for dry machining which effects the parts quality, surface roughness and production costs directly. Because of this significant effect, researchers are developing a variety of methods to reduce tool wear. Several authors have studied the surface texturing phenomenon and provided their justification for improving machinability with different techniques for performing surface texturing on the tool. In recent years, several studies have revealed that surface-textured cutting tools can effectively reduce the tool wear, thereby improving tool anti-wear performance, reducing the friction between the tool and chips, and lowering the cutting temperature and forces [2-4]. Most of the textures are accomplished by various authors in the rake face of the cutting tool using Femtosecond laser, grinding wheel, Rockwell hardness tester, electric discharge machining etc. Lei et al. [5] have studied the impact of cutting tool which are textured with micro-pits, by comparison against the conventional cutting tool, and found that tool with the micro-pits could effectively reduce cutting forces 10-30%. Liu et al. [6] reported a few surface textured tools with different texture figures. The research results showed that application of the surface textured tools can reduce cutting forces and cutting temperature. Rajbongshi et al. [7] have found that texturing helps in reducing the formation of white layer thickness and micro-hardness as compared to the non-textured tool. Sugihara and Enomoto [8] found that surface texturing on cemented carbide tool at the rake and flank faces in parallel to cutting edge direction caused reduction of crater and flank wear while machining. Wu et al. [9] wrote the surface textured tool could reduce the surface roughness of workpiece, and the tool life of surface textured tool was improved by 15% or so compared with the conventional one. Ze et al. [10] mentioned the benefits of rake or flank face fabricated structures of carbide using molybdenum disulfide in the textured places in the dry cutting of Ti-6Al-4 V alloy. With this texturing the authors were able to get improved machining performances in terms of cutting forces, cutting temperature, chip thickness ratio, and tool wear. Jianxin et al. [11] reported the effect of three microstructures made by lasers created on the rake faces of the cutting tool in machinizing of AISI 45 steel. The authors wrote that with this kind of texturing, temperature, cutting forces and coefficient of friction could be reduced. Furthermore, as mentioned above, many papers applied this surface texturing process on the rake faces of the tools and very few studies that tried to presents textured surfaces into tool flank face have been carried out, despite the importance of the flank wear resistance of cutting tools.

This study stands on the comparison of non-textured and textured tool wear characteristics. In order to understand the performance of textured tools, a comparative study was carried out using one perpendicular (PPT), one parallel (PT) textured to main cutting edge and non-textured (NT) tool. Femtosecond laser processing technology was used to produce the samples. In addition we have seen that, surface texturing effectted the surface roughness of workpiece and chip formations.

2. Experimental set up

2.1. Workpiece and tool material

The main objective of this experimental work was to investigate the effect of surface textures on flank wear and to observe how texturing was effecting the surface roughness and chip formations in dry turning of AISI 4140 32HRC steel with CVD coated conventional semented carbide tool. An orthogonal turning operation was used with cylindrical AISI 4140 32HRC workpieces with length of 250 mm and diameter of 60 mm. The chemical composition of AISI 4140 is given in Table 1.

### Table 1. Chemical composition of AISI 4140 Steel

<table>
<thead>
<tr>
<th></th>
<th>Cr</th>
<th>Mo</th>
<th>Mn</th>
<th>P</th>
<th>Si</th>
<th>S</th>
<th>Ni</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09-0.12</td>
<td>0.15-0.55</td>
<td>0.38-0.43</td>
<td>0.035</td>
<td>0.04</td>
<td>0.04</td>
<td>0.45-0.55</td>
<td>-</td>
<td>0.8-1.10</td>
</tr>
</tbody>
</table>

Turning was performed on machining centre Goodway GA-230. Figure 1 showed the experimental set up for dry orthogonal turning. In the experimental study, coated (CVD Ti(C,N)+Al2O3+TiN) cemented carbide was used. The type of the tool was Sandvik CNMG 12 04 08 PM 4315 according to the standard ISO 1832 with chip breakers. Tool holder was ACLNL 25 25 M12.

For surface roughness measurement, surface roughness tester Mitutoyo SJ-210 was used. The cut off length ($l_c$) was 0.8 mm and sampling length range was 2.5mm. SOIF model optical microscope and having 1.0µm precision OSM model ocular micrometer was used for flank wear measurement.

2.2. Surface texturing on cutting tool

Femtosecond laser was applied to produce textured tools on the flank face. The laser had a marking speed of 1000µm/s, skip speed of 125mm/s and repetition rate of 1000µm/s. The line gap was 100µm, pulse duration was 120fs. Laser had a wavelength of 800nm and laser power was 50mW. Texture grooves were produced perpendicular (PPT) and parallel (PT) to main cutting edge. In order to specify the effect on flank wear non-textured (NT) tool were used
for the comparison. The microscope views of surface textures are shown in Fig. 2.

**Fig. 1.** Dry orthogonal turning experimental set up

(a) PT tool                                         (b) PPT tool

**Fig. 2.** Microscope views of surface textures, (a) parallel to main cutting edge, (b) perpendicular to main cutting edge.

2.3. Cutting conditions

**Table 2.**

<table>
<thead>
<tr>
<th>Cutting condition parameters used in experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece</td>
</tr>
<tr>
<td>Tool</td>
</tr>
<tr>
<td>CNMG 12 04 08 PM 4315 (Sandvik Coromant)</td>
</tr>
<tr>
<td>Cutting velocity, Vc [m/min]</td>
</tr>
<tr>
<td>Feed rate, f [mm/rev]</td>
</tr>
<tr>
<td>Cutting depth, ap [mm]</td>
</tr>
<tr>
<td>Cutting fluid</td>
</tr>
<tr>
<td>Corner radius, rƐ [mm]</td>
</tr>
<tr>
<td>Rake angle, γ [°]</td>
</tr>
<tr>
<td>Clearance angle, α [°]</td>
</tr>
<tr>
<td>Wedge angle, β [°]</td>
</tr>
</tbody>
</table>

The cutting parameters are summarised in Table 2. For the observation of the flank wear, the cutting speed, feed and depth of cut were selected as follows: \( V_c = 180 \) m/min, \( f = 0.2 \) mm/rev, \( a_p = 1.5 \) mm were selected for proper chip formation.

3. Results and discussion

3.1. Effect of surface texturing types on flank wear and its comparison with a non-textured tool

Flank wear of cutting tools is often selected as a tool life criterion because it determines the dimension accuracy of machining, its stability and reliability.[8] In the study, flank wear of PT, PPT and NT surface of coated carbide tool were measured, thus, the difference between them was revealed. Two types of surface textures have been developed with femtosecond laser which are perpendicular and parallel to main cutting edge.

**Fig. 3.** Variation of tool flank wear with non-textured, perpendicular textured and parallel textured coated carbide tool.
Three samples per each test were used for the responses of flank wear and surface roughness and chip formation. The flank wear comparison of all samples is shown in Fig. 3. The tool wear was measured after every pass and all chips measured for after each of the experiment. Flank wear lengths on the tools were observed at certain intervals and the wear conditions were compared for the same cutting times. Camera images were taken at certain time intervals of three samples (see Fig. 4.).

![Flank wear images](image1.png)

**Fig. 4.1.** Flank wear values at cutting time 32 seconds.

![Flank wear images](image2.png)

**Fig. 4.2.** Flank wear values at cutting time 98.2 seconds.

![Flank wear images](image3.png)

**Fig. 4.3.** Flank wear values at cutting time 410.4 seconds.

As evident from the experimental data, a significant difference of flank wear for the all textured and non-textured tool was observed at same cutting conditions. The flank face textured tools with microscale grooves parallel to the main cutting edge (PT) had the most improved flank wear resistance (as shown in Figs. 3., 4.). The aim of the surface texturing is to decrease the contact area between the tool interface and workpiece area. On the occasion of the tool textured, the tool and workpiece friction reduced and consequently the adhesion and abrasion also decreased. Due to the less friction between tool and workpiece, the width of wear land at the flank face decreased. Hence, due to texturing on the flank face, the contact length of the cutting tool and tool wear reduced. As a result, the cutting forces generated during machining become less when it was compared to non-textured tool. In this regard, lower cutting forces, lower friction between tool and workpiece provided reduction in tool flank wear and the tool life improved. [11]

**3.2. Effect of surface texturing types on surface roughness and chip formation and its comparison to non-textured tool**

Fig. 5. showed the differences of average surface roughness on workpieces between textured and non-textured tools. From Fig. 5. It could be seen that PPT and PT tools have respectable effect on Ra. However, there has not been seen significant difference between PPT and PT.

![Surface roughness values](image4.png)

**Fig. 5.** Surface roughness (Ra) values of NT, PPT and PT tools

These data collected at the same cutting conditions which showed that lower flank wear that induced lower surface roughness values. In the light of all these experiments, the textured tool could reduce the surface roughness of the machined surface in comparison to that of the non-textured tool.

![Chip forms](image5.png)

**Fig. 6.** Chip forms of three samples. (a) NT tool chip form, (b) PPT tool chip form, (c) PT tool chip form.
On the other hand, in this paper the chip formation of all three samples were examined. As it is shown in Fig. 6, there has not been observed any visible changes on chip formation but it has seen that during cutting of the workpiece, on entering and exiting of PT tool, different chip formation occurred. Despite the tool has chip breaker, unbroken chip forms were seen on PT tool (Fig. 6.c).

4. Conclusions

In order to decrease tool flank wear and improve tool life in dry orthogonal cutting, two different types of surface texture were adopted. Surface textures were pretreated on flank faces of tools with femtosecond laser. All experiments completed under same cutting conditions with textured and non-textured coated carbide tools in turning of AISI 4140 steel. Experimental results are summarized below:

- It was found that surface texturing on flank face reduced flank wear and tool life was improved. Due to the reduction of tool chip contact, friction forces and the stress on the tool decreased.
- Parallel textured tool had more significant effect than that of perpendicular textured tool on the flank wear rate.
- It has been seen that, the decrease of flank wear improved the surface quality. But there has not been seen remarkable differences between surface roughnesses of the workpieces cut by PPT and PT tool.
- Additionally, it was observed that there was no visible changes on chip forms but during cutting of the workpiece, on entering and existing of PT tool, different chip formation occurred.

5. Acknowledgements

All surface texture applications were performed at “Konya Selcuk University” with femtosecond laser technology.

References

Abstract: Plasma arc cutting is a non-conventional manufacturing process that has potential for modern day metal cutting demands with good dimensional accuracy and high-quality surfaces without any extra operation. In this experimental study, AISI 304, AISI 430 and EN S235JR sheet materials having 5 mm. thicknesses, has cut with plasma arc cutting. Each material has cut with 6 different variations. Current, cutting speed, arc voltage, gas pressure and gas flow rate have been changed as process parameters. The quality of the cut has been monitored by measuring the edge roughness, the hardness of the heat-affected zone (HAZ) and the results has compared.

Keywords: STAINLESS STEEL; STRUCTURAL STEEL; PLASMA ARC CUTTING; HEAT-EFFECTED ZONE (HAZ)

1. Introduction

Modern manufacturing processes are widely employed for harder, stronger, and tougher materials those are known as “difficult to cut”. Moreover these methods are capable to produce complex geometries with high dimensional and surface accuracies. Plasma cutting is a modern manufacturing method which can be applied for cutting wide range of materials. The inert gas is blown with high speed out of a nozzle; at the same time, an electrical arc is formed through that gas from the nozzle to the surface, reaching high temperatures that are ionizing atoms to plasma form. The formed plasma melts the material being cut and swiftly moves blowing molten metal away from the cut [1-4].

‘Plasma’, as a term, had been used firstly in 1920s, it was firstly realized in 1950s that material can cut with it. Cutting with plasma arc, one of the thermal cutting methods has been improved as an alternative method for mostly stainless steel, aluminium and non-ferrous metals being cut with oxy-acetylene. Plasma cutting of the workpiece is the result of melting/vaporizing of material through a very hot cylindrical (theoretical) plasma beam which burns and melts through the material (Fig. 1).

Nowadays, with the increasing of stainless steel, aluminium and metal and non-metal materials’ consumption in industry, the importance of rapid, cheap and delicate cutting for these materials have scaled up. At initial application of plasma cutting, generally, argon and 35% hydrogen mixture was used as a plasma gas. However, this mixture is expensive and cutting operation will be costly. Reducing operation costs would be reached by changing mixture of gas to air as a plasma gas. Simply, plasma can be identified as a state of matter. The differences between states of matter is the energy that they have. For the transition from a state to another, it is required to supply energy and reverse transition is also possible [5]. The solid material can be turned into fluid state by supplying energy, the fluid material can be converted to gas with energy and gaseous material can be ionized and converted to plasma by supplying energy.

The plasma cutting technology is sometimes compared to laser and waterjet cutting methods. This technology seems providing more advantages over both cutting methods such as lower operation costs, widely used in cutting high-alloy steel and aluminium materials in medium and larger thickness, excellent performance in small and medium-sized thickness of steel (30 mm), high cutting speeds, high automation, etc [3-7].

Stainless steel is identified ferrous alloys having at least 10.5% chromium (Cr). The thin but dense chromium oxide layer on surface of stainless steel provides high resistance against corrosion and inhibits oxidation to move deeper [8,9].

There are five different types of stainless steels which are ranked from completely austenitic to completely ferritic varying in regard to additives that they contain. These are respectively:

- Austenitic Stainless Steel
- Ferritic Stainless Steel
- Martensitic Stainless Steel
- Dual phase Stainless Steel
- Precipitation-hardened Stainless Steel

Austenitic Stainless Steel includes 200s and 300s quality series and 304 quality is the most commonly used which its basis element is chromium nickel. Ferritic Stainless Steel is an alloy that cannot be hardened and 405,409,430,422 and 446 quality stainless steels are Ferritic Stainless Steel. Martensitic Stainless Steel has almost the same chemical properties, yet it has high incidence of carbon and less chromium that’s why they can be hardened with heat treatment. 403,410,416 and 420 qualities are Martensitic Stainless Steel. Dual phase Stainless Steel is obtained by forming a microstructure having almost equal austenite and ferrite and it definitively contains %24 chromium and %5 nickel. It doesn’t include any of quality series from 200s, 300s and 400s.

Various studies have been reported regarding the application of plasma cutting in stainless steels using different process parameters [10-15]. These studies have provided useful and
In this experimental study, the plasma method is selected to cut some commonly used metals (AISI 304, AISI 430 and EN S235JR). The selected cutting parameters were current, cutting speed, arc voltage, gas pressure and gas flow rate and the effects of these parameters on edge roughness, the hardness of the heat-affected zone (HAZ).

2. Experimental Study

In this experimental study, AJAN CNC 2x6m PP260A plasma cutting bench was used (Fig. 2.). 6 different experiment scenarios having different parameters were applied (Table 1.). 3 different materials shown in Table 2. having same thickness of 5mm were subjected to these experiments.

The materials were cut flat sided oval shape having 90mm length and 40mm width. Totally, 18 cutting operations were performed, yet it was not accomplished to cut S235JR material in 5st scenario.

### Table 1. Parameters of Experiment Scenarios

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>CURRENT (A)</th>
<th>GAS</th>
<th>GAS PRESSURE (BAR)</th>
<th>GAS FLOW RATE (LPM)</th>
<th>MATERIAL THICKNESS (MM)</th>
<th>VOLTAGE (V)</th>
<th>SPEED (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>O2</td>
<td>4.56</td>
<td>18.3</td>
<td>5</td>
<td>120</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>O2</td>
<td>4.8</td>
<td>5.4</td>
<td>5</td>
<td>114</td>
<td>1300</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>O2</td>
<td>6.51</td>
<td>9.6</td>
<td>5</td>
<td>120</td>
<td>1200</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>O2</td>
<td>4.49</td>
<td>16.4</td>
<td>5</td>
<td>111</td>
<td>4500</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>N2</td>
<td>5.51</td>
<td>9.7</td>
<td>5</td>
<td>129</td>
<td>1050</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>AIR</td>
<td>6</td>
<td>28</td>
<td>5</td>
<td>151</td>
<td>1200</td>
</tr>
</tbody>
</table>

Table 2. Materials subjected to the experiment

<table>
<thead>
<tr>
<th>Material</th>
<th>C%</th>
<th>Cr%</th>
<th>Ni%</th>
<th>Mn%</th>
<th>P%</th>
<th>S%</th>
</tr>
</thead>
<tbody>
<tr>
<td>S235JR</td>
<td>0.17</td>
<td>-</td>
<td>-</td>
<td>1.4</td>
<td>0.015</td>
<td>0.005</td>
</tr>
<tr>
<td>AISI304</td>
<td>0.08</td>
<td>18</td>
<td>8</td>
<td>2</td>
<td>0.015</td>
<td>0.08</td>
</tr>
<tr>
<td>AISI430</td>
<td>0.12</td>
<td>16</td>
<td>0.75</td>
<td>1</td>
<td>0.015</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The surface roughness (Rz) of cut materials was measured with Mitutoyo SJ201P equipment. Then by, the materials were divided into 3 sections by bandsaw bench branded Mossner. The middle sections of materials are rubbed with P240 emery sheets by using Netkon and Forcipol 2V grinders. The hardness of material which its surfaces were polished and the hardness of heat affected zone (HAZ) were measured with HMV Sumadzu Micro Vickers Hardness test device.

### 3. Results and Discussion

3.1. Surface Roughness

Surface roughness is one of the major process outputs when metal is cut. This value will affect the dimensional accuracy as well as surface quality. In surface roughness measurement, for S235JR material, the least roughness was experienced in the 4th experiment scenario (2,385µm). The highest roughness value (6,7975 µm) was beheld in the 6th experiment scenario.

For AISI304 stainless steel, the least roughness (2,3175 µm) was seen in the 5th experiment scenario. The highest roughness value (41,125 µm) was experienced in the 1st experiment scenario. For AISI430 stainless steel, the least roughness (1,6925 µm) was met in the 5th experiment scenario. The highest roughness value (38,2725 µm) was observed in the 1st experiment scenario.

The surface roughness of 3 different materials resulted by 6 different experiment scenarios are indicated in Fig.3.

3.2. Hardness

The hardness of cut sections in plasma cutting application is examined and the results have been presented in Fig 4. The obtained minimum and maximum hardness results for the materials after plasma cutting operations are as follows:

- For 235JR, between 130HV-150HV
- For AISI304, between 190HV-225HV
- For AISI 430, between 340HV-395HV

It was noticed that the hardness value has not changed with using different cutting conditions. The hardness of cut sections were similar in all cutting conditions.
3.3. Hardness of Heat Affected Zone (HAZ)

The Heat-Affected Zone (HAZ) presents to a non-melted area of cut metal that has experienced changes in its material properties as a result of exposure to high temperatures. The HAZ is identified as the area between the cut and the main metal. These areas can vary in size and severity depending on the plasma cutting parameters.

The height hardness for 235JR material was obtained in 6th experiment scenario and the least one was sought in 4th experiment. When it is compared roughness of HAZ and of the material, it is realized that HAZ roughness is higher than the one that the material has.

For the austenitic AISI 304 stainless steel, after the 6th experiment scenario, the highest hardness value was occurred. The lowest hardness value was obtained after 4th experiment scenario. The HAZ hardness is higher than the one that material has.

Comparing to ferritic AISI 430 stainless steel, highest value was experienced in 3rd experiment scenario and the lowest value was observed after 6th experiment scenario. Contrast to other materials, the HAZ roughness is less than the roughness of material.

The Heat Affected Zone (HAZ) hardness of the materials cut with plasma cutting are shown in Fig. 5.

During plasma cutting operations, the depth of the HAZ is related to cutting speed, material properties, and material thickness. It is known that plasma cutting process that operates at high temperatures and slow speeds produce large HAZs. Furthermore, cutting processes that operate at high speeds tend to reduce the width of the HAZ.

![Fig.5. HAZ hardness after plasma cutting](image)

Note: Due to that S235JR couldn’t be cut with 5th experiment scenario, HAZ hardness was not measured.

4.Conclusion

Plasma cutting is one of the modern cutting methods that is applied for various materials. The process has different cutting parameters and these are should be examined to find optimum industrial application. In this experimental study, 5mm thick austenitic and ferrite stainless steels were cut by plasma method. The selected cutting parameters on surface roughness, hardness and HAZ were examined. The following conclusions are obtained:

- When oxygen was used as plasma cutting gas, the surface roughness value was higher than the other applications with different gases.
- The lowest surface roughness value (1.6μm) was observed when nitrogen is used.
- The HAZ hardness of austenitic stainless steel increased after plasma cutting, whereas HAZ hardness of ferritic stainless steel decreased.

Industrial application of plasma arc cutting process presents many unique advantages and cost effective technology comparing to other cutting methods. It should be noted that more efforts put to optimize the process parameters in any industrial application of material cutting.

References

1. ВВДЕНЕ
Дългогодишната практика за развитие на сплавите се състои в производството на многобройни проби с променящи се състави и вариации на елементите, както и режим на обработката, за да се определят състави с оптимални свойства [1]. Този подход води до високи разходи за експериментиране [2]. Числените металургически данни са не само проектиране на основата на състава и вариация на елементите по вид, брой и количество, но и върху техния синергетичен ефект. Необходимо е да се изолира такъв синергичен ефект по комбинации от елементи, в който по-скъпо струващите елементи да са в по-малки количества. Наред с изпълнението на тази задача, металургията на състава трябва да използва и търсене компромис между свойствата на продукта, зависейки от параметрите на обработката. Тези няколко фактора би трябвало да формират общо параметри на обработката и състава. Сложността на така дефинираната задача се състои в големия брой на фактори, както и на проби и вариации на елементите, както и режим на обработката. Дългогодишната практика за развитие на сплавите се основава на множество материали от изследвана група или даден клас [3]. Най-характерното за тези подходи е, че те не използват по-скъпо струващите елементи, като съставна състава и вариация на елементите по вид, брой и количество, но и върху техния синергетичен ефект. Необходимо е да се съберат експериментални данни. Да се обработят с цел получаването на математически модели, годен за предсказание. Накрая с оптимизационна процедура се намалява броя на фактори, като се определят максимальни стойности между които се изменят. В таблица 1 са дадени факторите, техните номера, минимални и максимални стойности между които се изменят.

В таблица 2 са посочени възможните изходи с минимални и максимални стойности между които се изменят. За всеки изход Re, A, HB са пресметнати математичен символ и 

\[ Y(X) = C_0 + \sum C_i X_i + \sum C_{ij} X_i X_j + \sum C_{ijk} X_i^2 \]

Този модел при 8 фактори има 45 коефициента. Направен е статистически анализ на всеки модел. Коефициента не е възможно да се направи коначни предложения подобряващи параметрите на създаваните изделия и технологии. С това се проследява влиянието и взаимодействието между легирания елементи и техния

2. СЪСТОЯНИЕ НА ПРОБЛЕМА
В експерименталните изследвания съществува връзка между технологичните фактори на количество, брой и вид легиращи елементи, като се използват комбинации от една страна и свойствата на техническите показатели, като се вземе предвид, че се използват различни бази от данни при изследване на зависимостите. Необходимо е да се съберат експериментални данни. Да се обработят с цел получаването на математически модели, годен за предсказание. Накрая с оптимизационна процедура се намалява броя на фактори, като се определят максимальни стойности между които се изменят. В таблица 1 са дадени факторите, техните номера, минимални и максимални стойности между които се изменят. В таблица 2 са посочени изходи с минимални и максимални стойности между които те се изменят.
което следва, че математичния модел може да се използва за предсказване [7].

2.3. Цифрова оптимизация.


Методът на Хук и Дживс е един от най добrite, a и броя на факторите, допълнително предопределя, неговия избор.

Коefициентите на математичния модел са цитирани със седем значещи цифри – вж. приложение 1, 2, 3. Максимумите са цитирани там с две цифри след десетичната точка.

2.4. Избор на начална точка.

При всяка задача като разглежданата тук, крайната цел е намирането на по добър в някакъв смисъл краен резултат. Това най общо се формулира като „усъвършенствуване“.

Когато се каже „усъвършенствувам нещо“ то се рабира, че това „нещо“ го има и то съществува реално.

Всеки алгоритъм за екстремум започва с „избира се начална точка“. Единствените изисквания до момента към нея е да бъде в границите на допустимото за факторите. Точно тук се забравя че се усъвършенствува нещо и за да го усъвършенствуваме трябва да търсим от него. Проблемът е цитиран с две цифри след десетичната точка.

Изхождайки от това се решава да се направят 80 търсения на максимум, като във всеки отделен случай за начални точки се използват стойностите на факторите от експерименталните данни.

3. АНАЛИЗ НА ПОЛУЧЕНИТЕ РЕЗУЛТАТИ

Получените резултати са показани в приложение 1, 2 и 3. Приложение 1 – Изход Re, Приложение 2 – Изход A, Приложение 3 – Изход НВ.

И за трите приложения – горе в ляво коefициентите на математичния модел с пресмятаните стойности на коефициента на множествена корелация R и изчислената стойност на F критерий. В дясно сортираните в нарастващ ред, получени стойности на максимуми. Долу в ляво на фигурата – хистограма на сортираните максимуми.

Получените стойности на максимумите не са различни за всеки случай, а се групират около отделни стойности. За изход Re, (таблица 3) те са със 14 броя. За изход A, (таблица 4) те са със 7 броя и за изход НВ (таблица 5) те са със 8 броя. Там стойностите на максимумите са сортирани в нарастващ ред. До тях са посочени броя на случаите , когато е получена тази стойност и в дясно са сортирани нараствайки постепенно стойностите на отделните фактори.

За всеки случай, стойностите на получените максимуми на изходите са по големи от съответните им в експерименталните данни. За някоя от тях стойностите на отделните фактори съвпадат с границите в които те се изменят. Това т.н. условни максимуми. За изход Re, те са за стойност: 5638,2, 6333,8 и 9601,3. За изход A те са за стойност 32,3, 91,6, 96,2 и 122,88. За изход НВ за стойност 509,8, 932,4 и 1156,7. В останалите случаи имаме поне един един фактор който се намира във вътрешната интервала в който се изменя. Те оформят t.н. безусловни максимуми.

Обръща се внимание на това като началци стойностене на факторите на условия максимуми, не позволяват използването им като начални точки за търсене на по-голяма от тях стойност на максимум.
Табл. 6. Численни стойности на максимума за границата на провлачване, и решения от ново търсене.

<table>
<thead>
<tr>
<th>Максимуми от които са използвани стойностите на факторите за начална точка</th>
<th>Получена стойност на максимума. Стоянностите на факторите са използвани за ново търсене на максимума</th>
<th>Стояност На максимума</th>
</tr>
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</tr>
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<td>7478.0</td>
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</tr>
<tr>
<td>10094.42</td>
<td>10094.42***</td>
<td></td>
</tr>
</tbody>
</table>

* Новополучена стойност на максимум с координати: $X_1 = 0.125, X_2 = 0.027, X_3 = 1.75, X_4 = 0, X_5 = 0.035, X_6 = 3.25, X_7 = 1.5, X_8 = 0$
** Условен максимум, не позволява по нататъшно търсене
*** Потвърдена най-голяма стойност на максимум

Както се вижда математическата модел на този изход предлага сложна много екстремална функция. Тръгвайки с начални точки от максимуми 4113.0, 4370.2 и 44250 се стига до новополучен максимум със стойност 9597.98. Използвайки неговите фактори за начални стойности при търсене на максимум се достига максимум със стойност 10094.42. С тази стойност се потвърждава три пъти получената най – голяма стойност.

По нататък факторите на максимуми 5969.6, 7473.9 и 7478.0 използвани като начални точки, водят до максимум със стойност 7478.0.

Най-отдалеченият максимум, от 7479.7, позволява факторите му да бъдат използвани за начална точка. Тръгвайки от нея, крайния резултат е същата стойност на максимум. Това показва, че този резултат не може да бъде подобрен.

При максимум 93.06 стойностите на факторите използвани за начална точка, водят до максимум на максимума 122.88, което е потвърждение на получената до момента най – голяма стойност. Това позволява тази стойност да бъде обявена за глобален максимум. Получен е в 18 случай.

Не цитираните максимуми са условни и не позволяват търсене на максимуми. И тук е валиден аналога със стълбата.

За случая с твърдостта, посочена в табл. 8. може да се каже, че използваните стойности на факторите от максимуми 421.6, 439.8 и 441.4, водят до получаване на максимум със стойност 590.8, който съвпада с четвъртата след тях. При него стойностите на факторите вече са определени условен максимум.

Факторите на максимум със стойност 944.9 използвани за начална точка, водят до максимум със стойност 1160.5, което потвърждава до момента получената най – голяма стойност. Най-отдалеченият максимум 1160.5 за начална точка, водят до стойност 1160.5, което показва че няма по голяма от нея.

Това позволява стойността 1160.5 да бъде обявена за глобален максимум, получен в 22 от случаите. И тук е валиден аналога със стълбата.

** Условен максимум, не позволява по нататъшно търсене
*** Потвърдена най-голяма стойност на максимум

При този изход, картината е подобна на описаната вече. Вторият по ред максимум имащ стойност 35.2, позволява факторите му да бъдат използвани за начална точка. Тръгвайки от нея, крайният резултат е същата стойност на максимум. Това показва, че този резултат не може да бъде подобрен.

При максимум 93.06 стойностите на факторите използвани за начална точка, водят до максимум на максимума 122.88, което е потвърждение на получената до момента най – голяма стойност. Това позволява тази стойност да бъде обявена за глобален максимум. Получен е в 18 случай.

Не цитираните максимуми са условни и не позволяват търсене на максимуми. И тук е валиден аналога със стълбата.
Табл.8. Численни стойности на максимума за твърдостта, и решения от ново търсене

<table>
<thead>
<tr>
<th>Максимуми от които са използвани стойностите на факторите за начална точка</th>
<th>Получена стойност на максимума. Стойностите на факторите са използвани за ново търсение на максимума</th>
<th>Стойност На максимума</th>
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</tr>
</tbody>
</table>

** Условен максимум, не позволява по нататъшно търсене
*** Потвърдена най-голяма стойност на максимум

4. РЕЗУЛТАТИ ОТ ИЗСЛЕДВАНЕТО.
При търсене на глобален максимум на даден математичен модел най-правилно е това да започне с използване за начални точки стойностите на факторите във всеки отделен случай. По този начин продължава да се използва информацията заложена в експерименталните данни.
Сортирането и групирането около отделни стойности е следващата стъпка. Най-голямата от тях е желания глобален максимум.
Следващия етап ако е възможно се използват стойностите на факторите от получените максимуми за начални точки за последващо търсение на нови максимуми.
Това продължава до изчерпване на тази възможност. Най-голямата от тях се обявява за глобален максимум.
Факта, че до глобалните максимуми се достига от малък брой начин точки, предлага, че това може да се постигне с едно сканиране на изходните данни, без да се наложат други методи за определянето им, например вероятностни методи и т.н..
Получените по този начин, стойности на факторите при отделните търсения може да се използват при експериментална проверка за тези резултати.

5. ЗАКЛЮЧЕНИЕ
Доказано е, че ползването на стойностите на факторите от експерименталните данни за начални точки при търсение на глобален максимум е правилно и оправдано. Така се улеснява намирането му. Продължава ползването на информацията заложена в експерименталните данни.

Глобалният максимум със същия потенциал се използва за отделни стойности.
Правилно използването на факторите на тези максимуми и за начинни точки за следващо търсение на максимум.
Получените при това най-големи стойности могат да бъдат обявени за глобални.
Счита се задължително тази процедура при търсене на глобален максимум.

В случай за търсене на глобален минимум трябва само да се замени „максимум” с „минимум”, „по-голямо” с „по-малко” и „най-голямо” с „най-малко”.
Новият подход е създаден така, че да предлага реална възможност за значително намаляване на разходите и времето за предсказване на химични концентрации за множество свойства на клас от сплави на железна основа, така, че новите сплави ще имат по-добри свойства.
Постигнатите резултати показваха, че предложената методика може напълно ефикасно да бъде използвана за определяне на съществените връзки между екстремалните стойности на механичните параметри.

ЛИТЕРАТУРА
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Приложение 1. Коефициенти на модела и екстремални стойности за границата на провлачване

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$R = 0.8748619$  
$E = 2.59499 \times 1.705517$

\[X_1(t) = 12000 + 10000 \cdot \sin(2\pi t) + 5000 \cdot \cos(2\pi t) + 100 \cdot t + 5]

Приложение 1. Коефициенти на модела и екстремални стойности за границата на провлачване
Приложение 2. Коефициенти на модела и екстремални стойности за относителното удължение

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$A_{12} (i)$

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$R = 0.884035$

$E = 2.884035 \times 1.705517$
Приложение 3. Коефициенти на модела и екстремални стойности за твърдостта

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$R = 0.9429393$  
$E = 6.379504 > 1.705517$

На диаграмата са показани стойности $x_{13}^i(i)$ за $i$ в интервал от 0 до 80.

**Приложение 3**. Коефициенти на модела и екстремални стойности за твърдостта
TECHNogenic RAW MATERIALS FOR THE PRODUCTION OF MAGNESIUM AND SILICON-CONTAINING COMPOUNDS

Candidate of technical sciences Shayakhmetova R.A. 1, 1st year PhD student Mukhametzhanova A.A. 1, 2, Candidate of geological and mineralogical sciences Samatov I.B. 1, doctor of chemical sciences, assoc. prof. Akbayeva D.N. 2

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2 Al-Farabi Kazakh National University, Department of Physical Chemistry, Catalysis and Petrochemistry, Faculty of Chemistry and Chemical technology, Republic of Kazakhstan, Almaty 050040, Al-Farabi Avenue 71 e-mail: narike.91@gmail.com

Abstract: This work considers technogenic waste from chrysotile asbestos production as a source of magnesium and silicon-containing compounds. The products obtained by hydrochloric acid dissection of chrysotile asbestos wastes were studied by chemical, scanning electron microscopy, thermogravimetric analysis.

KEY WORDS: CHRYSOTILE-ASBESTOS, TECHNOGENIC WASTES, LEACHING, SILICA, MAGNESIUM

1 Introduction

The anti-asbestos campaign launched in the countries of Western Europe and the USA, which is mainly competitive in nature and aimed against the use of amphibolite asbestos, has significantly reduced chrysotile-asbestos export opportunities. For this reason, many asbestos mining and processing plants in the world have created additional capacity for the production of nonmetallic building materials demanded by consumers. Complex processing of chrysotile asbestos raw materials, as well as industrial wastes from their enrichment has become very relevant for many mining and processing enterprises associated with asbestos under market conditions and a crisis situation around asbestos [1-3].

There are various mineral classes of asbestos, including amphiboles and serpentinites. In Kazakhstan and in Russia, the deposits of the latter are widespread. During the processing of chrysotile asbestos raw materials, only 6-8% is extracted into the commodity fiber, the rest, which is a serpentine raw material 3MgO·2SiO2·H2O, is irretrievably lost as waste. With the enrichment of serpentinite the target product - asbestos fiber (Fig. 1a) and waste (Fig. 1b) are obtained. Fibrous type of serpentinite - asbestos has an independent technical value. Waste from the production of the asbestos industry is a source of environmental pollution and at the same time represents a mineral reserve of mineral raw materials practically prepared for processing for metallurgy and the construction industry [4].

![Image 1](image1.jpg) Fig. 1 – Products of serpentine enrichment

The total reserves of the main useful components contained in industrial wastes are comparable to the reserves of a fairly large polymetallic deposit.

2 Results and discussion

The subject of the research was the sand fraction -1.25 + 0.25 mm technogenic wastes from the serpentine enrichment of the Zhitikara deposit.

Every year thousands of tons of high magnesium content waste are generated at Kostanay Minerals JSC, which occupy a huge area and carry an environmental hazard to the region (Fig. 1b). The question of the need to recycle the enterprise’s waste with the release of new products that are in demand, competitive with high value-added products is relevant for Kazakhstan, as well as for countries producing asbestos fiber.

Chemical, scanning electron microscopy, thermogravimetric analysis methods were used to perform the studies. Thermal analysis of the samples was carried out on a Q-1000/D derivatograph of the F.Paulik, J.Paulik and L.Erdey systems from MOM (Budapest) company. The survey was carried out in air, in the temperature range of 20–1000 °C, the heating mode was dynamic (dT/dt = 10), the reference substance was calcined with Al2O3, and the sample weight was 500 mg. X-ray phase analysis on a DRON-4 diffractometer, micro-X-ray fluorescence analysis on an EDAX ts1 ametek instrument. Chemical analysis data obtained using certified methods.

The mineral base of chrysotile asbestos production wastes, according to X-ray phase analysis, is serpentine-3MgO·2SiO2·2H2O, containing silica in crystalline and amorphous states (Table 3). Of the other components, up to 5-7 % of iron oxides in the form of hematite and magnetite are present in the feedstock.

![Image 2](image2.jpg) Figure 2 shows the results of the analysis of the initial waste obtained on a scanning electron microscope.

<table>
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<tr>
<th>Component</th>
<th>Formula</th>
<th>Mass composition, %</th>
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<td>3MgO·2SiO2·2H2O</td>
<td>61</td>
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<tr>
<td>Talcum</td>
<td>3MgO·4SiO2·H2O</td>
<td>19</td>
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<td>Brucite</td>
<td>Mg(OH)2</td>
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<td>Forsterite</td>
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<tr>
<td>Magnesium oxide</td>
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</table>

Table 3 – X-ray phase composition of asbestos waste

![Image 3](image3.jpg) FOV: 67.2 µm, Mode: 15kV - Point, Detector: BSD Fed

a b

Figure 2 – Electron microphotograph of chrysotile asbestos waste
In electron microphotographs, chrysotile asbestos wastes are represented by particles of different sizes with inclusions of asbestos filamentous fibers (Fig. 2).

Table 1 – The average composition of chrysotile asbestos waste

<table>
<thead>
<tr>
<th>Element Symbol</th>
<th>Atomic. %</th>
<th>Oxide Symbol</th>
<th>Stoich. wt %</th>
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<td>Mg</td>
<td>19.87</td>
<td>Si</td>
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<td>Si</td>
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<td>Fe</td>
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<tr>
<td>Al</td>
<td>0.79</td>
<td>Ca</td>
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<td>C</td>
<td>0.46</td>
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<td>Fe</td>
<td>0.46</td>
<td>Al</td>
<td>0.23</td>
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Table 2 – Chemical composition of technogenic wastes

<table>
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<tr>
<th>Fraction size, mm</th>
<th>MgO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>Fe₂O₃</th>
<th>NiO</th>
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<td>36.5</td>
<td>0.79</td>
<td>0.46</td>
<td>4.87</td>
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As can be seen from the data of Tables 1 and 2, the main components of chrysotile asbestos waste are (in %): MgO – 39.0-41.3; SiO₂ – 33.4-36.5; CaO – 0.5-1.4; Fe₂O₃ – 2.7, FeO₂ – 4.9. According to chemical analysis Nickel is present in small amounts.

The DTA curve captures a number of endothermic effects associated with the dehydration of the system. According to the literature, the first endoeffect (at T = 132 °C) corresponds to the melting of MgCl₂·6H₂O with water splitting. The second thermal development (at T=213 °C) according to the change in mass characterizes the removal of 3.03 mol of water, the third effect (246 °C) corresponds to the removal of 1.55 mol of water from the system, and the next stage of dehydration (291 °C) is associated with loss 1.18 mol of water. In our case, these endothermic effects are caused by a 64.8 % decrease in sample mass, which corresponds to a loss of ~ 9.7 moles of water.

The endoeffect at 480 °C corresponds to the decomposition of the products of hydrolysis of magnesium chloride and the formation of anhydrous magnesium oxide MgO. The decomposition of magnesium hydroxochloride is accompanied by a change in mass of 14.0 % in the first sample and 15.7 % in the second. This process ends at 635 °C and leads to a loss of 3.2 % by weight.

The endoeffect at 720 °C corresponds to the beginning of the melting of anhydrous MgCl₂, and weight loss of 0.6 % and 0.5 %, which can also be explained by evaporation or decomposition of magnesium chloride.

The chemical composition of the resulting product is, wt.%: MgCl₂·6H₂O 97.5; MgO 11.8; sulfate ions SO₄ 0.8; alkali metal ions (Na⁺, K⁺) 0.1; water insoluble residue 0.15.

Electron micrographs of the silicon-containing residue obtained in the process of hydrochloric acid leaching of chrysotile asbestos wastes with the following process parameters: the concentration of acid used is 18-20 %, S:L 1: 3, the process temperature is 85–90 °C, time is 120 min and four-stage washing is shown in Figure 4. The average composition of the silicon-containing residue is shown in Tables 3 and 4.

![Image](https://via.placeholder.com/150)

Fig. 3 – Derivatogram of sample MgCl₂·nH₂O

Silica cake after processing contains up to 13 % of magnesium oxide contaminated with impurities of iron, aluminum, chromium, manganese. This product will be of limited use.

In order to reduce the loss of magnesium, complete its transfer into the solution and obtain pure silica, the second stage of leaching with 18% hydrochloric acid at S:L rate 1: 3, temperature 85-90°C.

Electron microphotograph of the silicon-containing residue after the second stage of acid treatment and two-stage washing with water is shown in Figure 5. The average composition of the silicon-containing residue is shown in Tables 5 and 6.
**Figure 5** – Electron microphotograph of the silicon-containing residue after the second stage of acid treatment at different magnifications

**Table 5** – The average composition of the silicon-containing residue after the second stage of acid treatment

<table>
<thead>
<tr>
<th>Element Symbol</th>
<th>Atomic. %</th>
<th>Oxide Symbol</th>
<th>Stoich., wt%</th>
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<tbody>
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<td>Si</td>
<td>98.11</td>
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<tr>
<td>Mg</td>
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<td>Fe</td>
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<td>Cl</td>
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**Table 6** – The results of chemical analysis of the silicon-containing residue after the second stage of acid treatment

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<th>Element</th>
<th>Content, wt %</th>
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<tbody>
<tr>
<td>MgO</td>
<td>1.92</td>
</tr>
<tr>
<td>FeO</td>
<td>0.08</td>
</tr>
<tr>
<td>MnO</td>
<td>0.046</td>
</tr>
<tr>
<td>SiO₂</td>
<td>90-95</td>
</tr>
<tr>
<td>Cl</td>
<td>0.33</td>
</tr>
</tbody>
</table>

From the presented results it can be seen that the resulting amorphous silica contains almost no iron and other impurities, the magnesium content has decreased by 4 times.

3 Conclusion

Thus, according to the results of an electronic scanning microscope and chemical analysis data, it follows that with complex processing of chrysotile-asbestos wastes using hydrochloric acid technology, in addition to bischofite, amorphous silica with an SiO₂ content of 97-98%, which is recommended for use in as a filler in the rubber industry, in the production of paints, varnishes, silicate adhesives, the starting material for the production of high-purity silicon.

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GEOMETRIC METHOD FOR DETERMINING RADIANT HEAT EXCHANGE IN VACUUM FURNACE

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Abstract: Heating chamber in vacuum furnace is closed thermal system where heat exchange is predominantly radiant. Conductive heat exchange is defined by well-known formulas. In order to determine the temperature condition of the object during heating (cooling), it is necessary to determine the angular coefficient of radiant exchange on every other objects. The known in the literature methods, including the geometrical once, have a solution for heat exchange only between two objects. The applications for real heat systems is partial and limited. It is presented a geometric model for calculation the angular coefficients of radiant interchange for closed thermal system. Heat exchange is taking place between an unlimited number of objects and a free-standing arrangement between them. The model allows solutions for objects of different geometric form in the presence of intermediate objects, as well as barriers for heat radiant from their own surfaces. The paper has been verified by a solution of thermal problems for vacuum furnaces.

Keywords: vacuum furnace, heater, angular coefficient, radiant heat

1. Introduction
In vacuum furnaces the heat exchange is predominantly radiant as in diluted gas environment the convection heat transfer can be neglect.

In order to determine the temperature condition of the object during heating(cooling), it is necessary to determine the angular coefficient of radiant interchange. In the literature [2], it is derived dependancies for calculating angular coefficient between two objects in predtermiend geometrical surface and position.

In real-life thermal system those dependancies can have only partial application. The reason for that is the existance of various restrictions in the radiant interchange between two objects.

For example, on Fig. 1 it becomes clear that not all of the rays from p. A of radiating surface of Object 1 reach the surface of Object 2.

\[
\phi_{1,2} = \frac{1}{F_1} \int_{F_1} \int_{F_2} \frac{\cos \beta_1 \cos \beta_2}{\pi \cdot S} dF_1 dF_2
\]

\[
\phi_{2,1} \cdot F_2 = \phi_{1,2} \cdot F_1
\]

where \( \phi_{1,2} \) and \( \phi_{2,1} \) - angular coefficients of heat exchange, respectively:

- Object 1 to Object 2 and Object 2 to Object 1;
- \( F_1 \) и \( F_2 \) - the overall area of surfaces’ objects;
- \( \cos \beta_1 \) и \( \cos \beta_2 \) - cosine of angle between ray and a normal to the relevant surface;
- \( S \) - length of the ray between \( dF_1 \) и \( dF_2 \);
- \( n_1 \) и \( n_2 \) - normal to surfaces \( dF_1 \) and \( dF_2 \).

Additional constraint that is area from objects surface where heat exchange with another object is through conduction. These areas are not included in radiating surface.

In radiation theory determining the angular coefficients between two objects is accomplished through geometric task and it is represented mathematically with certain/insignificant dependences(1) [[1],[4]], (Fig. 1). With restrictions in free irradiation in variety in geometric surfaces as well as positioning of objects, solutions in (1) in most cases can not be found.

\[
S^2 = \Delta X^2 + \Delta Y^2 + \Delta Z^2 , \text{where}
\]

\[
\Delta X = X_{\text{av}} - X_{\text{no}}; \quad \Delta Y = Y_{\text{av}} - Y_{\text{no}};
\]

Fig.1. Scheme relating to determine angular coefficient of heat exchange to (1).

Calculations are undertaken through sequential solution of elementary integral parts on every object in respect to the rest. The result is average angular coefficient with acceptable margin of error for solution of practical tasks.

2. Solution of the problem
In [1] are summed up the possible types of tasks and restricting conditions for heat exchange between two objects.

In order for calculations to be done in (1), in any moment with every position of elementary integration parts, it must be determined: the length of the ray \( S \) and angles \( \beta \), between it and the normals to them.

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According to [1], the possible positions of the surfaces that \( \cos \beta \) is determined are:

- Plane with a normal parallel to one of the coordinate axes;
- Plane parallel to coordinate axe "X";
- Cylindrical outer and inner surfaces with a geometric axis parallel to X.
- Cylindrical outer surface with a geometric axis perpendicular to X.
- Obstruction object with a planar shape
- Obstruction object with cylindrical surface

On Fig.2 it is shown method for calculating \( \cos \beta \) for cylindrical surface with geometrical axe parallel to "X". The normal to the surface in point \( \mathbf{A}_{\text{обк}} \) is the continuation of \( \mathbf{O}' \mathbf{A}_{\text{обк}} = \mathbf{R} \) and lie in the plane of a triangle \( \mathbf{O}' \mathbf{A}_{\text{обк}} \mathbf{A}_{\text{внш}} \), and \( \mathbf{O}' \)’s coordinates \( \mathbf{X}_{\text{обк}}, \mathbf{Y}_{\text{обк}}, \mathbf{Z}_{\text{обк}} \) lies in a cross-section of the surface through the current crawl point \( \mathbf{A}_{\text{обк}} \). After calculating \( \mathbf{O}' \mathbf{A}_{\text{внш}} \) as a distance between two points in space and a substitution in a cosine theorem, for \( \cos \beta \) the result is (3).

The plus and minus characters refer respectively to the outer and inner surfaces and are obtained due to the different direction of the normal.

\[
O' A_{\text{внш}}^2 = R^2 + S^2 - 2R \cos(180 - \beta)
\]

In the second case (Fig 1 b), the plane is defined with p. S between it and angle \( \alpha_0 \) that intersect with the normal "- \( \mathbf{n} \)" with axe "Y". \( \cos \beta \) is calculated with dependencies 4b.

\[
Z_p = \frac{Z_c - (Y_c - Y_{\text{внш}}) \cdot \tan \alpha_0 + \tan^2 \alpha_0 Z_{\text{внш}}}{1 + \tan^2 \alpha_0};
\]

\[
Y_p = Y_{\text{внш}} - (Z_p - Z_{\text{внш}}) \cdot \tan \alpha_0;
\]

\[
PC = \sqrt{Y_c^2 + Z_c^2 - \sqrt{Y_p^2 + Z_p^2}};
\]

\[
\cos \beta = \frac{PC}{S}
\]
is center of cylinder base, point O’ is the center of the cross section through the $A_{обк}$. 

$$O'A_{внш} = (X_{A_{внш}} - X_{oc})^2 + (Y_{A_{внш}} - Y_{oc})^2 + (Z_{A_{внш}} - Z_{oc})^2$$  

(4)

where

$$k := Z_{oc} / Y_{oc};$$

$$Z_{oc} = k(Y_{A_{внш}} + Y_{A_{обк}}) / (k^2 + 1);$$

$$Y_{oc} = Z_{oc} / k;$$

In relation to the analogy in the algorithms for solving two tasks have been provided:

**Irradiation of external cylindrical surface with an axis parallel to the X-axis from a point outside of it.**

The possible direction of radiation from p. $A_{обк}$ are derived from tangent surface through cylindrical surface. The requirement for irradiation of p. $A_{внш}$ from $A_{обк}$ is for it to be in the zone of irradiation of point $A_{обк}$. On fig. 4 it is shown a solution with a plane that is perpendicular to the axis of the cylinder. The angular coefficient is determined for a straight line $OA_{обк}$ as well as the point of intersection P between it and a straight line through point $A_{внш}$ perpendicular to $OA_{обк}$.

For $A_{обк}$, a requirement must be met (point that lay on the section) where irradiation between two points has to be ensured. The coordinates $Y_p, Z_p$ are calculated according to (5).

If $Y_{A_{внш}} = Y_{oc};$ $Y_p = Y_{oc};$ $Z_p = Z_{A_{обк}}$; If $Y_{A_{внш}} \neq Y_{oc};$ $k := (Z_{A_{внш}} - Z_{oc}) / (Y_{A_{внш}} - Y_{oc});$

$$Z_p = [Z_{oc} + k^2 Z_{A_{обк}} + k(Y_{A_{обк}} - Y_{oc})] / (k^2 + 1);$$

$$Y_p = (Z_p - Z_{oc}) / k + Y_{oc}$$

(5)

**Obstruction object - planar figure.**

Every object is an obstacle if the point intersection of the ray (p. P) is inner for section $A_{внш} A_{обк}$ as well as it is in the contour of the object in the projection plane that is perpendicular to the normal. The coordinates $X_p, Y_p$ and $Z_p$ for different positions of the geometric normal are calculated through derived formulas and $\Delta X, \Delta Y$ and $\Delta Z$ with (3). On fig. 5 it is given a clarification for conditions that fulfill obstacle “circle” and “ring” with normal through X. For geometric normal that is perpendicular to X the solution is taking into account object “circle” with rotated coordinate system $XY'Z'$ (fig. 6). The coordinates $Y', Z', X_{A_{обк}}, Y', A_{обк}, Z', A_{обк}$ and for the center of the circle $Y', Z'$, it is calculated through derived formulas in different, $\Delta X, \Delta Y$, and $\Delta Z'$ with (3) for recalculated coordinates with point index $A_{внш}$ and $A_{обк}$. The coordinates of p. P are calculated according to (7).

**Fig. 5. Conditions for irradiation with given obstacles “circle” and “ring” with geometric normal $\perp X$.**

**Fig. 6. Conditions for irradiation with given obstacles “circle” with geometric normal $\perp X$.**

4. **Conclusion**

It is presented a geometric method for calculation the angular coefficients of radiant interchange for closed thermal system. Heat exchange takes place between an unlimited number of objects and a free-standing arrangement between them. The model allows solutions for objects of different geometric form in the presence of intermediate objects, as well as barriers for heat radiant from their own surfaces. The paper has been verified by a solution of thermal problems for vacuum furnaces.

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HOME PAGES, DEFINITION AND CLASSIFICATION OF THEIR ELEMENTS AND THEIR DISPLAY ON THE USERS’ COMPUTERS

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Abstract: The subject of the research in this scientific paper is a description of the home pages in websites, with special emphasis on definition and classification of elements, which are necessary for the proper functioning of a home page, from the aspect of functionality and creativity. The important part of my paper is an analysis of technical methods of their displaying on various users’ computers. Here the comparative analysis of similarities and differences between a home page and other pages of the same website is made. A special overview is made for the correlation between home pages and all the other pages on the website from a point of view of visual harmony and functionality of those websites. Additionally, here I give overall directions for using home pages when designing websites, and also a description of some opinions and advice on the same topic. After that, I analyze six problems which arise from displaying home pages on the user’s computer and topics connected with that. I will come across a few solutions for all of them, as well as recommendations for when to choose which solution.

Keywords: HOME PAGES, DEFINITION AND CLASSIFICATION OF ELEMENTS OF A HOME PAGE, THE COMPOSITION OF THE WEBSITES, WEB DESIGN

1. Introduction

The basic four rules of design that need to be considered when designing a website are:
- Contrast. The rule of contrast means that the placement of similar elements on the same page should be avoided. If the elements (font, color, size, line thickness, contour, interval, etc.) are not exactly the same, but only similar, then they should be shaped differently. Very often, initially the contrast attracts the attention of the user.
- Repetition. The elements of the design should be repeated through the entire edition. Colors, contours, textures, mutual relations, line thickness, fonts, proportions, graphic concepts, etc. can be repeated. Repetition helps for better structuring and enhances the sense of integrity.
- Alignment. Nothing should be placed on the page by chance. Each element should have a visual connection with the other elements. This gives to the page a clean, sophisticated and fresh look.
- Closeness. Elements that are in some way related to each other should be close to each other. So these elements represent one unity and not just a few fragments. It helps information’s to be well organized and reduces overcrowding, providing the reader with a clear structure.

Although the four basic rules apply also in the web design, repetition is the basic rule when shaping a website. The other three rules also help, but repeating is what shows visitors that they are still on the same site. There must be consistency in the navigation and the style of graphic design, repetition of the color scheme, the use of the same fonts, the placement of one styled graphic elements in the same way on each page, etc. [1]

A well-organized website should have: a logical structure, constant navigation, and clear inscriptions.

When determining the style for websites, it’s good to know these two rules: there should be consistency in using the features of the design, and in the overall style of the site less is better (sometimes the most effective design is simple but elegant).

Good websites are designed with the ability to increase so to meet the new needs of their users, as these needs change over time. An important rule regarding the structure of the website is to have a structure built in a way that reflects the user’s view of the site and its information and/or services. The basic mistake is the structure of the site to reflect the organization of the company, rather than the user’s point of view. [15]

Good websites are more than just random collected pages. They have to create a coherent overall impression on the visitor. [18]

When visitors move from page to page, they should always feel that they are on the same site. Although small decorative changes are good, the style and structure of the page should not be changed at once. Especially recommended are permanent background and unchangeable color scheme. Although the content of the pages is changed, the "containers” will be the same. On good sites, passing from page to page is unnoticeable.

Information that is repeated on many pages should be displayed in one and the same position. The structure and order of pages in a website should be logical. [17]

Each web page should have a clear visual hierarchy. Pages with a clear visual hierarchy are distinguished by three distinctive features:
- the more important a given element is, the easier it is to notice it (the most important titles should be larger, written in bold font, colored with a striking color, fused with more than the usual blank space or placed close to the top of the page).
- elements that are logically connected, should be also visually connected (certain elements which are similar, when grouped under one title, will be displayed on a screen in a similar visual style or will be put together in a clearly defined area).
- it is good for some elements to be visibly put inside another one to see which is from what part (if a book is part of a given section, it is appropriate that the title of the section is located above the title of the book, encompassing visually the whole area for the content of the page).

Also, the good visual hierarchy saves time. [6]

Every page should have a focus (attention center), from which the reader should start. This focus is created by implementing visual contrasts, for example: large and small elements, dark and bright, rectangular and round, many and just a few, etc. [2] Websites are a set of different types of pages, but the home page is an inevitable part of all sites.

2. Study Area

The home page of a website can be considered as a “facade” of that site. Facade of the site should always be carefully thought about. The face of the website should be attractive and unforgettable in order to gain visitors attention. Business people say “the first impressions sell”. [7]

Creating a good first impression is more than just looking good to everyone. The home page should seductively suggest the content of the site. [14]

The immediate goal of every home page is to answer the questions “Where am I?” and “What is this site for?” The home pages are relatively permanent places that do not change their position, and with that, they help the orientation of the visitors on the site. [9]

Everyone wants a "piece" of the home page. This is the page that almost every visitor sees, and for some users, it remains the only seen page. Everything that is clearly emphasized on the home page is visited a lot more times. [13]

An attractive presentation of some of the content on the home page is an essential part of the information architecture because it
allows visitors to immediately find new contents instead of having to search for them.

Without it being a binding rule, most home pages tend to cover all content in one screen, which is without vertical scrolling. It is often a difficult task. [11]

The content of the home page should be regularly renewed. If the success of the site depends on whether it will be visited often, the home page will, in every probability, have to contain content that will often be updated.

The home page can be designed in a way that differs from that of the other pages. Of course, the home and the other pages should have the same style, but sometimes, depending on the conditions, there may be some differences.

However, the most common communication weaknesses on the home pages due to the growing need for increasing the information density, including "on the input", are excessive overload with elements, as well as poor architecture or complicated site structure, whereby users feel helpless as in front of an impossible intellectual task.

To achieve that all communication functions on the home pages are enabled is a complex task that requires excellent professionalism by editors, designers, and developers. Not only should the space constraint be overcome in online communication, especially in the design of the home pages, but also the time limitations. And not only in terms of the duration of the loading of the optical forming factors but also in terms of the limited capacity of absorbing information and the resource of attention by the user.

3. Related Research

Defining all the elements of the home pages of websites is a very large task. Here are presented the most necessary elements and their possible different characteristics from the same elements in other pages of the same site:

- Basic information about the functionality of the site. It is needed to increase the efficiency of the pages by adding personal and contact information for the web designer. The basic information also includes the date of creation and the date of the subsequent or last update of the site.

- Logo. The logo of a website is usually placed in the upper left corner of the screen. The logo on the home page may sometimes be (but not necessarily) larger than on the following pages. I find it better if the size of the logo is the same for the whole website. From the aspect of advertising, less well-known websites can make the name and logo a bit larger compared to those of popular sites.

- A characteristic phrase. One of the most valuable parts on the home page is the space next to the site logo. When a phrase is visible, visibly related to the logo, it is known that it is a characteristic phrase, motto, and is therefore considered a feature of the entire site. In websites, a characteristic phrase stands directly under, above or next to the logo. [8]

The characteristic phrase should be a meaningful text that characterizes the whole venture - summarizes what it is about and what makes it so wonderful. Characteristic phrases are not from yesterday - for a long time they are involved in ads, entertainment and in printed editions.

Characteristic phrases are a very effective way to convey the message because they are the only place on the page where users expect to see a concise presentation for the purpose of the website and the company as a whole.

When selecting a characteristic phrase, the following thing should be taken into consideration:
- the good phrases are clear and informative;
- badly selected phrases are unclear;
- the good phrases are exactly as long as necessary.

Six to eight words are enough to express a complete thought and at the same time - just enough, so that they can be easily understood and remembered ("Let's make things better" - PHILIPS).

- Something influential (impressive). In order to attract the attention of the user, "something impressive" can be placed on the home page: graphics, animation, interesting textual content, background music, sound effects, video... They enrich users' experience, effectively direct attention, emphasize certain moments of communication, define the beginning and end of important phases, create an impression of the unity of the composition...

Using all of these "tricks" to attract visitors' attention is not necessary, but they add to the attractiveness and clarity of web pages and because of that it is often recommended to use them, normally in adequate proportions.

- An informative title. As has been said before, the immediate goal of each home page is to answer questions about where the user is located and what is the purpose of the visited website. The answers to both questions require a clear and extended version of the site's name. The name of the company or site should be prominently placed in a prominent place. It may also be recommended to use a domain address and an adequate window title.

The most visible and most obvious element of the design on the home page should be the name of the company or the site. This does not mean that the name should be the largest element, but at least it should be in a place where it is easy to see. Most often it's on the upper left side on the web page.

If the name of the site and the relevant company is of no significance or its significance is not related to what is done in the company, more efforts will have to be made to help users understand it.

Websites, which are less well-known, need to put a small amount of additional identification information on each of the internal pages. [8]

- Navigation. Navigation is the most important element of the home page. The way how the site is divided and the section names in it can in large amount suggest its functionality.

For those who visit the site for the first time, the answer to the question "What does this site do?" is perhaps the most important feature on the home page, but for most other visitors the most important function on the home page is to serve as the starting point for the site navigation scheme. [16]

The navigation itself can be done in a variety of ways. In order to increase navigation efficiency, it is accustomed to a greater number of different types of navigational elements that suit the needs of a wide range of visitors. Navigation links and buttons should be easily visible and consistent in place. Text links usually appear at the bottom of the page. They are usually written in a small font and contain only the most important links. The text links that are put that way are usually the second set of navigation elements.

Some authors believe that the home page does not need to have a "Home" button because it is quite uncomfortable to press a button that doesn't lead to another page. [4] This recommendation should be accepted conditionally because preserving the design composition and no-disrupting the convenience of surfing for the users (easier to get used to the placement of links) suggests that it is better to keep the navigation the same. In other words, it's better the "Home" button to be on the home page as well.

Often, the question arises as to how the navigation on the home page should be the same as in the rest of the site. It may be different, but not too much. Common differences may be the following: section descriptions, different orientation, drop-down menu, and logo size.

Also on the home page, more often than on the internal pages, pop-up windows can also be found by clicking on a specific link. [3]

- An emotional effect. Emotional effect on users is achieved by means of words, color, font and other elements. The home page and internal pages should have the same style. The colors chosen are of great importance both for the definition of the brand as for creating a mood for the site. Standard, easily readable fonts should always be used.

A very significant feature of the home page is that it is one and the same for all tastes. Unlike the lower-level pages, the home page should appeal to anyone who visits the site, no matter how diverse their interests are.
4. Findings/Results

In this part of the scientific paper are six problems that arise from the displaying of home pages and their elements from websites on users computers. There are several solutions to the problems and making recommendations for when to choose which solution.

4.1. Problems with Lack of Knowledge that the Site Logo Serves as a Link that Leads to the Home Page

The unwritten rule that the logo of the site also serves as a button, leading to the home page is increasingly imposed. This is a useful idea, which is good to be accepted from every website. That way it will be much easier to navigate through the site because users will always be able to go to the home page and start all over again.

But a surprising number of users do not know about this rule. To improve that, the word "Home" (home page) should be discreetly added to the logo on the site everywhere. In this way, users will know that they can click on the logo. While this unwritten rule becomes common knowledge, there should be a link to the home page in sections and/or tools.

4.2. Problems with the Different Navigation on the Home Page and all Other Pages in the Websites

One of the main rules for deploying navigation on all pages on one website is that it should be consistently equal. This rule has two possible exceptions. The first is the home page. It is not like other pages - it is burdened with other responsibilities and should be held to other promises. Sometimes it does not include permanent navigation.

The usual differences are the following:

- sections descriptions. Since the home page should show as much as possible from that what is behind it, it's not a bad idea to add a descriptive phrase to the name of each section, and even specify the subsections - something that not every page has space for.
- different orientation. The home page often requires a radically different layout compared to all others. This means that it may be more appropriate to use horizontal instead of the usual vertical navigation on site, or vice versa.
- more space for the logo. The site logo on the home page is sometimes larger than in the permanent navigation. It's good next to the logo to have a little free space for a characteristic phrase, which is not mandatory to appear on every page.
- drop-down menus. Because the space on the home page is severely restricted, web designers are constantly looking for ways to increase it. One of the most common ways to do this is by using drop-down menus.

It is also important not to make unnecessary changes. The home page navigation and permanent navigation should have enough common features so that visitors can immediately understand that it's about two different versions of the same thing. The most important thing is to preserve the same names of sections everywhere - sequencing, specific words, and grouping should not be different. It is also good not to change the visual features - the same font, colors, and registers of the letters.

4.3. Problems with the Visual Presentation of the Language on the Web Pages

The most used visual symbol for language is a flag, but, unfortunately, flags represent states, not languages. The problem
with the use of the flag as a symbol for language selection is that
some languages are spoken in more than one country, and in some
countries, the official languages are more than one. The example
can be used with the English language. Using the US flag to mark
the English language is the obvious insult for English people (they
are in fact its creators), but that also irritates Canadians and many
others. Of course, the use of the Canadian flag is also not
appropriate, because they speak English and/or French.

Alternative icons with national stereotypes can be set as well,
buts there is a risk that they will be offensive (for example, not all
Amercians wear cowboy hats). It is usually the best to avoid icons
and simply write languages with words. However, flags can be used
that correspond to the geographical location of the service and its
primary target audience. As an example, one tourist website in
continental Europe can use United Kingdom flag for the English
language, except if the website is primarily targeted for American
tourists, and on the other hand, one tourist website in America
could be using the USA flag if their primary targets are not European
tourists. An English flag can be used, but it is not recommended,
because not many people outside the UK know regional flags of
England, Scotland, Wales, Northern Ireland, etc.

The other possible solution is using two flags in the size of one
so that each flag will take half of the space. The separation can be
made horizontally in the middle, vertically or diagonally.

4.4. The Dilemma with Presenting the General
Information about the Site on the Internal Pages

The site name should be repeated on all internal pages because
users can enter the site from anywhere, not only from the home
page. The user entering the site using a search engine or tracking a link
from another site should be able to clearly define which site they
have entered. At the same time, however, the internal pages should
focus attention on the particular content rather than presenting a
general greeting or describing the site (these two goals should be
reserved for the home page).

It is clear that there is a contradiction - on the one hand,
between the need to make a presentation to people who have
entered from any page, and on the other - the need to isolate general
information and higher levels of navigation only on the home page.
The solution to the problem depends on how often is expected users
to enter the site from the internal pages and how much the site is
impressive and popular. If the site is unmistakably recognized by
most users, it is not necessary to place general information on
internal pages. Only, each page should have a clearly visible link to
the home page. It is recommended this link to be located in the
upper left corner of the page, which is the recommended place for
the name and logo of the site.

4.5. Problems with Overloading the Home Page with Ads

The problem with advertising on the home page is that it works
too well. Everything that has a clearly visible hyperlink on the home
page will surely have more visits (many more), which makes site
owners think: “Why not add another hyperlink again?”. The
problem is that the advantages and disadvantages of adding more
items to the home page are not distributed equally. The advertised
section is impressed by a large number of visits, while from the
overall loss of efficiency of the home page as a result of its
overcrowding, all the other sections suffer

Preventing that the home page doesn't get ad overload requires
constant care, as it usually happens gradually, with the slow, but the
unyielding addition of just one more thing. All website owners
should be aware of the danger of overloading the home page and
they need to use other methods to increase visits to their site, for
example, their ad placed on other popular websites or rotating ads
that use the same space on the home page.

4.6. Problems with Sounds on the Websites

An increasing lack of sound in web space is a complaint that is
often met among media professionals. Some of them think that
sound is the most powerful means of creating mood and
manipulating emotions. The real environment of the users should
never be forgotten. Unexpected sounds are frightening and violate
the sense of privacy and control. However, many websites play with
the idea of integrating audio - to give the mood, to follow the
action, to advertise the site, and so on.

Adding sound to the website (whether it’s an easy-to-use
surround sound for moods or sounds from the interface) is very
often chasing users away, especially when they cannot turn off the
sound. Of course, there are exceptions - certain types of sites are
expected to have sound (like for example, congratulations online).
But the ability to turn off the sound should always be available.
Therefore, a visible On/Off switch should be placed so that users
can get rid of the sound without having to leave the page.

Most often, the problem with audio on websites occurs upon
first entering a specific site (usually home page). The user is not
familiar with the sound component of the website and a variety of
inconveniences can arise during its use. It's good the “On/Off”
switch to be on every page of a certain website, but its existence
should be mandatory on the home page. The sound settings (will the
user hear the sound or not) should remain as same as it was at the
first choice (it’s usually made on the home page) while surfing the
entire website, with the possibility to it change on each page.

5. Conclusion

Modern website design allows designers themselves to decide if
and when will they use standard rules for a home page, of course,
together with all the other standards and norms that exist when we
want to shape one stylishly designed site.

The conclusion that can be made from all of the above
mentioned is that this area is extensive and offers many
opportunities for research and analysis. Due to a large number of
problems which occur in this area, usually, there is not only one
correct solution.

For the most appropriate solution to be chosen, a lot of data
should be collected about desires and habits of potential users, as
well as the technical features of their computers. The solution needs
to be found based on those information’s. Sometimes, depending on
the situation, it is possible to apply a combination of multiple
solutions simultaneously.

One of the decisions that will qualify the quality of that site and
its aesthetics and technical aspects is how good the quality of the
home page will be. The need to find the appropriate balance
between designer visions, users’ expectations, and technical
possibilities is one of most common problems which all website
designers meet.

Web designers must be aware of market needs and business
expectations of a site owner if they wish to create a visually perfect
website implementing all their ideas and imagination. The other
segment of this problem is users and their needs and requirements
when using the Internet. And at the end here are technical
parameters and limitations that very often can represent a key factor
in the decision if and which website should be visited and used.

Today, when there are millions of sites with the same or similar
topics, the downloading time is one of the main parameters when
choosing which website to visit.

All these aspects should be considered when deciding which
solution to choose to resolve these problems.

The conclusion is that there is no universal solution for all the
possible problematic situations. It should also be noted that the
abundance of a variety of program languages and codes allows
other solutions too, depending on the used languages and codes.

This subject, as well as everything else with web design, is very
progressive. Some other possible solutions to the problems in this
science area will be undoubtedly produced using many various new
innovations and opportunities.

6. Literature


Peachpit Press, USA, 2005.

1. Introduction

Success in modern operations is achieved by those forces and means of counter-fighting combatants that use reliable fire support. Recognizing that fire support includes strikes and fires with lethal and non-lethal effects of fire and impact systems of land, airborne, naval components and special operations forces executed under operative scenario with attracted operational forces, it is necessary to analyze the individual components of this complex system. In this article, we are limited to examining only the effectiveness of artillery fire systems. The analysis of the electronic fire operations at the end of the 90s shows that the proportion of MLRS and Artillery’s damage in the operations is 50-60%, which is distributed: 30-40% when the enemy damaged at near depth and 15 - 20% in case of a long range fire support [1].

The fire support of military formations is carried out by fire formations and firing systems and its effectiveness depends to a large extent on the efficiency of the used artillery systems.

A primary indicator in assessing the efficiency of fire systems is the probability of damage the target (object) using the damage function. Damage function is a part of the mathematical apparatus for determining the efficiency of fire support systems.

2. Results of discussion.

Damage function comparison.

2.1. Purpose: Presenting a theoretical analysis of damage functions used in evaluation of artillery fire support effectiveness.

2.2. Objectives:

- to analyze damage functions and artillery weapon systems effectiveness using them;
- to determine differences in damage functions and their appropriate usage.

The damage function determines the percentage impact of the weapon (system) on the target. It has two main components: distribution of the mean point of impact to the target center (the point of measurement) and the likelihood of target damage as a result of the deviation from the center of the target.

The mean point of attack can be characterized as a random value with bivariate normal distribution, range error probable (REP) and deflection error probable (DEP) and the probability density function \( f(x, y) \):

\[
(1) \quad f(x, y) = \frac{1}{2\pi \sigma_x \sigma_y} e^{-\frac{(x-\mu_x)^2}{2\sigma_x^2} - \frac{(y-\mu_y)^2}{2\sigma_y^2}} \quad [5]
\]

And cumulative density function:

The cumulative density function (continuous probability distribution) is determined by the formula:

\[
(2) \quad F(X, Y) = \int_{x=-\infty}^{x=x} \int_{y=-\infty}^{y=y} \frac{1}{2\pi \sigma_x \sigma_y} e^{-\frac{(x-\mu_x)^2}{2\sigma_x^2} - \frac{(y-\mu_y)^2}{2\sigma_y^2}} dx dy \quad [5]
\]

where \( \sigma_x, \sigma_y \) standard deviations in range and deflection, \( x, y \) mean deviations of the random value in range and deflection, \( \mu_x, \mu_y \) mathematical expectations.

In different cases, the distribution of the mean point of impact may also be different. For example, when the numerical value of standard deviation of the two dimensions is equal, and the mathematical expectation of the mean point of impact equals zero, then it is a normal circle-like distribution, which is characterized by a circular error probable (CEP) and a function of distribution, which can be calculated using the formula:

\[
(3) \quad (x, y) = \frac{1}{2\pi \sigma^2} e^{-\frac{x^2 + y^2}{2\sigma^2}} \quad [4]
\]

As a result of the assumption of radial distribution of the mean point of attack, the properties of the random magnitude will change.
One of the methods for determining the distribution function of a random variable with radial distribution is using Rayleigh distribution.

The Rayleigh distribution is used to characterize the radial distribution function shown in Fig. 2.

Random variable with the distribution function shown in Fig. 2.

Numerous asymmetric bivariate normal distribution law rather than a bivariate normal distribution law (circular) (symmetrical). Numerous numerical values rather than the errors in deflection. This is the result of the error value in range in the majority of cases has a higher case and makes it specific rather than universal. Practice shows that this assumption does not allow the use of the model in any case because it defines the covered area individually for each fire system. This makes the model more realistic about effectiveness evaluation.

In some cases, the following formula may be used:

\[ PD = 1 - 0.5 \frac{r^2}{\sigma^2} \]  
\[ \text{CEP} = 1.1774 \sigma \]  
where \( R \) radial variance of the random value, \( \text{CEP} \) circular error probable, \( \sigma \) standard deviations in range and deflection.

The other model that is primarily used to determine the effectiveness of fire systems for various purposes is the Carleton damage function or the diffuse Gaussian damage function.

\[ D(r) = e^{-\frac{r^2}{2 \sigma^2}} \]  
where \( b \) a damage factor dependent on fire system, \( r \) radial variance of the random value.

This model for determining the efficiency of the damage can be used in any case because it defines the covered area individually for each fire system. This makes the model more realistic about effectiveness evaluation.

In case the distribution law is asymmetric, the mathematical apparatus for calculating the probability of damage is as follows:

\[ PD = \frac{b_x b_y}{\sqrt{(b_x^2 + \sigma_x^2)(b_y^2 + \sigma_y^2)}} \]  
where \( b_x, b_y \) damage factors dependent on fire system in range and deflection, \( \sigma_x, \sigma_y \) standard deviations in range and deflection.

To analyze the damage functions, the Monte Carlo simulation modeling method is used.

When initializing an analysis, it is necessary to calculate the damage area. In the first case, the damage factor of the fire system and the covered area will have a bivariate normal distribution:

\[ A_i(\text{CC}) = \pi R^2 \]  
\[ A_i(K) = \pi b^2 \]  

The next stage of the analysis covers the calculation of the probability of damage. In the first case, the damage functions will have the type:

\[ PD(\text{CC}) = 1 - e^{-0.5 \frac{r^2}{\sigma^2}} \]  
\[ PD(K) = \frac{b}{\sqrt{b^2 + \sigma^2}} \]  

Using the statistical modeling method, we will analyze a series of mean points of impact away from the center of the target, respectively:

Input data for the analysis: \( A_i = 2500 m^2, \sigma_x = 0 \pm 50 m, \sigma_y = 0 \pm 50 m, b = 28, 2 m, R = 28, 2 m. \)

Analysis of damage functions when damaging target with bivariate shape.

Fig.3 Graphic representation of a Cumulative density function (CDF) of a random value distributed by radial law.

Fig.4 Carleton damage function (up) and Cookie-cutter function.

The "Cookie-Cutter" model characterizes the damage effect of fire support systems that have a constant radius of damage or impact area equal to \( \pi R^2 \). If the error in the fire data preparation is a mean circular error and the point of measurement is the center of the target, the distribution function is determined by the formula:

\[ f(x, y) = e^{-\frac{1}{2} \left( \frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} \right)} \]  
\[ PD = 1 - e^{-\frac{r^2}{2 \sigma^2}} \]  

It is evident that this model can be used effectively in fire systems having random errors equivalent to one another or equal in value. This assumption does not allow the use of the model in any case and makes it specific rather than universal. Practice shows that the error value in range in the majority of cases has a higher numerical value than the errors in deflection. This is the result of the fact that the sum of random errors is characterized by an asymmetric bivariate normal distribution law rather than a bivariate normal distribution law (circular) (symmetrical). Numerous integration, approximate formulas and other assumptions are used to solve this problem.

\[ (9) \ PD = 1 - 0.5 \frac{r^2}{\sigma^2} \]  
\[ (10) \text{CEP} = 1.1774 \sigma \]  
where \( R \) radial variance of the random value, \( \text{CEP} \) circular error probable, \( \sigma \) standard deviations in range and deflection.

The other model that is primarily used to determine the effectiveness of fire systems for various purposes is the Carleton damage function or the diffuse Gaussian damage function.

\[ D(r) = e^{-\frac{r^2}{2 \sigma^2}} \]  
where \( b \) a damage factor dependent on fire system, \( r \) radial variance of the random value.

This model for determining the efficiency of the damage can be used in any case because it defines the covered area individually for each fire system. This makes the model more realistic about effectiveness evaluation.

In case the distribution law is asymmetric, the mathematical apparatus for calculating the probability of damage is as follows:

\[ PD = \frac{b_x b_y}{\sqrt{(b_x^2 + \sigma_x^2)(b_y^2 + \sigma_y^2)}} \]  
where \( b_x, b_y \) damage factors dependent on fire system in range and deflection, \( \sigma_x, \sigma_y \) standard deviations in range and deflection.

To analyze the damage functions, the Monte Carlo simulation modeling method is used.

When initializing an analysis, it is necessary to calculate the damage area. In the first case, the damage factor of the fire system and the covered area will have a bivariate normal distribution:

\[ A_i(\text{CC}) = \pi R^2 \]  
\[ A_i(K) = \pi b^2 \]  

The next stage of the analysis covers the calculation of the probability of damage. In the first case, the damage functions will have the type:

\[ PD(\text{CC}) = 1 - e^{-0.5 \frac{r^2}{\sigma^2}} \]  
\[ PD(K) = \frac{b}{\sqrt{b^2 + \sigma^2}} \]  

Using the statistical modeling method, we will analyze a series of mean points of impact away from the center of the target, respectively:

Input data for the analysis: \( A_i = 2500 m^2, \sigma_x = 0 \pm 50 m, \sigma_y = 0 \pm 50 m, b = 28, 2 m, R = 28, 2 m. \)

Analysis of damage functions when damaging target with bivariate shape.

Fig.5 Analysis of damage functions when damaging target with bivariate shape.
Target with a bivariate shape, the Cookie-cutter model with little ballistic dispersion values provides a higher probability of damage, which is explained by the pattern distribution function. The Carleton damage function, with increase of standard deviation of ballistic dispersion, the probability of damage is gradually reduced.

In the second case, the damage factor of the fire system and the covered zone will have a rectangular shape and is determined by the formula:

\[
A_{\text{L}}(CC) = \pi R^2 \cdot R = \sqrt{x^2 + y^2} \quad [2,3,4]
\]

\[
A_{\text{L}}(K) = 2 \pi b_x b_y \quad [2,3,5]
\]

where \( R \) radial variance of the random value, \( b_x, b_y \) damage factors dependent on fire system in range and deflection.

The second step to determine the effectiveness of fire support of artillery is to determine the probability of damage on target. In the second case considered, the damage functions will have the type:

\[
PD_{\text{CC}} = 1 - e^{-0.5\pi^2 \sigma^2} \quad [2,3,4]
\]

\[
PD_{\text{K}} = \frac{b_x b_y}{\sqrt{(b_x^2 + \sigma_x^2)(b_y^2 + \sigma_y^2)}} e^{-\frac{1}{2} \left[ \frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} \right]} \quad [2,3,5]
\]

where \( R \) radial variance of the random value, \( b_x, b_y \) damage factors dependent on fire system in range and deflection, \( \mu_x, \mu_y \) mathematical expectations if random errors in range and deflection, \( \sigma_x, \sigma_y \) standard deviations in range and deflection.

Using the statistical modeling method, we can determine the mean point of impact and its deviation from the target center.

To illustrate the second case and perform the analysis, we use the following input data: \( A_1 = 2500 \text{m}^2 \), \( \sigma_x = 0 \div 50 \text{m} \), \( \sigma_y = 0 \div 50 \text{m} \), \( b = 28 \text{m} \), \( b = 28 \text{m} \), \( R = 28 \text{m} \).

\[ \text{Fig.6} \] Analysis of damage of damage functions when damaging target with rectangular shape.

When target have rectangular shape, the "Cookie-cutter" model shows a higher probability of damage than Carleton damage function. In both models the probability of damage decreases exponentially with an increase in ballistic dispersion.

3. Conclusion.

The results of this study allow us to draw the following conclusions:

1. The Cookie-cutter model shows a higher probability of damage than the Carleton damage function due to differences in the determination of the covered area.

2. The Cookie Cutter model does not account for changes in the angle of impact, so the shape of the covered area will always be round, which for most systems and impact angles does not fit the truth.

3. A more useful model of use is the Carleton damage function, because a small part of the fire system has a circle-impact area. In most cases, the covered area is determined by the impact angle and takes the shape of a rectangle, square or circle.

4. The Carleton damage function model gives a realistic view of the fire covered zone, taking into account the angle of impact. The numerical meanings of the target area in range and deflection allow the determination of the fire system's effectiveness.

Литература:


STEGANALYSIS OF IMAGES BY USING A MULTI-CLASSIFIER

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Abstract: Traditional image steganalysis techniques for classification of steganographic algorithms are conducted with respect to the entire image. In this work, we aim to design a multi-classifier which classifies stego images depending on their steganographic algorithms in addition to distinguishing stego images from cover images. This classification is based on steganalysis results of decomposed image blocks. As a natural image often consists of heterogeneous regions, its decomposition will lead to smaller image blocks, each of which is more homogeneous.

Keywords: STEGANOGRAPHY, MULTI-CLASSIFIER, STEGO IMAGES, COVER IMAGES.

1. Введение

Стеганализа е наука обратна на стеганографията и той се опитва да диференцира стегоизображенията от прикриващото изображение без знанието на използваните стеганографически алгоритми за вграждане [1]. Извъннайки характеристиките, извлечени от прикриващото и стегоизображенията при еднократни опити, класификаторът научава характеристикиите на прикриващото и стегоизображенията в многомерното пространство. Повечето от разработките в тази област се фокусират върху извличането на характеристики от изображения за целите на стеганализа с бинарен класификатор, който диференцира стегоизображенията от прикриващия такива [2], [3], [4].

В този доклад се представя мулти-класификатор, използвайки блоково базиран стеганализ на изображения [5]. Предложените подход за много класификатор започва с разделянето на изображенията на прикриващо и стегоизображения от различните стеганографски алгоритми, в комплект за обучение на по-малки хомогенни блокове. След това се третира всеки блок като основна единица на изображението и се извличат характеристиките на Марков и DCT [4] от блоковете на изображението за блоково базиран стеганализ. Във основа на характеристиките на блоковете, избрани чрез случайна извадка, техниката приема за класифициране блокове от множество класове. За всеки клас, специфичен класификатор може да бъде обучен като се използват блокови характеристики, които представляват характеристиките на този тип блок.

2. Прослед на изследванятия.

2.1. Анализ на елементите стеганализ

2.1.1. Двоичен класификатор

Предишните изследвания в тази област са фокусирани върху извличането на характеристики от изображения за целите стеганализа [2], [3], [4]. Коефициентите в DCT областта са извлечени за извличане на характеристики DCT-базираните характеристики са предложени в [2] за стеганализ, като се използва факта, че междублочната зависимост между съседни блокове често е засегната от стеганографски алгоритми.

2.1.2. Мулти-классификатори

При използване на няколко класификатора, слепия стеганализ първо се опитва да реши дали дадено тестово изображение е прикриващо или е стегоизображение. Освен това, ако определеното тестово изображение е определено като стегоизображение, този класификатор трябва да реши кой стеганографски алгоритъм е бил използван за вграждане на тайното съобщение.

2.2. Изпълнение на слепа стеганализ

2.2.1. Двоичен класификатор

Основната цел на слепия стеганализ е да реши дали данните, изпратени от потребител Алис на потребител Боб, съдържат тайно съобщение или не. С други думи, да се направи точно решение дали непознатото тестово изображение е прикриващо или стегоизображение. Преди да се извърши процедурата за изчисляване на вероятността за грешка, се въвеждат два вида грешки, направени в процеса на вземане на решение от статистиката: фалшиви положителни резултати и фалшиви негативни. След като стеганализ се опитва да минимизира тези две грешки, за да получи по-висока точност на откриване. Фалшиви положителни сигнали (фалшиви аларми) се случват, когато се открие тайно съобщение от дадено прикриващо изображение. Обратно, фалшиви негативни (пропускания) се появяват, когато тайното съобщение не се открива от дадено стегоизображение.

Таблица 1. Матрица на откриване на двоичен класификатор

| Решение | Реално | | | |
|---------|--------|--------|--------|
| Прикриващо изображение | Истински отрицателни сигнали | Фалшиви положителни сигнали |
| Стего изображение | Истински положителни сигнали |

2.2.2. Мулти-классификатор

Когато L различните стеганографски алгоритми се използват за създаване на стегоизображения вместо един стеганографски алгоритъм, трябва да се реши кой стеганографски алгоритъм е бил използван за вграждане на тайното съобщение.

2.2.1. Двоичен класификатор

Основната цел на слепия стеганализ е да реши дали данните, изпратени от потребител Алис на потребител Боб, съдържат тайно съобщение или не. С други думи, да се направи точно решение дали непознатото тестово изображение е прикриващо или стегоизображение. Преди да се обясни процедурата за изчисляване на вероятността за грешка, се въвеждат два вида грешки, направен в процеса на вземане на решение от статистиката: фалшиви положителни резултати и фалшиви негативни. След като стеганализ се опитва да минимизира тези две грешки, за да получи по-висока точност на откриване. Фалшиви положителни сигнали (фалшиви аларми) се случват, когато се открие тайно съобщение дадено прикриващо изображение. Обратно, фалшиви негативни (пропускания) се появяват, когато тайното съобщение не се открива от дадено стегоизображение.
3. Блоково базирани стегналнозащитни изображения

3.1. Общ преглед на системата

Блок-схемата на блок-базирана система за стегнална защита на изображения за класификация на множество стеганографски алгоритми е показана на фигура 1. Състоят се от процес на обучение и процес на тестване.

3.2. Процес на обучение

3.2.1. Блоково разлагане, извличане на функции и случайно вземане на проби

За всеки от L-стеганографските алгоритми, се вгражда тайното съобщение в прикриващо изображение, за да се получи съответното стегнаизображение. Този процес се прилага за всички изображения, за да се получат набори от изображения, състоящи се от прикриване изображение и съответните стегнаизображения. След това се разлагат всички изображения с размер MxN в комплекта за обучение на по-малки хомогенни блокове с размер BxB (като B=80; b = 2, 3, ..., min (M, N)/8), Обединените DCT и Markov характеристики [4] се извличат от всеки блок от изображения в набора от изображения. Ако броят на декомпозираните блокове изображения е твърде голям, може да се използва метод на случайна извадка, за да се избере подмножество от блокове на изображението, за да се намалят сложността на класификатора.

Например, за изображение с размер MxN, ако има около A=MxN=B2 блокове с размер BxB. Ако A е твърде голям, може да се избере подмножество от размер K на случайен принцип. Този процес е обозначен като "случайна извадка". За да се получат равен брой пробни блокове от L1 типове изображения, K=L1 пробни блокове се избират произволно от прикривашите изображения, заедно с K=L1 примерни блокове, които съответстват на същото място на стегнаизображенията, създадени от L различни стеганографски алгоритми. Най-общо казано, случайната извадка е по-добро от извадката в пространствен ред, тъй като позволява да се събират блокове с по-голямо разнообразие, тъй като могат да се използват по-представителни пробни блокове в процеса на класификация на блоковете.

3.2.2. Класифициране на изследвания блок

Базирайки се на обединените характеристики от блоковете BxB, може да се направи обичайната класификация на K блокове в С различни класове, след всеки клас се състоят от хомогени блокове. Блок класификацията е разгледана в различни контексти за обработката на изображения. Техниката на Tree-Structured Vector Quantization (TSVQ) се използва за класифициране на блоковете на изображението, използвайки двоична лървовидна структура на базата на блоково подобие. Като се вземат тази идея и се приложи към дадено приложение се получава основна разлика, че блоковото сходство се измерва от Euclidean разстоянието между пикселните различия на два блока на изображението в контекста на векторното квантуване.

3.3. Критерий за оценка

3.3.1. Класификация на блоковете и избор на класификатор

За дадено тестово изображение може да се извърши точно същото разграждане и извличането на характеристиките, като е описано в процеса на обучение. Всеки блок от тестовото изображение се класифицира в клас, като се използва минимална стойност на изкривяване. В зависимост от класа на всеки блок, се прилага класификаторът получен от процеса на обучение. Може да се нарече класификатори зависещи от съдържанието, тъй като те се подбират адаптивно според класовия блок. Зависимите от съдържанието класификатори са полезни, тъй като промяната на стойностите на характеристиките след стеганографско вграждане има по-висока корелация с блокове от същия клас от тези на различни класове.

3.3.2. Изчисляване на теглата

Преди да приложите правилото за гласуване с мнозинство, два вида тежести може да направи блокови решения по-точни: 1) тегла, които зависят от различни блокови класове, и 2) тегла, които зависят от различни типове изображения. Тези два вида тежести за блокове се използват, за да се получи теглото за всяко решение за блок.

4. Експериментални резултати

4.1. Експериментална настройка

В експеримента, се разглежда обучение и тестване на изображения с размер MxN=384x512 и се разлага всяко изображение на 48 блока с размер BxB = 64x64. След извличане на 274 обединени характеристики от всеки блок, K=20 000 блоковете за проби са избрани от прикривашите изображенията и съответните стегнаизображения с L=3 различни стеганографски алгоритми в набора за обучение чрез случайна извадка. Тези пробни блокове са класифицирани в C=8 класове. За дизайна на класификатора са получени 8 различни линейни класификатора на Байес за 8 клааса с параметър на регулиране R = S = 0.001.

4.1.1. База данни с изображения

Некомpresiónирания база данни за цветни изображения (UCID) [6] е използвана като прикривашщи изображения в комплект за обучение. В тестовия комплект е използван комплект данни на INRIA Holidays [7] за прикриване изображение. Базата данни за изображения на UCID се състои от 1338 изображения, а обогатената базата данни за изображения има 1491 изображения, които имат различни обекти, като естествени сцени и изкуствени обекти. Въпреки че оригиналните изображения са цветни изображения с различни размери, всичка изображения са пременени في 384x512 изображения в сиво и са запазени като JPEG файлове с фактор за качество 85 JPEG компресия.

4.1.2. Стеганографско вграждане

След избиране на прикриващи изображенията от базите данни за изображения, L=3 различни стеганографски
Тъй като различните изображения могат да имат различен капацитет на вграждане, степента на вграждане за всяко изображение се измерва в единици BPC (битове за ненулеви DCT AC коефициенти). За експериментите са тествани две различни скорости на вграждане (а именно 0.2, 0.3 BPC) за OutGuess (OG), F5 и MBS.

Таблица 2. Матрица на откриване на метода на Речу и разглежданата метод в случай на BPC = 0.2.

<table>
<thead>
<tr>
<th>Действия</th>
<th>Реално</th>
<th>Прикривано изображение</th>
<th>OG</th>
<th>F5</th>
<th>MBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Прикриващо изображение на метода на Речу и разглеждане методи в случай на BPC = 0.2.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Методът на Речу, (\lambda_{\text{огр}} = 63.63%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Прикриващо изображение</td>
<td>72.30</td>
<td>16.16</td>
<td>10.12</td>
<td>28.71</td>
<td></td>
</tr>
<tr>
<td>OG</td>
<td>2.41</td>
<td>57.14</td>
<td>2.55</td>
<td>5.77</td>
<td></td>
</tr>
<tr>
<td>F5</td>
<td>5.70</td>
<td>3.76</td>
<td>67.61</td>
<td>8.05</td>
<td></td>
</tr>
<tr>
<td>MBS</td>
<td>19.58</td>
<td>22.94</td>
<td>19.72</td>
<td>57.48</td>
<td></td>
</tr>
<tr>
<td>Предложен метод, (\lambda_{\text{огр}} = 70.93%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Прикриващо изображение</td>
<td>63.25</td>
<td>0.27</td>
<td>21.93</td>
<td>4.63</td>
<td></td>
</tr>
<tr>
<td>OG</td>
<td>2.35</td>
<td>83.03</td>
<td>3.49</td>
<td>8.05</td>
<td></td>
</tr>
<tr>
<td>F5</td>
<td>20.39</td>
<td>2.01</td>
<td>58.82</td>
<td>8.72</td>
<td></td>
</tr>
<tr>
<td>MBS</td>
<td>14.02</td>
<td>14.69</td>
<td>15.76</td>
<td>78.60</td>
<td></td>
</tr>
</tbody>
</table>

Точността на откриване на всички стеганозображения се подобрява с 18 - 18% в разглежданата метод. Подобно на случая с BPC = 0.2, точността на откриване се подобрява най-много с 18 - 20%, когато тестовите изображения са с вградени данни за изграждане на Out-Guess. Общата точност на детекция се подобрява от 76,79% на 78,62% в разглежданата метод, което е с 9,4% подобрение (вж. табл.2 и табл.3). Както е показано в експерименталните резултати, предложен блоков метод има значително подобрение спрямо метода на Речу за двата случая на BPC. Това е възможно, защото блоковото-базирано подобряване е по-голяма от 86.23% на 86.38%.

5. Заключение.

В този доклад е предложен блоков базиран стеганализ на изображения чрез използване на мулт-классификатор като са приети различни класификатори на бaza на техните характеристики. Експерименталните резултати показват, че предложен метод предлага значително подобрение в точността на откриване в сравнение с предишните опити, използвайки подход базиран на изображения.

Използвана литература:
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INCREASE IN STRENGTH PROPERTIES OF LOW-CARBON STEELS DUE TO STRUCTURAL TRANSFORMATIONS AT DEFORMATION BY ROTARY SWAGING

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Abstract: Mechanical properties of low-carbon St.20 and 07G2MFB steels after rotary swaging (RS) were studied. It was established that an increase in strain ratio and decrease in temperature increase strength but decrease plasticity. The ultimate tensile strength of 867-927 MPa was obtained in both steels after deformation at temperature of 400 °C with a true strain ratio of 2.3 at good ductility of 15-17%.

Keywords: LOW-CARBON STEEL, ROTARY SWAGING, ULTRAFINE-GRAINED (UFG) STRUCTURE, THERMAL STABILITY OF STRENGTHENING, MECHANICAL PROPERTIES

1. Introduction

It is well known that methods of severe plastic deformation (SPD) such as high-pressure torsion and equal-channel angular pressing lead to significantly refinement of structure and improve the strength and service properties of low-carbon steels [1,2]. But at the present time, SPD methods are difficult to embed into the industrial production. Therefore, it is important to obtain low-carbon alloys with ultrafine grained (UFG) structure by industrial deformation methods, such as rotary swaging [3].

The purpose of this research is to establish a possibility of producing ultrafine-grained (nano- and submicrocrystalline) structures of low-carbon steels by rotary swaging and to study of its mechanical behavior.

2. Materials and experiment

The deformation of St.20 (0.19%C, 0.49%Si, 0.21%Mn, 0.03%Ni, 0.25%Cr, 0.19%Cu, 0.05%As, and Fe as a balance in wt.%) and 07G2MFB (0.073%C, 0.252%Si, 1.58%Mn, 0.242%Ni, 0.007%P, 0.005%S, 0.151%Cr, 0.22%Cu, 0.037%Al, 0.018%V, 0.195%Mn, 0.015%Ti, 0.02%W, 0.08%Nb, 0.0029%N, and Fe as a balance in wt.%) low carbon steels was carried out by rotary swaging (Fig.1). St.20 was subjected to quenching in water from a temperature of 880°C (1 hour) and high-temperature tempering at 680°C (1 hour). The 07G2MFB steel was subjected to quenching in water from a temperature of 920°C (1 hour) and high-temperature tempering at 600°C (1 hour).

The initial structure of both steels was similar. It was a polyhedral (globular) ferrite with pearlitic colonies, and also oriented products of quenching (Fig. 2). Transmission electron microscopy (TEM) revealed that the quenching products are acicular ferrite and tempered martensite.

Fig. 1 Schematic of the rotary swaging (μ = Ax/Af, where Ax and Af are the initial and the final cross-sectional area of the billets, respectively)

Fig. 2 The structure of 07G2MFB steel after quenching and high-temperature tempering (optical microscopy)

Rotary swaging of 07G2MFB steel was carried out in two modes with a decrease in the deformation temperature: 650°C (true strain ratio – 0.6) – 575°C (total true strain ratio – 1.2) – 500°C (total true strain ratio –2.3) and 600°C – 500°C – 400°C with the same strain ratio. Rotary swaging of St.20 was carried out according to the second mode. The limited facilities of equipment and size of specimens did not allow an increase in the strain ratio during RS.

The microstructure was investigated using an Olympus PME 3 optical microscope and a JEM-1400 transmission electron microscope operated at 120 keV. Static tensile tests were performed using an INSTRON 3380 tensile testing machine with a load capacity of 100 kN. Measurements of microhardness were taken by means 402 MVD Wolpert Wilson with loading 1N.

3. Results and discussion

The structure of 07G2MFB steel after rotary swaging (RS) was studied in two modes with a decrease in the temperature of deformation: 650 °C - 575 °C - 500 °C and 600 °C - 500 °C - 400 °C. The structure after RS at 650 °C with a true strain ratio of 0.6 does not practically differ from the structure of this steel after quenching and tempering (Fig.2, 3a). Decreasing the temperature of RS to 575 °C and increasing the strain ratio to 1.2 led to the orientation of the initial grain structure (Fig. 3b). The final stage of
the RS at 500 °C with a total true strain ratio of 2.3 led to the formation of considerably oriented initial structure judging by the metallographic analysis (Fig. 3c). The TEM analysis revealed the formation of a submicrocrystalline structure with an average grain size of 343 nm inside this highly oriented initial structure. The metallographic analysis of 07G2MFB steel after RS by the mode of 600 °C - 500 °C - 400 °C with a total true strain of 2.3 revealed an even more oriented structure due to a decrease in the strain temperature (Fig. 4).

![Image](image1.png)

**Fig. 3. The structure of 07G2MFB steel after rotary swaging with a decrease in temperature of deformation: 650 °C (true strain ratio - 0.6) (a) - 575 °C (1.2) (b) - 500 °C (2.3) (c) (optical microscopy)**

It can even metallographically observed the substructure inside highly elongated initial grains (Fig.4b). In this case, the TEM analysis revealed a submicrocrystalline structure with a smaller average grain size of 312 nm (Fig. 5).

![Image](image2.png)

**Fig. 4 The structure of 07G2MFB steel after rotary swaging with a decrease in temperature of deformation: 660 °C (true strain ratio - 0.6) - 500 °C (1.2) - 400 °C (2.3) (optical microscopy).**

The metallographic analysis of St.20 after RS by the 600 °C - 500 °C - 400 °C mode (true strain ratio - 2.3) also revealed a highly oriented initial structure (Fig.6a). The TEM analysis revealed a submicrocrystalline structure with an average grain size of 285 nm (Fig.6b).

![Image](image3.png)

**Fig. 5 The structure of 07G2MFB steel after rotary swaging with a decrease in the temperature of deformation: 600 °C - 500 °C - 400 °C (true strain ratio - 2.3); (a) bright-field; (b) dark-field image obtained in [110]Fr.**

Thus, the selected modes of rotary swaging of St.20 and 07G2MFB steels made it possible to obtain a predominantly submicrocrystalline structure with grain sizes ranging from 285 to 375 nm in these steels.

![Image](image4.png)

**Fig. 6 The structure of St.20 after rotary swaging with a decrease in deformation temperature: 600 °C - 500 °C - 400 °C (true degree of deformation - 2.3): (a) - optical microscopy; (b) - TEM.**

The thermal stability of strengthening of St.20 and 07G2MFB steels after RS was studied according to the microhardness vs annealing temperature. The values of microhardness increase with decreasing temperature of RS and increasing strain ratio (Fig.7 and 8). After RS, the microhardness of 07G2MFB steel as compared with St.20 steel is higher (Fig.8).

![Image](image5.png)

**Fig. 7 The thermal stability of strengthening of 07G2MFB steel after quenching and tempering and RS by mode of 650 °C - 575 °C - 500 °C.**

The thermal stability for these steels of both treatments is about the same, but lower than that after quenching and tempering, despite a significantly higher level of strengthening.

For example, the thermal stability of the strengthening of 07G2MFB steel after the final stage of the RS at 400 °C is 400-450 °C, and after quenching and tempering it is 700 °C, but the microhardness level is 2.9 and 2.2 GPa, respectively (Fig.8a).

The mechanical properties of low-carbon St.20 and 07G2MFB steels after rotary swaging were studied. With a decrease in temperature and an increase in the strain ratio, the strength properties increased, and plasticity declined only slightly, which is observed both on 07G2MFB steel (Fig. 9 a, b, Table 1), and on St.20 (Fig. 9c, Table 1).

**Acknowledgements**

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Comparing the ultimate tensile strength both of steels, deformed by the second mode of 600 °C – 500 °C – 400 °C, it can be seen that swaging at 600 °C with a true strain ratio of 0.6 leads to a slightly greater tensile strength in 07G2MFB steel, and swaging at 400 °C with a true strain ratio of 2.3 leads to a higher tensile strength in St.20 (Fig. 9b, c, Table 1). But it should be noted in this case rather close values of the ultimate tensile strength. Therefore, it can be argued that the ultimate tensile strength of 867-927 MPa was obtained for both steels at the final stage of the RS at 400 °C and with a true strain ratio of 2.3 at good ductility of EL = 16-17%.

**Table 1: Mechanical properties of low-carbon 07G2MFB and St.20 (c) steels**

<table>
<thead>
<tr>
<th>Treatment /T_{ao}/°C</th>
<th>Ultimate Tensile Strength σTS, MPa</th>
<th>Yield Stress σYS, MPa</th>
<th>EL, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>07G2MFB</td>
<td>Quenching at 920°C (1h) → high-temperature tempering at 680°C (1h)</td>
<td>594</td>
<td>481</td>
</tr>
<tr>
<td>RS / T=600°C</td>
<td>654</td>
<td>604</td>
<td>28</td>
</tr>
<tr>
<td>RS / T=600°C→500 °C</td>
<td>690</td>
<td>654</td>
<td>22</td>
</tr>
</tbody>
</table>

1. Rotary swaging of 07G2MFB steel was carried out by two modes with a decrease in the deformation temperature: 650 ° C (true strain ratio - 0.6) - 575 ° C (1.2) - 500 ° C (2.3) and 600 ° C - 500 ° C – 400 ° C with the same strain ratio. Rotary swaging of St.20 was carried out according to the second mode.

2. Rotary swaging of low-carbon St.20 and 07G2MFB steels at the final stage of the RS at 400 °C with a true strain ratio of 2.3 leads to the formation of an ultrafine-grained (UFG) structure with a size of structural elements 285-312 nm.

3. The ultimate tensile strength in the range from 867 to 927 MPa with a true strain ratio of 2.3 and with good ductility EL = 16-17% was obtained in both steels at the final stage of the RS at 400 °C.

**4. Conclusions**

**5. References**


FEATURES OF STRUCTURE FORMATION AND MECHANICAL BEHAVIOR OF METALLIC MATERIALS UNDER CONDITIONS OF APPLICATION OF GRADIENT DEFORMATIONS

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Abstract. The study of technological methods of plastic structure formation is an urgent task. Taking into account that structure formation depends on many factors and, first of all, on the deformed state, studies of the deformed state and structural studies involving TEM were carried out in the work. It is known that reliable data of the structural state allows predicting the mechanical and operational properties of the obtained semi-finished products and products. In this regard, the analysis of the effect of the processing route (C, Bc) on the structural changes after high-cycle active bending was carried out. A numerical simulation of the active bending process was also carried out, and the accumulated strain values were determined for 8 processing cycles. Established patterns of structure formation, depending on the level of accumulated deformation and processing route.

KEYWORDS: PLASTIC STRUCTURE FORMATION, ACTIVE BENDING, MODELING.

1. Introduction

In the context of expanding industrial production, the need for new materials and for improving the physico-mechanical properties of known materials increases. Researches in this direction are conducted by many scientific centers all over the world. Great efforts are aimed at studying the features of the structural states of materials and their connection with the stress-strain state and other factors [1,2]. In this regard, there is an increasing need for the creation of promising industrial methods that allow to achieve improved properties of materials [3-5].

One of them is the method of active bending, which makes it possible to act on the initial structure under conditions of a continuous gradient under conditions of a strain gradient. In this regard, the aim of the work was to study the effect of the deformed state with two copper processing routes on the type of structure being formed.

2. Concept of process

A schematic diagram of the active bending used in research is presented in Figure 1. The proposed development is based on the well-known ECAP. "Conform" scheme, while in the deformation process, the workpiece 3 is pushed into the stationary bending matrix consisting of two elements of the matrix 1 and 2.

The method allows to combine the high-performance process "Conform" with bending deformation, which leads to a significant intensification of the hardening process of the deformable material due to the formation of a gradient structure. Active friction forces ensure process continuity. For the simulation, the Deform 3D program was used to analyze the three-dimensional (3D) behavior of the metal during pressure treatment. This made it possible to obtain important information about the nature of the material flow in the forming tool, as well as about the stress-strain state and the temperature distribution during the deformation process.

When modeling the bend according to the "Conform" scheme at an angle of 90°, a square section sample with a size of 10x10 mm and a length of more than 150 mm was used for the first deformation cycle, a bend radius of 10 mm. For the subsequent cycles, a sample obtained by modeling on the previous cycle was used in order to obtain generalized data after passing through four sample processing cycles.

3. Results and discussion

Description of the structure of copper (M1) after bending on a horizontal installation ECAP-Conform

After 8 passes of active bending along the Bc route, a fragmented, close to equiaxed microstructure with misoriented fragments with sizes of ~ 0.3-0.5 μm was formed in the alloy. In the body and the boundaries of a significant part of the fragments, dislocation clusters with a scalar dislocation density \( \rho_d \) are observed, reaching values \( \rho_d \) in individual fragments of ~ 10^11 cm^-2.

With a further increase in the number of passes (degree of deformation), the dislocation density practically does not increase, i.e., it reaches saturation after 8 passes.

The estimate of the dislocation density, determined from the results of X-ray structural analysis, corresponds to the maximum value of \( \rho_d \) obtained by electron microscopic studies of thin foils.

Analysis of microdiffraction patterns obtained on thin foils from deformed flexible materials, as well as EBSD analysis, indicates a significant disorientation of the fragments after four passes. In general, these studies showed that in the process of bending along the V-route, medium- (5-15 \(^\circ\)) and high-angle (~15 \(^\circ\)) boundaries of deformation type are formed in copper.

At the same time, eight passes, which are flexible along route C, lead to the formation of a microstructure with lengths stretching in the direction of ~ 35-45 \(^\circ\) to the rod axis with sizes of ~1-3 μm in length and 0.2-0.6 μm in thickness. In many elongated fragments and boundaries between them there are clusters of dislocations with a scalar density \( \rho_d \) exceeding 10^13 cm^-2. EBSD analysis showed the presence of a whole ensemble of fragment boundaries with different misorientations, among which medium- and high-angle deformation boundaries predominate.

The definition of microhardness in cross section of samples after bending is shown in Fig. 2 and 4. The magnitude of microhardness in the cross section varies in accordance with the character of the formed gradient structure, the features of which are higher HV values in the central rod area and a decrease in the HV value in near-surface areas for both bending paths (Fig. 2 and 4).
Obviously, such a dependence of the microhardness variation is due to the heating of the rods in the process of bending and the possible redistribution of dislocations and a decrease in their density in the near-surface region of the rods.

Figure 2. 8 passes are flexible: a - route Bc; b - route C; c, d – the dependence of the microhardness HV on the distance along the diameter of the rod, respectively, for routes Bc and C

4. Conclusion

1. Using numerical simulation, it is established that active bending provides, after 8 processing cycles, the level of accumulated deformation $e = 4.2$ in the middle region and $e = 5.0$ in the near-surface cross-sectional area of the workpiece.

2. It has been established that when using the method of active bending along the Bc route, a grain-subgrain equiaxial structure with an average grain size of $\sim 0.3-0.5$ µm is formed in a deformed copper sample; a cross section of $\sim 0.2-0.6$ µm and a length of $\sim 1-3$ µm. UMP range.

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5. References


TRIBOLOGICAL PROPERTIES OF COMMERCIALLY PURE COPPER AND A LOW-ALLOYED CHROMIUM BRONZE

ТРИБОЛОГИЧЕСКИЕ СВОЙСТВА ТЕХНИЧЕСКИ ЧИСТОЙ МЕДИ И НИЗКОЛЕГИРОВАННОЙ ХРОМОВОЙ БРОНЗЫ

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Abstract. In this paper, we present the results of the tribological studies of commercially pure copper (99.9% Cu) and a low-alloyed chromium bronze (Ca-0.5%Cr), contacting a graphite-containing material. The samples under study were produced with two types of microstructures: a coarse-grained (CG) one, having an average grain size of 100-130 µm after annealing, and a submicrocrystalline (SMC) one, having an average grain size of 0.30-0.50 µm after multi-cycle severe plastic deformation (SPD) processing via equal-channel angular pressing (ECAP) combined with Conform. It is shown that for the samples produced by ECAP-Conform, having an SMC structure, the friction coefficients are 12 - 20% lower than for the as-annealed samples, having a CG structure.

KEY WORDS: TRIBOLOGICAL PROPERTIES, FRICTION COEFFICIENT; SHEAR STRENGTH OF ADHESIVE BONDS, COMMERCIALLY PURE COPPER AND A LOW-ALLOYED CHROMIUM BRONZE, SEVERE PLASTIC DEFORMATION.

Introduction

In the last 40 decades of the 20th century, the high-speed passenger transportation systems were under intensive development. Such systems allow for motion speeds of up to 300 – 400 km/h, while the average speeds are only up to 160 – 200 km/h. In order to ensure the operation of high-speed railway lines, structural materials, and in particular, the materials for contact wires, must meet a whole range of special requirements which are difficult to provide when using conventional technologies.

In the case of regular electrified railway lines, the stress of a contact wire does not exceed 100 MPa, and in the case of high-speed railway lines, the tension stress of a contact wire is 250 MPa (2.5 times higher than in the case of regular railway lines). The highest allowable temperature of long-term heating is 150°C [1]. In this connection, a problem arises, related to the tribological parameters of the contact between copper wires and graphite-containing current collectors.

It is known that materials with a higher hardness ensure lower wear and friction coefficient [2]. In most cases, there are various ways to increase the hardness of alloys by means of heat treatment [3, 4]. However, a heat treatment aimed at hardness enhancement does not always enable achieving the desired effect. For this reason, the use of copper alloys in friction units is very limited. For such materials, various types of thermochemical [5 - 7] and surface plastic treatment [6 - 8] are used, which enable increasing the surface strength of the materials under treatment. The drawback of these methods is the relatively small depth of the strengthened surface layer, therefore they can be used only as a finishing treatment or for relatively simple and low-loaded parts of tribocouplings.

There are works evaluating the effect of the structural and phase compositions of metallic materials on their tribological properties [6, 7, 9 - 11]. In these works, tribological studies were performed on materials subjected to various types of heat treatment, resulting in microstructural changes.

To date, a technology has been developed, providing an efficient and manifold increase in strength, while preserving a high technological plasticity. This technology is based on severe plastic deformation (SPD) processing and enables producing high-strength bulk billets from metallic materials [12]. Among the SPD processing techniques is equal-channel angular pressing (ECAP) [13], used, in particular, for the fabrication of long-length billets and effected in several deformation cycles. The essence of this method for the strength enhancement of a material lies in the maximum refinement of grain structure down to submicrocrystalline (SMC) and nanocrystalline (NC) sizes [14]. Therefore, comprehensive tribological studies of copper in different structural states (as-annealed and SPD-processed) are of scientific and practical interest.

Methods for the evaluation of the integral value of the friction coefficient and its molecular component

In the tribological studies, we used two test configurations shown in Fig. 1.

![Fig. 1. Tribological test configurations: a) 1 – the lower sample (graphite-containing plate); 2 – the upper sample (under testing); 3 – holder; b) 1 – samples under testing; 2 – spherical indenter; 3 – cable; 4 – disc with a groove; 5 – current-carrying bases; 6 – electrically-insulating pads.](image)

The first test configuration under reciprocating motion (fig. 1, a) was used to evaluate the friction coefficient in the pairs «Cu» commercially pure Cu – EK-40 graphite-containing plate and «Cu-0.5%Cr» chromium bronze – EK-40 graphite-containing plate. The testing conditions were as follows: the normal load P was 80 N, the relative sliding velocity was 0.1 m/s, the time of each test was 60 min. The normal load was selected based on the maximum force of pressing of a contact wire to a graphite-containing current collector in railway transport. The speed regime of the testing was determined by the capabilities of the employed tribometer. Time was set on the basis of the previous experience of such tests. The testing was performed at room temperature.

The second test configuration (Fig. 1, b) was used to evaluate the shear strength of adhesive bonds and the adhesive component of the friction coefficient. Since the graphite-containing plate is a brittle material and an indenter made thereof cannot withstand normal loads while the strength of adhesive bonds is determined, it was proposed to coat an indenter from the Fe-18%W-4%Cr-0.8%C tool steel with a graphitic compound (graphitize) with a subsequent
drying at a temperature of 100-120°C. Hereinafter we will use the abbreviation «GTS» standing for «graphitized tool steel». Thus, the testing according to the second test configuration was conducted in the contacting pairs «commercially pure copper – Fe-18%W-4%Cr-0.8%GTS» and «Cu-0.5%Cr chromium bronze – Fe-18%W-4%Cr-0.8%GTS». For this purpose, samples were prepared from commercially pure Cu and the chromium bronze in the initial (CG) structural state (after annealing), and in the SMC and NC states after 4 cycles of SPD processing by ECAP-Conform. The samples under testing had the shape of a disc with a diameter of 10 mm and a thickness of 3 mm. The spherical indenter had a sphere radius of 2.5 mm, and the thickness of the graphitic material applied onto the indenter's spherical surfaces was about 50 μm. The testing was performed at temperatures of 20; 150; 250 and 450°C, using a one-ball adhesion tester [15]. There is a physical model underlying this method, which in a first approximation reflects the actual friction conditions in a local contact.

According to this model, a spherical indenter 2, imitating a single asperity of the contact spot between the rubbing solid bodies, compressed by two plane-parallel samples 1 (with a high precision and cleanliness of the contacting surfaces), rotates under a load expended on the indenter rotation and applied to the cable 3, laid in the groove of the disc 4, is primarily related to the shear strength τs of adhesive bonds. In order to use this method at elevated contact temperatures, a special apparatus has been designed that enables producing the electric-contact heating (through the buses 5 isolated from the body by pads 6) of the contact zone.

The initial roughness of the contact surfaces of the tested samples and the indenter in both test configurations was 0.06 – 0.16 μm in the Ra scale. The roughness of the samples was measured using an SE-3500K 2D-3D profilometer-profilograph.

The shear strength of adhesive bonds τn (MPa) was determined from the relation:

$$\tau_n = 0.75 \frac{M}{\pi \left( \frac{d_{1\lambda}}{2} \right)^3},$$

where \(d_{1\lambda}\) are the diameters of the impressions on the tested samples, \(mm\); \(M\) is the moment of indenter rotation, \(N\ mm\).

The adhesive component of the friction coefficient was determined as:

$$f_a = \frac{\tau_n}{P_n},$$

where \(P_n\) is the normal pressure, \(MPa\),

$$P_n = \frac{P}{\pi \left( \frac{d_{1\lambda}}{2} \right)^2},$$

where \(P\) is the force of compression of the samples, \(N\).

Before and after the tribological tests in accordance with the first test configuration (Fig. 1, a), the tested samples from commercially pure Cu were studied to determine the microhardness \(H_k\) using a Micromet-5101 device under a load of 0.98 N with exposure to the load for 15 s.

**Results of finding the friction coefficient and the strength of adhesive bonds under elastic contact conditions**

The results of the tribological tests performed in accordance with the first test configuration (Fig. 1, a) in the friction pairs «commercially pure Cu – EK-40 graphite-containing plate» and «Cu-0.5%Cr chromium bronze – EK-40 graphite-containing plate» are presented in Fig. 2.

As revealed by the presented diagram, the friction coefficient values obtained for the as-annealed samples from both commercially pure Cu (curve 1) and the Cu-0.5%Cr chromium bronze (curve 3), are higher than those for the samples from the same materials processed by ECAP-Conform and having an SMC structure (curves 2 and 4). It should be noted that after the friction coefficient grows, as the distance of friction increases, the samples from the chromium bronze having a SMC microstructure demonstrate a tendency for a slight decrease in the friction coefficient. It should be mentioned that the results obtained for the samples from the low-alloyed chromium bronze Cu-0.5%Cr having a CG structure (curve 3) show a slight decrease in the friction coefficient with increasing distance of friction. This fact can be attributed to a further increase in strength resulting from work hardening and a local structure refinement on the friction surface, followed by a transfer of chromium particles to the graphite-containing material used as a counterbody. The local structure refinement promotes activation of grain boundaries and enhancement of the diffusion interaction between the components of the Cu-0.5%Cr chromium bronze, having a CG structure, and the carbon in the graphite-containing material. This assumption requires further study.

As a result of finding the strength of adhesive bonds, it was established that in the case of commercially pure Cu, as the testing temperature is increased from room temperature to 150°C, the adhesive component of the friction coefficient practically does not change and equals 0.082 for the CG material and 0.061 for the SMC material. As the temperature increases further, from 150°C to 250°C, there is observed a steady growth in the adhesive component of the friction coefficient from 0.082 to 0.09 for the material with a CG structure and from 0.061 to 0.069 for the material with an SMC structure. The observed change is evidently related to the structural and phase transformations, as well as the diffusion processes occurring at grain boundaries in a temperature range of 150 – 250°C. Thus assumption requires further studies. As the temperature is further increased to 450°C, the values of the adhesive components of the friction coefficients practically do not change.

In the case of the samples from the low-alloyed chromium bronze Cu-0.5%Cr, with increasing temperature the adhesive component of the friction coefficient monotonically grows in both structural states, and there is some stabilization of the values in a temperature range of 350 – 450°C.

Fig. 3 presents the curves illustrating the results of the evaluation of the friction coefficient's adhesive component as a function of the temperature of testing performed using a one-ball tribometer according to the test configuration shown in Fig. 1 (b).
From the analysis of the results of finding the shear strength of adhesive bonds in the contact pairs «commercially pure Cu – Fe-18%W-4%Cr-0.8%C GTS» and «chromium bronze Cu-0.5%Cr–Fe-18%W-4%Cr-0.8%C GTS», it was established that the adhesive component of the friction coefficient is higher for the CG samples than for the samples with an SMC structure in the whole range of temperatures under investigation.

Table 1 lists the experimentally found values of the adhesive and deformation components of the friction coefficient at room temperature for commercially pure Cu and the Cu-0.5%Cr chromium bronze in different structural states.

<table>
<thead>
<tr>
<th>Material</th>
<th>Adhesive component of the friction coefficient ( (f_a) )</th>
<th>Deformation component of the friction coefficient ( (f_d) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu(CG)</td>
<td>0.082</td>
<td>0.080</td>
</tr>
<tr>
<td>Cu(SMC)</td>
<td>0.061</td>
<td>0.010</td>
</tr>
<tr>
<td>Cu-0.5%Cr(CG)</td>
<td>0.055</td>
<td>0.028</td>
</tr>
<tr>
<td>Cu-0.5%Cr(SMC)</td>
<td>0.051</td>
<td>0.024</td>
</tr>
</tbody>
</table>

* The deformation component of the friction coefficient was determined as: \( f_d = f_a \cdot f_0 \) [5].

It can be seen from table 1 that in the studied friction pairs in a dynamic contact an essential role is played by the adhesive component both for the materials with a CG structure and for the materials with an SMC structure. However, it was noted that for the commercially pure Cu samples there is a large difference between the deformation components of the friction coefficient, depending on the material’s structure. For the Cu samples with a CG structure the value of \( f_d \) is 8 times higher than the corresponding value for the SMC material. Apparently, this is related to the fact that commercially pure Cu with an SMC structure has a greater tendency for sticking. No such difference has been found in the Cu-0.5%Cr chromium bronze.

The values of the adhesive and deformation components of the friction coefficient for the chromium bronze samples have a small difference in the case of different microstructures. This observation is apparently an indirect evidence of the greater tendency of the commercially pure materials (in our case, Cu) for strain hardening.

The obtained results are in good correlation with earlier studies [17, 18].

Analysis of the friction surfaces of the as-annealed samples prior to and after the tribological tests

Prior to conducting the tribological tests according to the reciprocating-motion test configuration and afterwards, we performed chemical analysis of the investigated copper, bronze and graphite-containing samples (the graphite-containing samples were studied only in the condition after the tribological tests). For this purpose, we used an S-3500N scanning electron microscope with an EDS attachment for chemical analysis.

The analysis results show that the friction surface of the commercially pure Cu M1 in the process of its frictional interaction with a graphite-containing plate becomes saturated with carbon and oxygen.

Fig. 4, a) shows the friction path formed as a result of the frictional interaction between the investigated sample from the commercially pure Cu M1 and the graphite-containing plate. From the analysis of the topography of the surface shown in Fig. 4, b), it has been established that carbon is present on the surface in a free state, in the form of particles flaked from the graphite-containing plate. Oxygen is apparently in a bound state, in the form of oxides. Previously, it was noted elsewhere [17, 18] that the frictional interaction and structural changes initiate the process of oxygen content growth on the friction surfaces of metallic materials.

The chemical analysis of the results of which are presented in Fig. 7, reveals that the chromium particles, in the form of traces, have also been transferred from the chromium bronze surface onto the graphite-containing plate.
Main conclusions

1. As a result of a comprehensive evaluation of the tribological properties of commercially pure Cu and the low-alloyed chromium bronze, having different microstructures, it has been found that in the investigated contact pairs, regardless of the structural state of Cu and chromium bronze, the adhesive component of the friction coefficient has a considerable value. In the commercially pure Cu samples, there is observed a large difference between the adhesive and deformation components of the friction coefficient, depending on the material’s structure – for the Cu samples with a CG structure the values of $f_d$ are 8 times higher than the respective values for the SMC material.

2. We have obtained the correlation dependencies, considering the different structural states of the investigated materials, for the contact pairs «M1 commercially pure Cu – EK-40 graphite-containing plate» and «Cu-0.5%Cr graphite-containing plate» (for the evaluation of the friction coefficient’s integral value at room temperature), and the contact pairs «commercially pure Cu – Fe-18%W-4%Cr-0.8%C GTS» and «Cu-0.5%Cr chromium bronze – Fe-18%W-4%Cr-0.8%C GTS» (for the evaluation of the friction coefficient’s adhesive component at different temperatures). We have established that for commercially pure Cu and the low-alloyed bronze, the integral values of the friction coefficient and their adhesive components are structurally sensitive parameters, and their values are lower for the samples with an SMC structure than for the samples with a CG structure.

3. The chemical analysis of the friction surfaces of the samples and the graphite-containing plate has shown a mutual transfer of chemical elements, as well as an increase in the oxygen content, which is an evidence of the activation of the friction surface, resulting from the frictional interaction, and structural transformations in the near-surface layers.

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Literature

COMPARATIVE TRIBOLOGICAL PROPERTIES OF AZ91D MAGNESIUM ALLOY
AFTER STRENGTHENING BY SiC POWDER AND AFTER SEVERE PLASTIC
DEFORMATION

СРАВНИТЕЛЬНЫЕ ТРИБОЛОГИЧЕСКИЕ СВОЙСТВА МАГНИЕВОГО СПЛАВА AZ91D ПОСЛЕ
УПРОЧНЕНИЯ ПОРОШКОМ КАРБИДА КРЕМНИЯ И ПОСЛЕ ИНТЕНСИВНОЙ ПЛАСТИЧЕСКОЙ
ДЕФОРМАЦИИ

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Abstract. The paper presents the results of studies of tribological properties of the contact of the tool steel composition Fe-18W-4Cr-1,2V
with the magnesium alloy AZ91D strengthened by submicron powder filling out of SiC and severe plastic deformation (SPD), namely equal-
channel angular pressing (ECAP). It is stated that introduction of SiC powder filling to the magnesium alloy the friction coefficient on the
moving frictional contact increases, the wear rate reduces. These tribotechnical characteristics are influenced by the size and volume of the
particles of powder filling, normal loading force and slip rate. SPD of the initial material results in reduction of the adhesion constituent of
the friction coefficient.

KEYWORDS: MAGNESIUM ALLOY; METALLIC COMPOSITE MATERIAL; POWDER FILLING; SEVERE PLASTIC DEFORMATION;
EQUAL-CHANNEL ANGULAR PRESSING; SILICICUM CARBIDE; FRICTION COEFFICIENT; ADHESIVE BOND SHEAR STRENGTH ; WEAR RATE.

Introduction

In modern mechanical engineering, in particular in friction knots, one of the ways to reduce the weight of cars is to apply light
alloys with enhanced mechanical properties. Magnesium is attractive to be applied as structural material due to attractive
strength-to-weight ratio that exceeds the one for aluminum and other light metals and alloys [1-3]. High damping capacity of
magnesium alloys allows using them effectively to manufacture automobile and aircraft wheels, various components for motor-
and-tractor and aerospace engineering, rollers for cargo conveyors [6, 7] etc. The strength of magnesium could be enhanced without
significant change in the strength due to addition of small amount of submicron powder filling of SiC [3-5]. Besides, severe plastic
deformation is known to effectively increase the strength of bulk metals due to fabrication of ultrafine-grained structure [8, 9]. SPD
techniques can be considered as alternative techniques to dispersion strengthening of composite materials.

However, tribological behavior of these materials is studied insufficiently for application in friction knots [10, 11].

In this paper the results of definition of wear rate of the magnesium alloy, the friction coefficient and its molecular
constituent depending on the content of the powder filling are given. Comparative evaluation of the adhesive bond shear strength and
molecular constituent of the friction coefficient of the magnesium alloy AZ91D strengthened by ECAP in the slipping
tribological contact with the tool steel composition Fe-18W-4Cr-1,2V is presented.

Experimental procedure and materials

Magnesium alloy AZ91D (89.89%Mg-9.0%Al-0.68%Zn-0.13%Mn) was used as material for study. In comparative tests there
were employed matrix composite materials, containing submicron powder filling out of SiC, and the magnesium alloy
AZ91D after 2 ECAP passes.

The variants of investigated composite materials differing in dispersity and amount of added powder of SiC and strain-hardened
magnesium alloy of the initial state are the following: AZ91D in the initial state; AZ91D + 3% SiC with an average particle size of
5 μm; AZ91D + 3% SiC with an average particle size of 11 μm; AZ91D + 6% SiC with an average particle size of 11 μm; AZ91D + 3% SiC with an average particle size of 15 μm; AZ91D after 2 ECAP passes.

Tribological tests of the initial alloy and dispersion-strengthened composite materials were carried out on the friction
machine “Timken”. Fig. 1 presents the set and the processing scheme.

Fig. 1. Machine of friction “Timken” (a) and testing scheme (b): 1 – tested sample; 2 – rotating steel disk.

Testing of the initial and dispersion-strengthened materials was conducted under normal loading of 10N and 50N and a disk
rotation speed of 250 min⁻¹ and 1000 min⁻¹, the slip distance was 1650 m in all the tests. Friction force \( F \), loss of sample mass \( Q \) and geometric area
of the contact \( S_0 \) were recorded during tests. The wear rate \( J_s \) value was defined with the help of the mentioned parameters.

The diameter of the disk out of tool steel composition Fe-18W-4Cr-1,2V was 70 mm, the thickness was 20 mm. The wear of
the disk quenched to the hardness of HRC58...65 was neglected due to its low value as compared to the wear of the tested samples.

The friction coefficient \( \mu \) was calculated according to the formula:

\[
\mu = \frac{F}{P},
\]

where \( F \) – friction force, \( N \); \( P \) – normal loading force, \( N \).

The wear rate \( J_s \) value was defined according to the formula:
\[ J_h = \frac{Q}{\rho S_c L} \]  \hspace{1cm} (2)

where \( Q \) – sample mass loss, g; \( \rho \) – material density, g/cm\(^3\); \( S_c \) – geometrical area of the contact, cm\(^2\); \( L \) – slip distance, cm.

Fig. 2 presents the ECAP scheme that was chosen for strain hardening of the initial material [12, 13].

The employed scheme allows achieving high degrees of accumulated strain as a result of shear in the conjugating channels. In this case the angle between the conjugating channels \( \varphi \) was \( 120^\circ \).

Studies on the evaluation of the adhesive bond shear strength and molecular constituent of the friction coefficient were carried out on the one-ball machine of friction at temperatures of 20, 150 and 300 °C according to the scheme that is presented in Fig. 3 [14].

Adhesive bond shear strength \( \tau_n \) was defined from the ratio:

\[ \tau_n = 0,75 \frac{M}{\pi \left( \frac{d_{1,2}}{2} \right)^2} \] \hspace{1cm} (3)

where \( d_{1,2} \) – diameters of prints on the tested samples, mm; \( M \) – indenter rotary moment, N mm.

Adhesive (molecular) constituent of the friction coefficient was defined as:

\[ f_M = \frac{\tau_n}{p_r} \] \hspace{1cm} (4)

where \( p_r \) – normal pressure, MPa

\[ p_r = \frac{P}{\pi \left( \frac{d_{1,2}}{2} \right)^2} \] \hspace{1cm} (5)

where \( P \) – force of sample compression, N.

Results of experiments and their discussion

Figs. 4 and 5 present the charts with the results of tribological tests conducted according to the scheme “block-disk” (Fig.1).

It is seen from the charts that addition of powder filling of SiC to the magnesium alloy increases the friction coefficient. The lower the normal loading force and the slip rate, the higher friction coefficient.

In order to explain these results, let us consider the data received with the help of the one-ball machine of friction.

Fig. 6 demonstrates that the dependence of the adhesive bond shear strength \( \tau_n \) on the normal pressure \( p_n \) is described by the binomial dependence:

\[ \tau_n = \frac{A_p}{p_n} \] \hspace{1cm} (6)

where \( A_p \) – coefficient of the friction coefficient.

Fig. 4. Dependence of the friction coefficient on the size of SiC particles

Fig. 5. Dependence of the friction coefficient on the volume of powder filling

Fig. 6. Dependence of adhesive bond shear strength on the normal pressure in the contact with tool steel composition Fe-18W-4Cr-1,2V: a) - AZ91D in the initial state; b) - AZ91D + 3% SiC with an average particle size of 5 μm; c) - AZ91D + 3% SiC with an average particle size of 11 μm; d) AZ91D + 6% SiC with an average particle size of 11 μm; e) AZ91D + 3% SiC with an average particle size of 15 μm; f) AZ91D after 2 ECAP passes.
where $\tau_n$ – adhesive bond shear strength without normal loading force; $\beta$ – piezoelectric coefficient.

The molecular constituent of the friction coefficient $f_m$ can be defined as:

$$f_m = \frac{\tau_m}{p_r} = \frac{\tau_m}{p_r} + \beta$$

(7)

It is seen from formula (7) that the molecular constituent of the friction coefficient increases, when the normal pressure $p_r$ decreases. This fact explains the enhancement of the friction coefficient when the normal loading force reduces (Figs. 4 and 5).

Decrease in the slip rate reduces the temperature of the friction contact, which according to the data in Fig. 7 enhances the molecular constituent $f_m$ and the total friction coefficient $f$ (Fig. 4 and 5).

Increase of the friction coefficient after addition of SiC powder filling into the magnesium alloy can be explained by enhancement of the deformation constituent of the friction coefficient $f_d$ (Figs. 4 and 5). It is known that in accordance with the mechanical and molecular friction theory [15] the deformation constituent of the friction coefficient is formed by the resisting forces of the deformation roller that runs in front of introduced irregularities to the surface of the softer contacting slipping bodies. The value of the deformation constituent of the friction coefficient $f_d$ depends on the amount of introduced irregularities and their relative introduction can be defined analytically [15] or experimentally as:

$$f_d = f - f_m$$

(8)

The calculations of the values of the molecular constituent of the friction coefficient $f_m$ conducted in the comparable conditions on the basis of experimental data given in Figs. 4, 5 and 7 demonstrate that addition of the SiC powder filling to the magnesium alloy enhances the value of the deformation constituent $f_d$ from 0.09 to 0.20. The higher the $f_d$ value, the higher the volume and size of SiC particles in the magnesium alloy. These particles characterized by high hardness are added to the contact surface of the counterbody, and the deformation constituent and total friction coefficient increase.

Solid SiC particles in the form of powder filling provide reduction of the wear rate of the dispersion-strengthened magnesium alloy (Fig. 8 and 9).

It should be noted that the wear rate decreases with the increasing size and volume of the filling particles in the magnesium alloy, as in this case the areas containing hard-wearing SiC particles increase. This effect can be observed on babbit bearings. The solid filling is added to the soft matrix of bearings.

The experimental data given in Figs. 6 and 7 testify to the fact that the magnesium alloy AZ91D after 2 ECAP passes is quite alternative to the composite magnesium alloy strengthened by the powder filling out of SiC. The preliminary deformation treatment of the initial magnesium alloy provides lower value of the adhesive constituent of the friction coefficient at a rather high bearing capacity of the frictional contact [16]. As the research results showed (Fig. 6), the bearing capacity of the frictional contact of the material processed by SPD technology is comparable with the composite material on the basis of the magnesium alloy AZ91D that contains 3% SiC with an average particle size of 15 μm.

**Conclusion**

1. Addition of the powder filling of SiC to the magnesium alloy results in enhancement of the integral value of the friction coefficient, as in this case its deformation constituent increases. In the investigated range the normal loading force and the rate of relative slip impact the total value of the friction coefficient as the factors that change its molecular constituent.

2. Addition of the powder filling of SiC to the magnesium alloy AZ91D results in reduction of the wear rate, as in this case the areas containing hard-wearing SiC particles increase.

3. Employment of the magnesium alloy after ECAP in the friction knots is promising. The molecular constituent of the friction coefficient reduces significantly with the enhanced bearing capacity of the frictional contact.

**References**


PREPARATION AND PROPERTIES OF CARBON ADSORBENTS BASED ON PLANT RAW MATERIALS AND POLYMERIC WASTE

РАЗРАБОТКА ОСНОВ ТЕХНОЛОГИИ АКТИВНЫХ УГЛЕЙ НА ОСНОВЕ ОТХОДОВ ПОЛИМЕРОВ И РАСТИТЕЛЬНОГО СЫРЬЯ

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Реферат: Объектом исследования являются отходы полиэтилена, полиамида и полиэтилентерефталата, поливинилхлорида и полиуретана, подвергаемые утилизации методом пиролиза с растительным сырьём в качестве носителя. Цель исследования – термическая переработка названных отходов в углеродные адсорбенты и анализ их адсорбционных свойств. Комбинации наиболее распространённых полимерных отходов и растительного сырья (древесины, торфа, каменного угля и его кокса) изучены в качестве сырья для получения углеродных адсорбентов. На основе термографического анализа установлен температурный режим пиролиза растительного сырья. Оценино влияние вида сырья и полимерных отходов на выход и показатели пористой структуры адсорбентов, среди которых определены наиболее качественные образцы.

КОНТРОЛЬНЫЕ СЛОВА: РАСТИТЕЛЬНОЕ СЫРЬЕ, ПОЛИМЕРНЫЕ ОТХОДЫ, УТИЛИЗАЦИЯ, ПИРОЛИЗ, АДСОРБЕНТЫ

1. Введение

Настоящие исследования направлены на реализацию государственной стратегии в области утилизации отходов производства и потребления [1], в частности, отходов упаковочных полимеров. Объём образования полимерных отходов в России по разным оценкам составляет 700-900 тыс. т в год, причём в их составе преобладают упаковочные материалы из полистирола (ПЭ, 34 %), полиэтилентерефталата (ПЭТФ, 20 %) и полиамида (ПА, 14 %). Поливинилхлорид ПВХ (пластиковая посуда) и пенополиуретан ППУ (наполнитель мягкой мебели) также составляют заметную часть твёрдых коммунальных отходов. Внедрение с 2019 г. системы раздельного сбора коммунальных отходов будет стимулировать их утилизацию, однако загрязнённая и смешанная часть их не подлежит утилизации. Основной объём отходов по разным оценкам составляет 700-900 тыс. т в год, причём в их составе преобладают упаковочные материалы из полистирола (ПЭ, 34 %), полиэтилентерефталата (ПЭТФ, 20 %) и полиамида (ПА, 14 %). Поливинилхлорид ПВХ (пластиковая посуда) и пенополиуретан ППУ (наполнитель мягкой мебели) также составляют заметную часть твёрдых коммунальных отходов. Внедрение с 2019 г. системы раздельного сбора коммунальных отходов будет стимулировать их утилизацию, однако загрязнённая и смешанная часть их не подлежит утилизации. Основной объём отходов по разным оценкам составляет 700-900 тыс. т в год, причём в их составе преобладают упаковочные материалы из полистирола (ПЭ, 34 %), полиэтилентерефталата (ПЭТФ, 20 %) и полиамида (ПА, 14 %). Поливинилхлорид ПВХ (пластиковая посуда) и пенополиуретан ППУ (наполнитель мягкой мебели) также составляют заметную часть твёрдых коммунальных отходов. Внедрение с 2019 г. системы раздельного сбора коммунальных отходов будет стимулировать их утилизацию, однако загрязнённая и смешанная часть их не подлежит утилизации. Основной объём отходов по разным оценкам составляет 700-900 тыс. т в год, причём в их составе преобладают упаковочные материалы из полистирола (ПЭ, 34 %), полиэтилентерефталата (ПЭТФ, 20 %) и полиамида (ПА, 14 %). Поливинилхлорид ПВХ (пластиковая посуда) и пенополиуретан ППУ (наполнитель мягкой мебели) также составляют заметную часть твёрдых коммунальных отходов. Внедрение с 2019 г. системы раздельного сбора коммунальных отходов будет стимулировать их утилизацию, однако загрязнённая и смешанная часть их не подлежит утилизации. Основной объём отходов по разным оценкам составляет 700-900 тыс. т в год, причём в их составе преобладают упаковочные материалы из полистирола (ПЭ, 34 %), полиэтилентерефталата (ПЭТФ, 20 %) и полиамида (ПА, 14 %). Поливинилхлорид ПВХ (пластиковая посуда) и пенополиуретан ППУ (наполнитель мягкой мебели) также составляют заметную часть твёрдых коммунальных отходов. Внедрение с 2019 г. системы раздельного сбора коммунальных отходов будет стимулировать их утилизацию, однако загрязнённая и смешанная часть их не подлежит утилизации. Основной объём отходов по разным оценкам составляет 700-900 тыс. т в год, причём в их составе преобладают упаковочные материалы из полистирола (ПЭ, 34 %), полиэтилентерефталата (ПЭТФ, 20 %) и полиамида (ПА, 14 %). Поливинилхлорид ПВХ (пластиковая посуда) и пенополиуретан ППУ (наполнитель мягкой мебели) также составляют заметную часть твёрдых коммунальных отходов. Внедрение с 2019 г. системы раздельного сбора коммунальных отходов будет стимулировать их утилизацию, однако загрязнённая и смешанная часть их не подлежит утилизации. Основной объём отходов по разным оценкам составляет 700-900 тыс. т в год, причём в их составе преобла...
а – сосновые опилки:
навеска 141 мг, шкала G 200 мг

б – торф:
навеска 323 мг, шкала G 200 мг

c – каменный уголь
(Мьянма):
навеска 821 мг, шкала G 500 мг

в – бурый уголь:
навеска 364 мг, шкала G 200 мг
Изучаемые материалы различаются характером термического разложения при пиролизе в инертной среде. Следует отметить, что термостойкость (выход твёрдого остатка при данной температуре) их ожидается повышается по мере превращения растительной массы в углеродный материал. Для всех материалов кроме каменного угля характерна одна ступень разложения, т.е. интервал интенсивной потери массы, но при переходе от древесины к коксу он смещается к большим температурам. Обычно эти процессы сопровождаются поглощением тепла (отрицательные пики DTA), но в случае опилок – выделением (рис. 1а). Констатировано, что основные превращения не коксированных материалов происходят до 500 °С, выход карбонизатов при этом за исключением опилок превышает 50 масс. %, при 700 °С он ниже на 9-15,6 %. Дальнейшее нагревание сопровождается плавной потерей массы без выраженных тепловых эффектов.

Полученные промышленно из каменного угля виды кокса, естественно, относятся к термостойким материалам, заметное разложение которых (потеря массы более 2 %) протекает лишь при 500-900 °С (табл. 1). Карбонизат каменного угля имеет наиболее практическую зернистую форму, остальные материалы образуют порошковые продукты.

Пиролиз древесины и торфа хорошо изучен [например, 6], парогазовые продукты пиролиза представлены водой, диоксидом углерода, метаном, алкенами, спиртами, кислотами, смолами. Каменные угли при пиролизе (коксовании) образуют полиароматические соединения, бензол и его производные, а также воду, метан и водород.

3.2. Выходы углеродных адсорбентов

Внешний вид полученных адсорбентов на основе названного сырья и полимерных материалов изображен на рис. 2. Согласно фотографиям рис. 2 наиболее макропористыми материалами после пиролиза являются опилки и кокс. Изучение их пористой структуры приведено ниже в табл. 4.

Табл. 3 – Показатели выхода адсорбентов

<table>
<thead>
<tr>
<th>Сырье</th>
<th>Масса сырыя, г</th>
<th>Масса адсорбента, г</th>
<th>Выход адсорбента, %</th>
<th>Выход адсорбента от массы носителя, %</th>
<th>Изменение массы адсорбента, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Опилки</td>
<td>1,5</td>
<td>0,37</td>
<td>24</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>Опилки + ПЭ</td>
<td>1,5</td>
<td>0,26</td>
<td>17</td>
<td>34</td>
<td>10</td>
</tr>
<tr>
<td>Опилки + ПП</td>
<td>1,45</td>
<td>0,24</td>
<td>16</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td>Опилки + ПЭТФ</td>
<td>1,47</td>
<td>0,38</td>
<td>26</td>
<td>52</td>
<td>28</td>
</tr>
<tr>
<td>Опилки + ПВХ</td>
<td>5,07</td>
<td>1,72</td>
<td>34</td>
<td>68</td>
<td>44</td>
</tr>
<tr>
<td>Опилки + ППУ</td>
<td>1,66</td>
<td>0,75</td>
<td>45</td>
<td>90</td>
<td>66</td>
</tr>
<tr>
<td>Торф</td>
<td>3,1</td>
<td>1,54</td>
<td>50</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Торф + ПЭ</td>
<td>2,72</td>
<td>0,87</td>
<td>32</td>
<td>64</td>
<td>12</td>
</tr>
<tr>
<td>Торф + ПП</td>
<td>1,66</td>
<td>0,35</td>
<td>21</td>
<td>42</td>
<td>-</td>
</tr>
<tr>
<td>Торф + ПЭТФ</td>
<td>1,57</td>
<td>0,45</td>
<td>27</td>
<td>54</td>
<td>4</td>
</tr>
<tr>
<td>Торф + ППУ</td>
<td>2</td>
<td>1,30</td>
<td>65</td>
<td>130</td>
<td>80</td>
</tr>
<tr>
<td>Металл. кокс</td>
<td>3,08</td>
<td>1,61</td>
<td>52</td>
<td>104</td>
<td>4</td>
</tr>
<tr>
<td>Пековый кокс</td>
<td>3,08</td>
<td>1,7</td>
<td>55</td>
<td>110</td>
<td>10</td>
</tr>
<tr>
<td>Каменный уголь</td>
<td>2,32</td>
<td>2</td>
<td>84</td>
<td>84</td>
<td>-</td>
</tr>
<tr>
<td>Уголь + ПЭ</td>
<td>3,08</td>
<td>1,85</td>
<td>60</td>
<td>120</td>
<td>36</td>
</tr>
<tr>
<td>Уголь + ПП</td>
<td>3,08</td>
<td>1,77</td>
<td>57,5</td>
<td>115</td>
<td>31</td>
</tr>
<tr>
<td>Уголь + ПЭТФ</td>
<td>3,08</td>
<td>1,68</td>
<td>54,5</td>
<td>109</td>
<td>25</td>
</tr>
<tr>
<td>Уголь + ППУ</td>
<td>3,08</td>
<td>1,90</td>
<td>62</td>
<td>124</td>
<td>40</td>
</tr>
<tr>
<td>Уголь + ПВХ</td>
<td>3,08</td>
<td>1,85</td>
<td>60</td>
<td>120</td>
<td>36</td>
</tr>
</tbody>
</table>

Выходы целевых продуктов пиролиза сырья – адсорбентов – охарактеризованы в табл. 3. Результаты варьировались в некоторых случаях в зависимости от природы сырья. В табл. 3 приведены значения выходов целевых продуктов пиролиза на основе названного сырья и полимерных материалов.

3.3. Пористая структура адсорбентов

Характеристики пористой структуры материалов отражены в табл. 4 в виде объёмов пор, сорбирующих вещества с различным размером молекул: H₂O (субмикропоры) <C₆H₆ (микропоры) <CCl₄ (мезопоры). Анализ показал, что при пиролизе древесины образуется преимущественно микропоры, сорбирующие органические вещества. Микропоры, сорбирующие воду, наиболее развиты у образца из опилок, мезопоры, поглощающие CCl₄ – у образца из торфа. Каменный уголь остаётся низкопористым.

Совместный пиролиз сырья и полимеров в большинстве случаев приводит к развитию их пористой структуры. Предположительно это происходит по механизму сужения существующих пор носителя за счёт покрытия их слоем пироуглерода [7]. Для адсорбентов на основе опилок и термопластичных полимеров появляются новые микропоры, объём которых рекордный для ПП (табл. 4), для ПЭТФ и ПВХ – также мезопоры. Наибольший выход микропор и ПП по объёму микропрор (0,523 – 0,025 = 0,498 см³/г) преобладает в адсорбентах, полученных с примесью пироуглерода, что связано с образованием дополнительных пор на поверхности носителя. Однако на примере ППУ видно, что эффект отложения пироуглерода может быть избыточным — объёмы всех пор соответствующего адсорбента уменьшены относительно карбонизата опилок.
## Таблица 4 – Показатели пористой структуры адсорбентов

<table>
<thead>
<tr>
<th>Сыре</th>
<th>Объем сорбирующих пор (см$^3$/г) по парам</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H$_2$O</td>
</tr>
<tr>
<td></td>
<td>C$_6$H$_6$</td>
</tr>
<tr>
<td></td>
<td>CCl$_4$</td>
</tr>
<tr>
<td>Исходные опилки</td>
<td>0,152</td>
</tr>
<tr>
<td>Опилки</td>
<td>0,144</td>
</tr>
<tr>
<td>Опилки + ПЭ</td>
<td>0,17</td>
</tr>
<tr>
<td>Опилки + ПП</td>
<td>0,361</td>
</tr>
<tr>
<td>Опилки + ПЭФ</td>
<td>0,320</td>
</tr>
<tr>
<td>Опилки + ПВХ</td>
<td>0,328</td>
</tr>
<tr>
<td>Опилки + ППУ</td>
<td>0,025</td>
</tr>
<tr>
<td>Исходный торф</td>
<td>0,077</td>
</tr>
<tr>
<td>Торф</td>
<td>0,103</td>
</tr>
<tr>
<td>Торф + ПЭ</td>
<td>0,052</td>
</tr>
<tr>
<td>Торф + ПП</td>
<td>0,195</td>
</tr>
<tr>
<td>Торф + ПЭТФ</td>
<td>0,052</td>
</tr>
<tr>
<td>Торф + ППУ</td>
<td>0,058</td>
</tr>
<tr>
<td>Каменный уголь</td>
<td>0,056</td>
</tr>
<tr>
<td>Уголь + ПЭ</td>
<td>0,018</td>
</tr>
<tr>
<td>Уголь + ПП</td>
<td>0,017</td>
</tr>
<tr>
<td>Уголь + ПЭТФ</td>
<td>0,029</td>
</tr>
<tr>
<td>Уголь + ППУ</td>
<td>0,021</td>
</tr>
<tr>
<td>Металл. кокс + ПЭ</td>
<td>0,010</td>
</tr>
<tr>
<td>Пековый кокс + ПЭ</td>
<td>0,017</td>
</tr>
<tr>
<td>Уголь + ПВХ</td>
<td>0,015</td>
</tr>
</tbody>
</table>

Для адсорбентов на основе торфа результирующая структура зависит от строения полимера: максимальный объём субмикропор обусловлен добавкой ПП, микро- и мезопор по бензолу – добавкой ПЭТФ. Последний образец обладает способностью преимущественно поглощать органические растворители по сравнению с водой (табл. 4). Взаимодействие торфа с ППУ при пиролизе также снижает показатели продукта. Положительные изменения пористой структуры адсорбентов на основе древесины и торфа соотносятся с содержанием в них пироуглерода 4-28 % (табл. 3).

Все адсорбенты на основе каменного угля и полученных из него коксов несмотря на макропоры (рис. 2 г) и осаждение 4-40 % пироуглерода обладают низкими показателями пористой структуры, часто уступающими карбонизованным материалам. Их единственное преимущество – более высокая прочность зёрен.

### 4. Заключение

В данной работе изучено пиролитическое разложение древесины, торфа, бурого и каменного угля и кокса, обоснован температурный режим их переработки с полимерными отходами при 500 °C, найдены выходы целевого продукта пиролиза, определены показатели пористой структуры сырья и его карбонизатов.

Выявлено влияние совместного пиролиза сырья и полимеров в соотношении 1 : 1 на показатели пористой структуры адсорбентов: добавки полиэтилена, полипропилена, полиэтилентерефталата обеспечивают повышение объёмов сорбирующих пор по H$_2$O, C$_6$H$_6$, CCl$_4$. Максимальный объём пор по бензолу образца на основе опилок и полипропилена (0,52 см$^3$/г) превосходит таковой большинства промышленных активных углей. Каменный уголь и кокс не образуют пористых адсорбентов в сочетании с любыми полимерами.

Нахождение наилучших условий синтеза изучаемых адсорбентов требует варьирования соотношения компонентов и температуры пиролиза. Для низкопористых адсорбентов на основе угольных материалов можно рекомендовать парогазовую активацию.

### 5. Ссылки

1. Стратегия развития промышленности по обработке, утилизации и обезвреживанию отходов производства и потребления на период до 2030 года. Распоряжение Правительства РФ от 25.01.2018 № 84-Р.
GEOPOLYMERS BASED ON BULGARIAN RAW MATERIALS – PRELIMINARY STUDIES

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Abstract: The geopolymers are novel class of inorganic polymer materials consist of chains, sheets or networks made of covalently bonded mineral molecules. The main precursors of the geopolymers are reactive aluminosilicate material and hardener solution. Various suitable raw materials are located in Bulgaria. The present paper shows successful examples of geopolymers based on Bulgarian raw materials – fly ash, metakaolin, natural zeolite and iron-rich waste from copper industry. The properties and structure of the prepared geopolymers greatly depend on the composition and type of the raw material, as well as concentration and type of the activator solution. The results show the potential of geopolymers based on Bulgarian raw materials as building materials.

Keywords: GEOPOLYMER, METAKAOLIN, FLY ASH, IRON-SILICATE FINES, IRON-RICH, NATURAL ZEOLITE, CLINOPTILOLITE, MICROSTRUCTURE

1. Introduction

Geopolymers are novel class of inorganic materials consist of chains or networks of mineral molecules linked with co-valent bonds. The geopolymers is an X-ray amorphous material at ambient and medium temperature [1]. The geopolymers have also been described in the academic literature as ‘mineral polymers’, ‘inorganic polymers’, ‘inorganic polymer glasses’, ‘alkali-bonded ceramics’, and a variety of other terms [2]. First the French scientist Joseph Davidovich coined the term ‘geopolymer’ in 1978 when he mixed sodium hydroxide and kaolin clay. The actual breakthrough was done years later when metakaolin was used for the first time. Since then up to nowadays, metakaolin is the most common geopolymer precursor [3]. The geopolymers are two component system. The main precursor is usually (but not always) aluminosilicate powder material. The three most common raw material classes used in geopolymerization are metakaolin, slags and coal fly ashes. In addition to the reactive solid components a hardening solution, so called ‘activator’, is required to initiate the geopolymerisation reaction. The mechanism of geopolymerisation is described in several overlapping stages: dissolution of the precursor; special equilibrium, gelation, reorganization, polymerization and hardening [4]. The main difference between Portland cement hardening mechanism is the role of the water. In conventional cements the water react with the cement particles and the main products of the reaction are hydrates (C-S-H). Other hand, in geopolymerisation the water provides workability and ensures the hardening solution, so ca.

2. Experimental

3.1. Method of analysis

The chemical composition of the used precursors is presented in table 1. The chemical composition of the used precursors is presented in table 1. The activator solutions were prepared by using solid KOH pellets, sodium silicate (SiO2/Na2O=3) and tap water. The ingredients were mixed by magnetic stirrer and tempered prior usage as activator.

<table>
<thead>
<tr>
<th>Table 1 Chemical composition of the geopolymer precursors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metakaolin</td>
</tr>
<tr>
<td>-----------------</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Iron-silicate fines [5]</td>
</tr>
<tr>
<td>Fly ash [6]</td>
</tr>
<tr>
<td>Natural Zeolite</td>
</tr>
</tbody>
</table>

The present paper describes results with geopolymers prepared from Bulgarian raw materials – metakaolin, iron-silicate fines, fly ash and natural zeolite.

The metaoloin was provided by Kaolin AD, Bulgaria. The wet residue of the material was 0.40% on 45µm. The iron-silicate fines are industrial by-product from local copper plant (Aurubis, Bulgaria). The iron-rich precursor was dried to constant mass in oven at 105°C. Fly-ash class F from TPP Maritsa East 2, Bulgaria. The powder XRD patterns were obtained by Bruker D-2 Phaser diffractometer with Bragg-Brentano geometry using a CuKα source. SEM images were obtained with different magnification by using electron microscope – SEM 515 Philips.

2.2. Materials

The metaoloin was provided by Kaolin AD, Bulgaria. The wet residue of the material was 0.40% on 45µm. The iron-silicate fines are industrial by-product from local copper plant (Aurubis, Bulgaria). The iron-rich precursor was dried to constant mass in oven at 105°C. Fly-ash class F from TPP Maritsa East 2, Bulgaria. The chemical composition of the used precursor is presented in table 1.
2.3. Geopolymer synthesis

The geopolymer precursor and activator solution were mixed and homogenized with mechanical stirrer for 1 min. The mixtures were rested to mature for 5 min, then mixed again for 30 seconds. The fresh geopolymer paste was moulded in polypropylene cylindrical moulds (50x30mm). The samples are stored in plastic bags and cured at laboratory conditions (20°C).

3. Results and Discussion

3.1. Geopolymer based on metakaolin

Five series of geopolymer specimens were prepared. The samples were demoulded after 24 hours of curing and placed in laboratory conditions (20°C and 65% relative humidity). At 28-th day compressive strength was determined by using three specimens of each series. The composition and results from compressive strength is presented in Table 2. Series MM1 showed maximal strength.

<table>
<thead>
<tr>
<th></th>
<th>MM1</th>
<th>MM2</th>
<th>MM3</th>
<th>MM4</th>
<th>MM5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂/Al₂O₃</td>
<td>3.55</td>
<td>3.55</td>
<td>3.55</td>
<td>3.55</td>
<td>3.29</td>
</tr>
<tr>
<td>H₂O/M₂O</td>
<td>15</td>
<td>13</td>
<td>17</td>
<td>11.6</td>
<td>14.6</td>
</tr>
<tr>
<td>M₂O/Al₂O₃</td>
<td>1</td>
<td>1.2</td>
<td>0.85</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Compressive strength, MPa</td>
<td>33.7</td>
<td>27.8</td>
<td>31.5</td>
<td>30.3</td>
<td>20.6</td>
</tr>
</tbody>
</table>

The metakaolin and geopolymer series MM1 was examined by Powder X-ray diffraction. The results are presented in Fig. 1. Both metakaolin and geopolymer MM1 showed amorphous structure with inclusion of quartz. The amorphous halo shifted after geopolymerisation from 15-30 2θº to 22-35 2θº, which is typical for geopolymers. The crystalline quartz stayed inert.

Fig. 1 Powder X-ray diffraction patterns of metakaolin (MK) and obtained geopolymer (series MM1). Q- quartz

The chemical purity of metakaolin is very high, represented almost entirely by SiO₂ and Al₂O₃, which helps to investigate the ongoing reactions in the synthesis of geopolymers and the analysis of the results. Bulgarian Metakaolin from Kaolin AD has sufficient reactivity and is a potential raw material for the production of geopolymers.

3.2. Geopolymer based on iron-rich waste from copper industry

Five series of geopolymer specimens were prepared with water to solid ratio equal to 0.15. The samples were cured at laboratory conditions in plastic bags until 10-th day, when were placed in oven for 12 days at 80°C. At 22-th day the specimens were demoulded and placed at laboratory conditions (20°C and 65% humidity). At 90-th day compressive strength was determined by using three specimens of each series. The composition and results from compressive strength is presented in Table 3. Series 15F2 and 15F3 showed highest strength. Both results are similar, but 15F3 was obtained by lower concentration of the activator solution.

<table>
<thead>
<tr>
<th></th>
<th>15F1</th>
<th>15F2</th>
<th>15F3</th>
<th>15F4</th>
<th>15F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃/M₂O</td>
<td>0.32</td>
<td>0.32</td>
<td>0.5</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>H₂O/M₂O</td>
<td>7.59</td>
<td>7.64</td>
<td>11.4</td>
<td>5.46</td>
<td>5.36</td>
</tr>
<tr>
<td>Fe₂O₃/M₂O</td>
<td>2.5</td>
<td>2.5</td>
<td>4</td>
<td>1.75</td>
<td>1.75</td>
</tr>
<tr>
<td>Compressive strength, MPa</td>
<td>19.36</td>
<td>27.96</td>
<td>27.53</td>
<td>3.87</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The results from powder X-ray diffraction showed the mineral composition of the iron-silicate fines. It contains mostly fayalite and magnetite (Fig. 2). Minor changes between raw material and obtained geopolymer (series 15F3) were observed.

Fig. 2 Powder X-ray diffraction patterns of iron silicate fines (RAW) and obtained geopolymer (series 15F3). M- Magnetite, F – fayalite.

The presented studies showed that geopolymer technology is capable to reduce the huge amounts of fayalite slag generated for the last decades as a result of copper production.
3.3. Geopolymer based on fly ash

In previous study [7] four series of geopolymers were prepared using different concentration of the alkaline hardener solutions and water to solid ratio equal to 0.40 (w/w). The series B1 with following molar ratio: \(\text{M}_2\text{O}/\text{Al}_2\text{O}_3=1.4\), \(\text{H}_2\text{O}/\text{M}_2\text{O}=10\) showed lowest absorption to water – 20.0\%. Thus the obtained geopolymer showed high porosity which motivated the research team to develop highly porous lightweight geopolymer by addition of 1\% by mass \(\text{H}_2\text{O}_2\) as gas forming agent (Fig. 3). The decomposition of the peroxide produce oxygen, which form small interconnected pores. The resulted porous geopolymer was characterized by 0.44 g/cm\(^3\) density, 2.64 g/cm\(^3\) absolute density and 83.3\% relative porosity. Preliminary fire-resistance test of the material was examined. Simple jet-torch test was conducted to observe the behavior of the porous geopolymer at high temperature and direct fire. The lightweight geopolymer was exposed to direct fire from butane jet-torch for 3 minutes at 5 cm distance. During the fire exposure the color of the specimens in the hottest area turned into red-orange, which is associated to temperature about 1000\(^\circ\)C. After the fire test the specimen preserved its integrity, which indicates its potential as fire-resistance materials.

The raw fly ash, light-weight geopolymer and fired samples were examined with SEM. The fly ash contained cenosphere, which contributed to better workability of the fresh geopolymer mixture (Fig. 4). There were cracks on the hardened geopolymer before and after the fire test (Fig. 5, Fig. 6). The particles of the fly ash contains small micron-sized pores. The presence of such micro pores provides a road of escape for hot gases generated by the elevated temperature.

It can be concluded that mixing fly ash from Maritsa TPP with a suitable activating solution lead to formation of geopolymer material characterized relatively large porosity. Lightweight geopolymers could be also successfully prepared by using suitable gas forming agent. The fire torch test indicates the potential as fire-resistance materials.

3.4. Geopolymer based on natural zeolite (review)

In-depth studies on possibility of using natural zeolite clinoptilolite from local large deposit Beli Plast were done within the PhD thesis of Nikolov, A. [8]. The optimal results were obtained using activator solution - mixture of potassium hydroxide, sodium silicate (molar ratio modulus MR=\(\text{SiO}_2/\text{Na}_2\text{O}=3\)) and water. However, the obtained material hardens slowly at normal temperature. Demoulding was possible after at least one week at 20\(^\circ\)C. The hardened geopolymer activated with silicate activators showed high shrinkage. However, applied in thin layers as coating the material did not showed shrinkage cracks. The adhesion to concrete was significant – over 2MPa [9]. Thus geopolymer based on natural zeolite are suitable for plasters or coatings.

The effect of modulus of sodium silicate was investigated. Using higher modulus of water-soluble sodium silicate (WG3) leads to bigger rate of strength gain. Geopolymers obtained with WG2 showed higher final strength and slightly higher degree of geopolymerization. However, due to the crystallinity of the natural zeolite the alkali concentration of the used sodium silicate reagents solution (MR= 2\(+3\)) were not sufficient to dissolve the raw material. Thus, using sodium silicate solution with MR above 2 leads to certain quantity unreacted clinoptilolite, which preserves the beneficial properties of the clinoptilolite per se.

The calcination of the natural zeolite at 900 \(^\circ\)C leads to full dehydroxylation of the clinoptilolite structure thus transforming the natural zeolite into ‘metazeolite’. The shrinkage of the hardened geopolymer was reduced twice and the compressive strength
increase 3 times when calcined zeolite (metazeolite) was used as a geopolymer precursor instead of natural zeolite [10].

4. Conclusion

The presented studies showed that Bulgarian raw materials could be successfully used as geopolymer precursor. The properties and structure of the prepared geopolymers greatly depend on the composition and type of the raw material, as well as concentration and type of the activator solution. Further more detailed studies are needed to develop materials with practical application.

5. Acknowledgement

The results in this work have been achieved in fulfilment of a project financed by the National Science Fund of Bulgaria under contract No. DM17/3 from 12.12.2017.

6. Literature

[8]. Nikolov, A., Geopolymers based on natural zeolite for construction applications, composition, structure, properties 2016, Sofia ,University of Architecture, Civil Engineering and Geodesy.


1. Introduction

The ability of the material to resist the propagation of cracks in the body is called crack resistance \( K_c \).

**Conventional crack resistance testing**

In the fracture mechanics [1-5] the value of crack resistance \( K_c \) is named “fracture toughness” for plane deformation [1-5]. The value of \( K_c \) by means of conventional testing [1,2], according to Tetelman [3, 8, 9] is determined. For aluminum alloys, ASTM B 645-10:2015 (USA) is used. The condition for mechanical testing is

\[
1 \geq \chi \left( \frac{Y}{\sigma_{YS}} \right)^2,
\]

where \( B \) is the minimum thickness that specimen a condition of plastic strain energy at the crack tip in minimal, \( \chi \) is the empirical coefficient. According ASTM B 645-10:2015 (USA) for the parameter there is \( \chi \approx 5.0 \). A most commonly used specimen for mechanical testing are given on fig.1.

![SEN'B Specimen](image)

![CT Specimen](image)

**Fig.1. Test specimen for mechanical testing**

The mechanical testing to obtain of \( K_c \) is difficult to realize, due to the large size \( B \) is needed. This testing is destructive. Often, it is not possible to prepare a test sample from the subject who is tested. It is needed of methods for non-destructive evaluation (NDE) of crack resistance to develop. These methods must be directly applicable to the test subject. The specimen for the test subject is

**NDE of crack resistance - \( K_c \)**

In practice there is interest for NDE of crack resistance \( K_c \) in direct on constructive elements manufactured by aluminum alloys. Such an approach does not require the preparation of test specimens from the test material. In this case a relationships are looking [1-7]

\[
K_c \propto (\overline{D}; E; \psi; \sigma_{YS}; \sigma_{UTS})
\]

where respectively average grain size, elasticity modulus, relative contraction, yield stress, ultimate tensile stress) there are also the relationships are known [3, 8, 9]

\[
(E; \psi; \sigma_{YS}; \sigma_{UTS}) \propto \overline{D}
\]

In addition, deterministic or stochastic the relations [8-10] are view

\[
\left( \frac{\overline{D}}{E} \right) \propto (V_L; V_T; HB)
\]

where \( \left( \frac{\overline{D}}{E} \right) \) are velocity of longitudinal and transverse ultrasonic waves, HB is Brinell’s hardness. In this case the norms ASTM E 494:2015 and ASTM E 10:2018 are used.

2. NDE of grain size - \( \overline{D} \)

An important stage of NDE of \( K_c \) is NDE of \( \overline{D}, \) mm.

To obtain a dependency for \( \overline{D} \) the following relationships are considered:

A/ Hall–Petch’s dependency [8,9]

\[
\sigma_{YS}, MPa = \sigma_0 + K_Y (\overline{D}, mm)^{1/2},
\]

where the reference values for Al+3,5%Mg alloys [5,6] is \( \sigma_0 \approx 50,00 MPa \) and \( \sigma_0 \approx 8,5 MPa/mm^{1/2} \).

B/ Bussinesq’s dependency [10]

\[
\sigma_{YS}, MPa = k_{buus} \phi(v) (HB, kgf / mm^{2})
\]

where \( \phi(v) = \frac{1}{2} (1-2v) + \frac{9}{2} \left( 1+v \right) \left[ (1+v) \left( 1+\frac{2}{3} \right) \right]^{1/2},\)

\( v = \frac{0.5-\left( V_T/V_L \right)^2}{1-\left( V_T/V_L \right)^2}, \)

for Al+3,5%Mg, according BGN EN 1706.

\( k_{buus} \in (1.21 - 3.53), med k_{buus} \approx 2.8. \)

After excluding \( \sigma_{YS}, MPa \) from (5), (6) equation for \( \overline{D}, mm \) is obtain

\[
K_Y \left( \overline{D} \right)^{1/2} \propto \left[ \sigma_0 - k_{buus} \phi(v) HB \right] = 0
\]

The equation (7) is non-linear, regarding \( \overline{D}, mm \), by set \( k_{buus}, \psi; \sigma_0, K_Y \) and \( V_T, V_L \). \( HB, kgf / mm^{2} \) are measured. To solve the equation (7) a bisection method, ZEROIN algorithm [11] and on-line compiler for C++ are used. The rots is searching in the interval (0;1). The accuracy \( 10^{-6} \) is set. The number of iteration is \( N \sim \log_{2} \left( \frac{X_K - X_{L}}{TOL} \right) \), where \( (X_K, X_{L}) \) is searching interval. In this case \( N \sim 170 \) (time of work is \( 3-4 \) seconds).

3. NDE of \( K_c \) according Tetelman

In [5] a relation \( K_c = K_{k'} (\overline{D}; \sigma_{YS}) \) is considered. The Tetelman’s model [6] is

\[
\left( \frac{K_{k'}}{\sigma_{YS}} \right)^2 = 25.23, \chi \left( \frac{\sigma_{YS}}{\sigma_{YS}} \right) (\overline{D}).
\]

**Abstract:** The crack resistance in fracture mechanics is defined as critical value of stress intensity factor in the plane-strain fracture toughness. A mechanical test is used to assess it under certain conditions. This is a complicated, long and expensive procedure. In practice, it is of interest to determine the crack resistance for construction elements by means of non-destructive evaluations (NDE).

**KEY WORDS:** CRACK RESISTANCE, Al + 3,5 % Mg ALLOYS, ULTRASONIC VELOCITIES, HARDNESS
where $\frac{\sigma_c}{\sigma_{YS}} = \left[\exp\left(\frac{\sigma_c}{\sigma_{YS}} - 1\right)\right]^{-1}$, $\sigma_c$ is critical value of stress in crack tip. For Al alloy with 3.5% Mg (BGN EN 1706) there are $\sigma_{\text{max}} \equiv \sigma_c \sim \sigma_{UTS} \approx 2.0 \sigma_{YS}$ (Fig. 2.).

After necessary conversions of (8) is done

$$\left(\frac{K^A}{K_{YS}}\right)^2 \approx 43. D,$$

where $D = D(V_L; V_T; HB, K_v; \sigma_0; k_{\text{Calc}})$, calculated by (7).

4. NDE of $K^A_{\text{FC}}$ according Andreykiv

Andreykiv’s relationship [7] is a model includes not only $(\overline{D}; \sigma_{YS})$, but also the mechanical properties of the material $(E; V_L; \psi)$. Andreykiv’s relationship can be write as

$$\left(\frac{K^A}{K_{YS}}\right)^2 = \frac{\varepsilon(\bar{D}) E}{1 - V^2},$$

where $\varepsilon(\bar{D})$ - structural function is defined as

$$\varepsilon(\bar{D}) = \sqrt{\frac{3}{2}} \left[\frac{\sigma_0 + K_v(D)^{-1/2}}{\overline{D}}\right]^{-1};$$

$$\overline{D} = D(V_L; V_T; HB, K_v; \sigma_0; k_{\text{Calc}}),$$

where

$$E = \frac{3 - 4(V_L/V_T)^2}{1 - (V_L/V_T)^2}, \quad V = \frac{0.5 - (V_L/V_T)^2}{1 - (V_L/V_T)^2}.$$

$(V_L; V_T)$ are velocity of longitudinal and transverse ultrasonic waves and obtain by means ASTM E 494:2015.

$$\psi/100 = m(V_L, \text{mm/µs}) + b,$$

$R^2 \approx 99.9\%$, for Al + 3.5% Mg alloy $m = 0.1016; b = 0.0038$.

5. Experiment

For samples from Al + 3.5% Mg alloys [13], BGN EN 1706:2010, measurements have been made.

5.1. Equipment.
For NDE measure the following equipment are used:

1. Leeb hardness tester M – 295, WILCON, Germany, for measure of HB, kgf/mm$^2$;
2. Digital ultrasonic flaw detector, SONATEST, England and transducers for L and T waves are used, for measures of $V_L, \text{mm/µs}$ and $V_T, \text{mm/µs}$;
3. Digital micrometer DIGIMATIC, Mitutoyo, Japan, for thickness measures.

In Table 1. the images of Leeb hardness tester and digital ultrasonic flaw detector and transducers are given.

5.2. Measurements
For Al alloy with 3.5% Mg (BGN EN 1706). Velocity, $(V_L; V_T) \text{mm/µs}$, ASTM E 494:2015 $(6.36 \pm 0.030) : (3.15 \pm 0.015)$. Note: Minimum thickness of test object is 5 mm. Hardness, $HB, \text{kgf/mm}^2$, ASTM E 10:2018 $(90 \div 120) \pm 10.$

Note: Minimum weight of test object is 5 kg.

6. Calculations
According BGN EN 1706 for Al + 3.5% Mg alloy, the average value $\sigma_{YS} \text{MPa} \approx 70$ is accept.

The results of calculations and reference values, are presented in Table 1. and Table 2.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>According Tetelman 1971 year</th>
<th>According Andreykiv 1982 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(K_v/\sigma_{YS})_{\text{CALC}}$</td>
<td>$\approx 2.95$</td>
<td>$\approx 5$</td>
</tr>
<tr>
<td>NDE $\text{Err}%$</td>
<td>$\approx 7$</td>
<td>$\approx 4$</td>
</tr>
</tbody>
</table>

The results of calculations are need correction by

$$\left(\frac{K^A}{\sigma_{YS}}\right)^2 = \frac{\left(\frac{K_{\text{CALC}}}{\sigma_{YS}}\right)^2}{\overline{D}}$$

and $K_v \approx \frac{1}{3} K_{\text{CALC}}$. This coefficient takes into account the difference in dimensions of the quantities participating at calculated of the values.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>[Wikipedia 2,3,4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(K_v/\sigma_{YS})_{\text{CALC}}$</td>
<td>$3.1 \div 3.3$</td>
</tr>
<tr>
<td>$K_v, \text{MPa.m}^{1/2}$</td>
<td>$30 \div 33$</td>
</tr>
</tbody>
</table>

Table 1. Devices for NDE

5.1.1. Leeb hardness tester M – 295, WILCON, Germany. 
5.1.2. Ultrasonic flaw detector, SONATEST, England.
5.1.3. Digital micrometer DIGIMATIC, Mitutoyo, Japan.

Table 2. NDE of constants

5.2.1. Velocity, $(V_L; V_T) \text{mm/µs}$, ASTM E 494:2015 $(6.36 \pm 0.030) : (3.15 \pm 0.015)$.

Note: Minimum weight of test object is 5 kg.

5.2.2. Hardness, $HB, \text{kgf/mm}^2$, ASTM E 10:2018 $(90 \div 120) \pm 10.$

Note: Minimum weight of test object is 5 kg.
7. Example

One of important applications of the conception for crack resistance $K_c$ is the condition for fracture [1,3]. The head of a diesel engine (aluminium alloy) with semi-elliptical crack between the cylinders, fig.3, is considered.

Fig.3. Semi-elliptical crack between cylinders in the diesel engine

The diesel engine does not break if provided [1,5]

$K_c(\sigma, t, c/a; t) \leq K_c(E; \psi; \psi; HB),$

where $\sigma$ - stress; $t$ - depth of the semi-elliptical crack; $c$ - length of elliptical crack, fig.4, by means lens (10X optical zoom) with measuring scale is determined.

$K_c(\sigma, t, c/a; t) = M_c(\sigma_c, t, c/a; t)$

where correction factor $M_c$ by means Table 4, is obtained.

B/ If $a \leq 0.3t$, then $E_2(a/c) = (0.9 - 1.1) E_2(a/c)$.

After carry out the necessary transformations of (9), for the computing depth of crack $a_{CALC}$ the inequality is obtain

$K_c = K_{c}(\sigma, t, c/a; t) \leq K_{c}(E; \psi; \psi; HB)$

where $c_{VT} = c_{VT}$, results are obtained.

The non-linear equation (12) by bisection method, algorithm ZEROSIN [11] and on-line compiler for C++ is solved.

Making a decision for the acceptability of the crack depth - $a_{ACC}$ is according $a_{ACC} \leq a_{CALC}$. Therefore the condition for $a_{ACC}$ is

$X = D_{VT}/c_{VT}$

where $X$ and $c_{VT}$ respectively by means solution of (12) and method VT are obtain.

8. Conclusion

This article describes the NDE of crack resistance by means ultrasonic velocities and hardness. The calculated of value $K_{c}(\sigma, t, c/a; t)$, is simply, but does not produce a good result. The calculate the value $K_{c}(\sigma, t, c/a; t)$ gives a better result as it takes more information about the material.

The follow NDE are used:

$D = D(V_L; V_T; HB)$ is NDE of $D$.

$\sigma_{YS} = \sigma_{YS}(V_L; V_T; HB)$ - yield stress by Hall-Petch’s relationship is NDE.

$E(\psi) = \psi(V_L; V_T)$ - regression, with coefficient of determination $R^2 = 99.8\%$.

$K_{c} = K_{c}(\sigma, t, c/a; t)$ is NDE of crack resistance. The errors of NDE for $K_{c}^A/\sigma_{YS}$ is ~ 5 % and NDE for $K_{c}^A$ is ~ 4 %.

Used norms

BGN EN 1706:2010, Aluminium and aluminium alloys - Castings - Chemical composition and mechanical properties (Bulgaria)

GOST (Russian GN) 25.506-85, Design, calculation and strength testing. Methods of mechanical testing of metals. Determination of fracture toughness characteristics under the static loading (Russia).
9. References

5. Siratori M., T.Meysi, H.Micusyta, Computational fracture mechanics, MIR, Moscow, 1986./in Russian/.
10. Markovtiv, M.P, Non-samples methods for determining the mechanical properties of metals, MPEI, Moscow, 1983. /in Russian/.


**Keywords:** THERMOSYPHON, GEYSER BOILING, NANOFLUID, GRAPHENE, HEAT PIPE, BOILING REGIME

**Abstract:** Two-phase closed thermosyphons are efficient passive devices with potential for using in many heat transfer applications. One of the boiling regimes that may occur is the geyser boiling. It is a repetitive irregular process of pushing liquid without its previous evaporation in the direction of condenser. Although it does not affect time-averaged thermal performance of the device, it causes additional mechanical load and shortens the life-time of the device. Unfortunately, geysering is not well investigated, thus no precise definition exists. This paper focuses on the process of data reduction that leads to geyser boiling detection. It may be applied for various working fluids and operating conditions. Two parameters are crucial for recognizing geyser events from the background noise (pressure variations followed by the geyser): the minimum amplitude of pressure increase and waiting period between ensuing events. We compared two working fluids: water and graphene oxide nanofluid. In general, with increase of heat flux the frequency of geysers increases and their amplitude decreases.

1. Introduction

Two-phase closed thermosyphons show great potential for efficiency improvement in many applications covering energy transport. Operation principle is based on the evaporation-condensation closed cycle of working fluid. The energy from external source of heat is applied to the lowest part of the pipe - evaporator. Working fluid evaporates and the vapor goes up through the adiabatic section. It condenses in the upper part (condenser) as a result of contact with colder walls. Heat is released to the surrounding environment (cooling medium, e.g. water) and condensate returns to the evaporator relying on gravity. It imposes location of the evaporator below the condenser.

For some working conditions, the nucleate pool boiling in the evaporator may be turned into pseudo-stable boiling regime, called geyser boiling. It occurs mostly under low pressure conditions, for high filling ratios, and during start-ups. Figure 1 schematically showcases such a process.

![Scheme of geyser boiling phenomena](http://creativecommons.org/licenses/by/4.0)

During geyser event vapor bubble that grew to the size of pipe diameter, (a) superheat between the evaporator wall and working fluid in the evaporator increases, (b) nucleation of the bubble and its quick growth to the size of pipe diameter, (c) bubble expansion and propulsion of the fluid trapped above the bubble, (d) and downfall return of the displaced liquid. Reprinted from [1] under the terms of the CC BY 4.0 (http://creativecommons.org/licenses/by/4.0/).

Experiments were conducted using copper thermosyphon with the dimensions shown in Fig. 2. Tested device is divided into three parts: evaporator heated by circulating water, adiabatic section and condenser cooled by another coil filled with water. The whole device was insulated with Armaflex shell. Inlet temperatures of heating medium controlled by thermostat varied between 40°C and 85°C in 5°C steps. The inlet temperature of cooling water was 25 ± 0.14°C for each test case presented here. Volume flow rates of both cycles were set on 12 l/h and measured with magneto-inductive flow meters. The inlet and outlet temperatures of heating and cooling water were determined by Pt100 – elements with the maximum uncertainty of ± 0.32°C. The pressure inside the device was characterized by three pressure transmitters with an accuracy of ± 0.25% located along the thermosyphon and two parallel gauges with different measurement range at the top of the device. For each combination of operation conditions, all parameters were recorded for an hour after reaching a steady-state condition. Detailed characterization of the device is described in [1].
Deionized water and graphene oxide nanofluid were used as working fluids. Graphene oxide flakes (GO) were prepared at Institute of Electronics Materials Technology in Warsaw, in Poland through modified Hummers method [1]. The concentration of flakes was 0.1 g/L and no additional stabilizer was added [1].

3. Results

Time-averaged data

One of the fundamental parameters showing the efficiency of heat transfer in the thermosyphon is its thermal resistance. It is defined as the ratio of average temperature difference between evaporator and condenser section and the amount of heat released in the condenser [1]. Figure 3 showcases the difference between the thermal resistance when device is filled with water and graphene oxide nanofluid. Arrows indicates the result obtained for the same operating condition (inlet temperature of cooling and heating water). For low temperatures of the evaporator and small differences between evaporator and condenser, nanofluid allows not only for lowering the thermal resistance but also transfers higher amount of energy in form of heat. It makes it interesting for application with specific requirements, such as heat recovery, geothermal or HVAC systems. Although for high heat fluxes (and high temperatures of the evaporator) the time-averaged data suggests that working fluid does not affect the thermal performance of the device, in this region different processes of boiling occurs, including geysering.

Time-dependent data

Precisely characterized definition of geyser boiling does not exist in the literature. The phenomenon is rather understood as explosive and irregular boiling process. It leads to difficulties with data analysis to determine whether the pressure increase may be counted as geyser event. One of typical pressure patterns describing such a phenomenon is shown in Fig. 4. All the figures presented in this section are based on the pressure signal p3, pressure transmitter closest to the boiling pool. It was located in the adiabatic section, 500 mm from the bottom of the device and 100 mm above the evaporator section.

Geyser event is characterized by abrupt and prominent increase in pressure. The increment in pressure signal is detected by subsequent transmitters, starting from the lowest one (p3, see insert of Fig. 4). Depending on working fluid and operation conditions, the speed of pushed working fluid calculated from the time difference of peak detected by subsequent transmitters is about 3-10 m/s. After the return of expelled liquid to the evaporator, the period of nucleate boiling starts and long-lasting pressure drop occurs.

To automatize detection of geyser events, two parameters must be defined: the minimum amplitude of pressure increase and the minimum waiting period between following geyser events. The first one – the lowest pressure difference between the current and time-averaged values - protects from counting the noise following from liquid eruption or intensive nucleate boiling. As various working fluids behave differently depending on operating conditions, it is impossible to set one threshold value for all cases. Thus, we propose to use the probability density. We assumed that all pressure values that describe geysering are likely to be outside the range of $-2\sigma$ to $2\sigma$ (standard deviation) from the pressure averaged over the experiment time at given conditions. Then, every peak exceeding the threshold line given by $2\sigma$ value (see mph value in Fig. 6) with rising trend is further examined as potential geyser event.

The second crucial parameter is waiting period ($mpd$) determining the minimum time step between consecutive geyser events. It protects against calculating the noise following from violent abruption of liquid and its return due to gravity forces. The determination of minimum time step starts with an analysis of the waiting period effect on the final results. The example for water at high temperatures of evaporator is presented in Fig. 5. We choose the value on the constant line after bending the curve. The last step is to check if events marked by described script [3] overlaps the ones seen with the naked eye.
Fig 4. Example of geyser pattern for water (inlet temperature of heating water: 75°C). The insert presents the same event but in different time-scale.

Fig 5. Analysis of waiting period (minimum time step between two successive geyser events) depending on working conditions. c25 indicates the temperature of condenser (25°C), e65-85 indicates the inlet temperature of heating medium in the evaporator (65-85°C).

The importance of properly chosen waiting period is presented in Fig 6 and 7. Two time steps are compared: 0.1s and 2s (mpd of 5 and 100, respectively). Figures covers the same operating conditions (inlet temperature of heating medium: 75°C, of cooling medium: 25°C). For both working fluids, noises following from geyser event are marked in the case of mpd 5. At waiting period of 2s some peaks are missed for water case, e.g. the small event before the highest peak in the upper plot of Fig. 6. According to analysis shown in Fig. 5, time step for water at given conditions should be between 1-1.5 sec. For GO nanofluid, this waiting period seems to be properly selected – all big peaks are included in calculations and increases coming from unsteady state following the real geysers are eliminated.

Fig 6. Geyser events (peaks) for water at evaporator temperature of 75°C included in calculations for different waiting periods (mpd)

The amplitude and waiting period differ significantly between individual events for water pattern (see Fig. 6). Weaker peaks following the main event may occur. In case of GO nanofluid (see Fig. 7), pressure peaks show almost constant value of 1.3-1.4. They occur less often and pretend to be more ordered. The nucleate boiling period following the liquid throw seems to be rather short and not intensive. Sporadically, additional weak event appears but opposed to water it is not preceded by a pressure drop.
The frequency and amplitude of detected geysers events differs depending on working fluid and operation conditions. In general, increase in the evaporator temperature leads to increase in the time-averaged frequency (see: Fig. 8). This trend follows previous conducted experimental research [4]–[7].

At the same time, the mean amplitude of detected events (Fig. 9) decreases with evaporator temperature increment. It may be deduced that boiling becomes more violent but less impetuous with evaporator temperature increase. The effect of heat flux on the geysers amplitude was analyzed only in two papers, from which Khazaee et al. [6] showed the same trend as in this paper and Casarosa et al. [4] did not notice any difference.

4. Conclusions

The paper presents the analysis of time-averaged and time-dependent behavior of two working fluids: water and water-based graphene oxide nanofluid. To the best authors knowledge, no strict definition of geyser boiling exist in the literature. That is why the methodology of data reduction is proposed. As a result, the time-averaged frequency of geysers events occurrence and their amplitude are calculated and compared. In general, with the evaporator temperature increase, frequency of geysers increases but their amplitude decreases. It suggests that for higher heat fluxes the boiling process becomes more violent but less impetuous.

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References

**GRADIENT STRUCTURE AND METHODS FOR THEIR PREPARATION**

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**Abstract.** The development of new technological methods of SPD for the production of mass production with improved properties due to the deep grinding of the original structure is an important task. The purpose of this work was to study the active bending to grind the structure and create promising, for operational use, gradient structural states in long rods of copper grade M1. Active bending was performed using an extruder according to the “Conform” scheme. The results of the analysis stress-strain state is using computer simulation and structures using optical microscopy. It is established that the active bending method provides over four processing cycles high strain accumulation (\(e = 3-4\)) and formation subgrained-structure UFG type.

**KEYWORDS:** METAL PROCESSING BY PRESSURE, SEVERE PLASTIC DEFORMATION, FINITE ELEMENT METHOD.

**1. Introduction**

In the modern world, the need for new materials is increasing, as well as for the improvement of their physical and mechanical properties. In this regard, there is an increasing need for the creation of promising industrial methods allowing to achieve improved properties in the material. The most effective methods are SPD [1,2]. However, their development is hampered by low manufacturability of the proposed technical solutions, especially for the production of mass products. In this regard, the paper considers the method of active bending, based on the use and advantages of the “Conform” scheme [3-5]. Its main advantage is the improvement of the tribological situation in the process of the formation of ultrafine-grained (UFG) gradient structures providing products with increased wear resistance and ductility at high strength indices [6,7]. The object of the study was a long rod of technically pure copper.

**2. Concept of process**

Principal diagram of active bending used in research is presented in Figure 1. The proposed development is based on the well-known ECAP. “Conform” scheme, while in the deformation process, the workpiece 3 is pushed into the stationary bending matrix consisting of two elements of the matrix 1,2 due to active friction forces of the drive roll with engraving 4. The method makes it possible to combine the high-performance “Conform” process with bending deformation, which leads to a considerable intensification of the hardening process of especially the near-surface layers of the deformable material due to the formation of the structure. Active friction forces ensure continuity of the process.

For the simulation, program Deform 3D was used, intended for the analysis of three-dimensional (3D) metal behavior in the processes of pressure treatment. This made it possible to obtain important information about the nature of the material flow in the forming tool, the stress-strain state and the temperature distribution in the deformation process.

When modeling the bend according to the “Conform” scheme at angle of 90 degrees, a square section blank of 10x10 mm in length and more than 150 mm in length was used for the first deformation cycle, the bending radius was 10 mm. For the subsequent cycles, a samples obtained by modeling on the previous cycle was used in order to obtain generalized data after passing through four samples processing cycles.

**3. Results and discussion**

The conducted virtual experiment and its analysis showed that in the process of processing on the surface of the workpiece during bending at angle of 90 degrees, maximum values of the strain intensity are observed. So after one cycle in the upper part of the workpiece, the accumulated strain intensity reached \(e = 1.04\), and in the lower \(e = 0.88\) and increased proportionally with the number of sample passes through the deforming channel (see Fig. 4).
Plastic deformation by the proposed method leads to formulations that allow one to obtain a gradient of properties in a deformable material. So, with a subsequent analysis of the accumulated strain in the process of bending an angle of 90°, it can be seen that with an increase in the number of bends, the accumulated strain also increases. So after four cycles of deformation processing, the accumulated deformation is \( e = 2.8 \ldots 3.5 \) for an angle of 90°, with the maximum value of accumulated deformation observed in the near-surface region of the deformable sample, and lower values in the middle area.

The results of laboratory studies for obtaining experimental samples and structural studies are presented in Figure 5. It has been established that a finer grain-subgrain-type structure is formed in the surface layers.

4. Conclusion

It is established that when using the method of active bending in a deformable copper sample, a gradient of a grain-subgrain structure of the UFG range is formed. Using virtual simulation, it is shown that the method of bending according to the “Conform” scheme provides, after 4 processing cycles, the level of accumulated deformation \( e = 2.8 \) in the middle region and \( e = 3.5 \) in the near-surface region of the cross section of the sample.

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5. References

SURFACE HARDENING OF METALLIC MATERIALS BY USE OF COMBINED MAT-FORMING TREATMENT AND ELECTROSPARK DOPING

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Abstract: Analysis of the structural state and phase composition of surface metal layers after combined treatment of steel which includes preliminary surface plastic deformation of the workpiece, electrospark doping with use of rotating disk electrode 2 mm thick, made of WC-Co hard alloy and subsequent surface ball smooth rolling, has been performed. It was shown that the use of combined treatment provides a gradient-layered structure with low surface roughness. Phase composition of the obtained layer consist of ferritic α-Fe phase and a number of carbide phases formed during the interaction of the electrode material with steel: Fe₃C, WC and W₁_C semi-carbide. Wear resistance of the material after treatment exceeds similar properties of the original carbon steel up to 4 times.

Keywords: ELECTROSPARK DOPING, SURFACE PLASTIC TREATMENT, MICROSTRUCTURE, HARDNESS, WEAR RESISTANCE.

1. Introduction

The improving and raise of competitiveness of engineering products require the use of new technological processes, allowing to increase the service life and reliability of equipment in the conditions of increasingly stringent requirements for the operational characteristics of products. A promising way for the improvement of the bearing capacity of structural materials is to strengthen their surface layers or to deposit strengthening coatings, that increase the surface strength and wear resistance as, and as a consequence, the operational lifetime of the construction and tool materials.

Various methods have been developed to enhance wear resistance of parts of friction units. Each of the currently known methods has its merits and deficiencies limiting its scope. The most common ways to restore the worn surfaces of metal parts at the present time are various types of gas-thermal coating and welding deposition. However, during welding deposition, a large amount of heat is supplied to the part, which leads to skellering and the need for subsequent processing.

Recently electrospark doping (ESD) is becoming more common for obtaining the coatings with high wear resistance of the metallic materials.

The spark discharge occurs only in local volume in microscopically small volumes during 100–400 microseconds, when in the local metal-coating contact zone the high-temperature plasma regions appear, which provides the necessary adhesion of the formed coating to the base material. Very high densities of energy flows are realized in this process without the noticeable heating of the specimen under treatment. The process is characterized by an essential inequilibrium, so it is impossible to obtain fundamentally new materials in the surface layers of the coatings, which is impossible under the usual equilibrium conditions [1, 2].

The method of electrospark doping differs from other surface treatment methods in its simplicity, reliability, and cost-effectiveness. Depending on the anode material, an extended surface layer with high strength, tribological, and other properties is formed on the work piece [3, 4]. For the instantation of the ESD processes the devices containing manual or mechanical end electrode vibrators and generators of electrical voltage pulses of a certain shape and duration that are applied to the spark gap (between the electrode and the surface of the workpiece) [5] have found the greatest distribution.

However the ESD methods have some disadvantages as follows: high surface roughness of the treated surface of a workpiece, the presence of cracks, discontinuities and micropores. Besides, such devices have low productivity - up to 3 cm²/min.

To reduce the roughness introduced by the electrospark doping, the methods based on the mechanical impact on the modified surface are used (surface-plastic strain, running the ball, nonabrasive ultrasonic treatment, etc.), as well as treatment with concentrated energy flows (plasma flow, electron and ion beams, laser beams) [6-9].

Significantly higher performance and surface condition are provided by mechanized devices with a rotating disk electrode, which is pressed against the material of the workpiece with a small controlled force [10].

An effective type of surface treatment of metallic materials is also surface plastic deformation [6, 7]. As a result of its application, due to work hardening in the surface layers, the shape and size of crystal grains are modified, accompanied by changes in the substructure and microstructure of the metal of the surface layer. The hardness of materials increases and compressive stresses are formed, contributing to increased wear resistance and resistance to fatigue failure.

Therefore the aim of the present paper is to specify the effect of combined surface treatment on structure and properties of the surface layer of carbon steel subjected to mat-forming plastic processing and electrospark doping.

2. Experimental Procedure

For realization of complex processing of the axially symmetrical bodysurface, a device was developed and made (fig. 1) on the basis of turning-screw-cutting machine, allowing to combine preliminary surface plastic deformation of the workpiece and mechanized ESD process with rotating disk electrode 2 mm thick, made of WC-Co hard alloy installed in a special water-cooled unit, attached to the tool holder.

The design for the surface plastic deformation device (fig. 2) includes a main deformation tool fixed in the carriages - a ball 3 with ∅10 mm hardened to 62-65 HRC, which in the process of operation leans on the bearing 4. The force of pressing the ball 3 to the treated surface at processing is changed by changing the force of the spring 2 compression by the adjusting screw 1. The surface treatment of the experimental samples was carried out according to the scheme: plastic surface treatment with a ball - electrospark doping - surface treatment of the applied coating.

The microstructure of the alloys was studied on the XJL-17 optical microscope. X-ray phase analysis of the samples was carried out on DRON-3 diffractometer in filtered Co-Kα radiation using step-by-step scanning in the angular range of 20-130°. The microhardness distribution over the sample section was determined on a PMT-3 microhardness meter.

To assess the comparative wear resistance of the obtained coatings, friction tests were carried out according to the “shaft-insert body” scheme with contact force of 400 N using a M-22M friction machine while cooling a friction couple with water.
Fig. 1. Three-dimensional scheme of the device for the formation of combined wear-resistant coating: 1 - device for ESD; 2 - unit for surface plastic deformation; 3 - carriage of the turning-screw-cutting machine; 4 - machined part; 5 - center.

Fig. 2. The scheme of the unit for surface plastic deformation: 1 - adjusting screw; 2 - spring; 3 - ball; 4 - bearing.

3. Experimental results and their discussion

As our preliminary studies had shown [10], the optimum pressing force of the ball to the treated surface of ductile steels is 2.0÷3.5 kN. The increase in pressure leads to a violation of the integrity of the metal on the surface and the emergence of the peeling of the surface. At the same time, the hardness of the parts when rolling should not exceed 50 HRC.

The results of investigations of microhardness and material structure distribution over the depth of the sample (fig. 3, 4) showed that it can be conditionally divided into three zones. The base material I of Y7 carbon steel, has a ferritic-pearlitic structure (fig. 4, a, c) with an initial hardness of HV 220÷240.

Intermediate transition layer II (fig. 4), that was formed during the primary surface plastic processing of the specimen, is located at a depth of 100÷250 μm from the surface. It differs in monotonically decreasing hardness from the surface over the layer thickness (from HV 650 to HV 250) (fig. 3) and is of distinctly more fine-grained structure compared to the base metal (fig. 4, c).

The upper layer III of maximum hardness (HV 650-1040) with a depth up to 100 μm (fig. 3, fig. 4, a, b) is formed as a result of the interaction of electrode material (ВК8 hard alloy) with surface material of the sample being processed during the electrospark doping.

The layer resulting from the electrospark treatment is characterized by an extremely highly dispersed cellular substructure. According to the X-ray structure analysis and electron microscopy, cited in [1, 11, 12], the dimensional parameters that characterize the coating cellular substructure that was formed in the ESD process is of range within 20-200 nm, that provides entirely new physicomaterial properties of the materials. The separate micropores with size of up to 2 μm are observed in the coating structure too.

It is noteworthy that after the electrospark doping with the rotating electrode and the subsequent surface plastic processing of the coating obtained, the surface is characterized by sufficiently high continuity and low surface roughness, while the electrospark coatings obtained with use of devices with end electrode vibrators are usually characterized by high surface roughness of the treated surface [1, 5].

Fig. 3. Distribution of microhardness throughout the depth of the coating.

Fig. 4. The microstructure of steel surface subjected to combined superficial plastic processing and electrospark doping: I – carbon steel base material; II – intermediate transition layer; III – the layer of electrospark coating.
The results of X-ray spectral analysis of the initial material and the layers subjected to various types of processing (surface plastic deformation, ESD) showed that, in the initial state, Y7 steel contains α-Fe and cementite Fe₃C phases (fig. 5, a). The value of the bcc lattice parameter of α-Fe is \( a = 0.28664 \) nm. The diffraction lines of the matrix α-Fe phase are narrow, which indicates a low concentration of lattice defects (fig. 5a).

X-ray diffraction lines of α-phase from the intermediate layer, obtained after surface plastic deformation, are significantly diffused (fig. 5, b). In particular, the magnitude of the physical broadening of the α-Fe diffraction line increases to the level of \( \beta_{220} \approx 21 \times 10^{-3} \) rad, whereas for steel in the initial state, the value of \( \beta_{220} \approx 2.5 \times 10^{-3} \) rad. Such increase in the value of physical broadening is associated with an increase in the concentration of lattice defects (dislocations, vacancies, etc.) in the α phase in the process of intense surface plastic deformation. The fact that the ratio \( \beta_{220}/\beta_{110} \approx \tan \theta_{220}/\tan \theta_{110} \) testifies in favor of this conclusion too.

Besides, the value of the crystal lattice parameter of α-Fe significantly increases after surface plastic processing in comparison with non-deformed steel and reaches values of 0.28679 nm. The authors of [1, 11, 13] consider that such an increase in α-Fe crystal lattice parameter can be caused by deformation-induced dissolution of cementite particles Fe₃C in the process of steel intense plastic deformation when it is rolled.

The analysis of phase composition of the samples upper layer after electrospark doping showed, that in addition to ferritic α-Fe phase, it contains a number of phases formed during the interaction of the electrode material with steel. The predominant compound is \( W_3C \) carbide with a cubic lattice, WC semi-carbide and possibly high-temperature \( \beta-W_2C \) carbide are fixed (fig. 5, c). The lattice parameter of the α-Fe phase increased in the alloying process from 0.28654 nm of the initial steel to 0.28689 nm for the coating surface.

The broadening of the X-ray \( \beta_{220} \) line profile of the surface layer treated with ESD reaches \( 36.14 \times 10^{-3} \) rad, which indicates the formation of a substructure in the alloyed steel surface. The ratio \( \beta_{220}/\beta_{110} \) is close to the ratio of the tangents of the angles \( \tan \theta_{220}/\tan \theta_{110} \), which is caused by a significant deformation of the α-Fe phase crystal lattice. Since the composition of electrodes for electrospark doping includes Co, that can form an unlimited solid solution with iron, and also taking into account the rather high solubility in tungsten iron (up to 30%) at liquidus temperatures, it can be assumed that the increase in α-Fe phase lattice parameter after ESA is conditioned by dissolution of the electrode components in Fe.

Comparative assessment of the wear resistance of the original Y7 steel and the material of the samples subjected to complex surface treatment including surface plastic deformation, ESD followed by rolling of the applied layer with a ball showed (fig. 6) that the wear of the original steel after the path of 25 km exceeds the wear of samples subjected to surface treatment for ~4 times, and the amount of wear obtained on the original steel after the path of 50 km (450 mg) is achieved on samples subjected to processing only after 200 km.

**Fig. 5.** Fragments of X-ray diffractograms from the internal (a), intermediate (b) and surface (c) layers of the specimens

**Fig. 6.** Dependence of mass wear for the samples from Y7 steel (HV 220 ... 240): 1 – samples without surface treatment; 2 – samples subjected to complex surface treatment
4. Conclusions

1. It is shown that the use of combined treatment of steel surface, including surface plastic deformation processing, electrospark doping and additional smooth rolling of the applied coating with a steel roller, provides a gradient-layered structure with entirely new physicomechanical properties and low surface roughness.

2. Based on the X-ray analysis of the surface obtained after the electrospark treatment, it has been established that the phase composition of the layer in addition to the ferritic $\alpha$-Fe phase contains a number of carbide phases formed during the interaction of the electrode material with steel: $\text{Fe}_3\text{W}_2\text{C}$, WC and $\text{W}_2\text{C}$ semi-carbide. The lattice parameter of the $\alpha$-Fe phase increased during the doping process from 0.28654 nm for the initial steel to 0.28689 nm of the coating surface, which may be caused by electrode components dissolution in Fe.

3. The efficiency of complex surface treatment of steel is shown, which provides surface layers, the wear resistance of which exceeds similar properties of the original carbon steel up to 4 times.

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Influence of the Synthesis Method on the Crystalline Structure, Phase Composition and Properties of TiCrFeNiCuC Equiatomic Alloys

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Abstract: Equiatomic alloys TiCrFeNiCuC were made by two methods of powder metallurgy – vacuum sintering and hot forging followed by annealing. In the process of sintering the TiCrFeNiCuC blanks, the influence of entropy of mixing resulted in the formation of solid substitution solutions mainly on the basis of the FCC lattice, and also formed titanium carbide (TiC$_{0.74}$). In samples obtained by hot forging and subsequent annealing, two carbides TiC and Cr$_7$C$_3$ were found, and titanium carbide being formed with lower carbon content (TiC$_{0.58}$). In addition, the forged samples showed significantly higher values of the defect of the crystalline structure, which leads to increase in their hardness.

Keywords: EQUIATOMIC ALLOYS, MICROSTRUCTURE, PHASE COMPOSITION, HARDNESS, SINTERING, HOT FORGING.

1. Introduction

In the field of creating new classes of materials with increased physical, mechanical and operational properties, the approaches based on the development of high entropy alloys (HEAs) are the most promising.

A characteristic feature of such alloys is the content in their composition of not less than 5 basic elements, mainly in the equiatomic ratio. The presence of a large (not less than five) number of heterogeneous, but in an equal number of atoms, having different individual properties, imposes its specificity on the formation of a solid solution of high entropy alloys. The high entropy of mixing causes the minimization of the free Gibbs energy, which leads to the preferential formation of solid solutions with a BCC, FCC or FCC + BCC structure. The phases formed on the basis of solid solutions are more stable [1-3]. Alloys with such structures have high hardness, strength, wear resistance, oxidation resistance, etc. These properties of high entropy alloys are due to the slow diffusion of atoms in a multicompontent matrix, a significant distortion of the lattice, which arises in connection with the difference in the atomic dimensions of the constituent elements of the alloy, as well as the interaction between elements in phases based on a solid solution [4-9]. When giving carbon in the alloys, high entropy carbides will form.

To obtain HEAs the most widely used were various casting technologies [1-6]. However, in recent years, the methods of powder metallurgy are gaining increasing popularity in the development and production of these alloys [7-10].

The purpose of the work is to study the influence of the manufacturing method on the crystalline structure, phase composition and properties of the TiCrFeNiCuC equiatomic alloys.

2. Experimental Procedure

The initial Ti, Cr, Ni, Cu, Fe, and C powders with the purity of 99.5 - 99.9% were used as the starting elements for the preparation of the equiatomic alloys of the Ti-Cr-Fe-Ni-Cu-C system. Alloys were produced by two methods of powder metallurgy – vacuum sintering and hot forging with subsequent annealing.

The starting powders were dosed on an electronic scales. The charge of the equiatomic composition was prepared by mixing the powders in a drum mixer with a diagonal axis for 2 hours with the addition of alcohol. From the obtained mixture, cylindrical billets with a diameter of 20 and 40 mm at a pressure of 700 MPa were extruded in a steel matrix. Consolidation of powder blanks by hot forging was carried out on a Dougostat press at a temperature of 1050 °C in argon. Sintering of the samples and annealing of the forged samples were carried out in a vacuum induction furnace at 1200 °C for 2 hours.

X-ray diffraction studies were carried out on a DRON-3 X-ray diffractometer in filtered Co radiation by a step-scan method in the angular range 2θ = 130°. A quantitative micro-X-ray spectral analysis was performed on a CAMECA MS-46 X-ray microprobe at a probe mode of 20 kV, 12 nA and a probe diameter of 3 μm. The microstructure of the alloys was studied with an XJL-17 optical microscope and with a JEOL Superprobe 733 scanning electron microscope. The density and porosity of the alloys were determined by hydrostatic weighing. The microhardness was measured on a PMT-3 device. The hardness was measured on a TK-14-250 hardness tester. The theoretical density of the alloy, calculated from the additivity formula, is equal to 6.55 g/cm$^3$.

3. Experimental results and their discussion

X-ray diffraction studies of high entropy TiCrFeNiCuC alloys, obtained by different methods, revealed features both in the phase composition and in the detectiveness of their crystal unit cell. Regardless of the method of preparation, alloys had a heterogeneous structure. On the X-ray diffraction pattern of the alloy obtained after sintering at 1200 °C for two hours, a number of lines characterizing the phase with a FCC lattice are fixed, as well as TiC carbide. On the lines with the indices of the atomic planes (311) and (222), we can assume the presence of two phases with FCC lattices with close values of the crystal lattice parameter (Fig. 1, a). The phase with the BCC structure is fixed weakly.

Fig. 1. XRD patterns of TiCrFeNiCuC alloys, obtained by vacuum sintering (a) and hot forging with subsequent annealing (b)

On the X-ray diffraction pattern of the sintered alloy, the diffraction maxima (111) and (222) were divided into two components (Fig. 2). The calculated crystal lattice parameters for both FCC phases are: $a = 0.36098$ nm and $a = 0.35877$ nm. It is known that nickel and copper are systems with unrestricted solubility based on the structural type of FCC. It should be assumed that one phase of FCC with $a = 0.36098$ nm is formed with a high nickel content (0.36176 nm), another phase $a = 0.35877$ nm – with a high nickel content (0.35195 nm). An analysis of the structural state of phases with a FCC structure indicates that both...
phases of the FCC have a number of imperfections in their crystal lattice and a difference in the quantitative ratio of their defectiveness, characterized by the values of the parameters of the fine structure elements. Thus, for FCC with a high copper content with \( a = 0.30988 \text{ nm} \), the defectiveness of the crystal structure is denoted by the following parameters: coherent scattering region (CSR) = 36.2 \text{ nm}, microdistortion \( \Delta a/a = 54.6 \times 10^{-3} \), dislocation density \( \rho = 8.2 \times 10^{11} \text{ cm}^{-2} \). For a FCC structure with a high nickel content \( a = 0.35877 \text{ nm} \). Data on the imperfections of the FCC alloy structure is much higher in comparison with the analogous results for the phase with the predominant copper content and are denoted by the following parameters: CSR = 10.0 \text{ nm}, \( \Delta a/a = 77.2 \times 10^{-3} \), \( \rho = 17.3 \times 10^{11} \text{ cm}^{-2} \). The FCC phase, which is formed with the predominant content of the more ductile element of copper, naturally has a less distorted crystal lattice in comparison with the FCC lattice with a harder nickel base. This conclusion is confirmed by microhardness measurements: a FCC structure with a crystal lattice parameter equal to \( a = 0.36098 \text{ nm} \) has a microhardness of 4.9 GPa, a structure with a crystal lattice parameter equal to \( a = 0.35877 \text{ nm} \) has a microhardness of 6.8 GPa.

Along with solid solutions of the FCC type in the highly entropic TiCrFeNiCuC alloy obtained by sintering at 1200 °C for two hours, titanium carbide with a crystal lattice parameter of 0.43215 \text{ nm} is formed. According to the dependence of the TiC cell parameter on the amount of carbon bound in it [12] in the sintered alloy, there is a TiC phase with an atomic ratio of carbon to titanium of 0.74 (TiC_{0.74}).

The formation of phases in highly entropic alloys, the appearance of two or three phases is associated with a certain electronic concentration in the alloy, with the difference in the atomic radii of the components that make up the alloy. Hot forging is a significant influence on the formation of the crystal structure of high entropy alloys. Hot forging of porous blanks can be considered one of the cycles of thermomechanical processing, during which a developed substructure is created. This developed substructure is the primary factor determining all other structural causes of thermomechanical hardening of steel. [11].

X-ray diffraction studies of the alloy TiCrFeNiCuC, obtained by hot forging and subsequent high-temperature annealing, indicate the formation of a heterophasic structure of the alloy. The X-ray spectrum of the alloy is represented by phases of FCC, BCC, TiC and Cr_{2}C_{3} carbides (Fig. 1 b). Analysis of the X-ray spectrum of the alloy revealed the following features. Estimating the nature of the profiles of the X-ray lines of the FCC structure, several blurred profiles should be noted that describe the phase with the FCC grating, which is especially noticeable at large reflection angles. Thus, for a FCC lattice along lines with indices of atomic planes (311) and (222), it is possible to assume the presence of two phases with FCC lattices with close parameters. This is confirmed by calculations on the lines (222): \( a_1 = 0.36460 \text{ nm} \) and \( a_2 = 0.35815 \). On the XRD pattern of the forging alloy, the diffraction maxima (111) and (222) were decomposed into two components (Fig. 3).

One of the phases with the parameter \( a_1 = 0.36046 \text{ nm} \) \( a_2 = 0.35815 \) copper i.e. with a high copper content, another phase of FCC with \( a_2 = 0.35815 \text{ nm} \) is closer to the nickel parameter, i.e. with a high content of nickel. An analysis of the structural state of phases with a FCC structure indicates that both phases of the FCC have a number of imperfections in their crystal lattice and a difference in the quantitative ratio of their defectiveness, characterized by the values of the parameters of the fine structure elements. Thus, for the FCC lattice with a high copper content \( a = 0.36098 \text{ nm} \), the defectiveness of the crystal structure is denoted by the following parameters: CSR = 5.2 \text{ nm}, microdistortion \( \Delta a/a = 90.4 \times 10^{-3} \), dislocation density \( \rho = 22.6 \times 10^{11} \text{ cm}^{-2} \). For a FCC structure with a high nickel content \( a = 0.35815 \text{ nm} \). Data on distortion of the lattice of the FCC structure of the alloy is much higher in comparison with the analogous results for the phase with the predominant content of copper and are denoted by the following parameters: \( \Delta a/a = 119.8 \times 10^{-3} \), \( \rho = 42.0 \times 10^{11} \text{ cm}^{-2} \). There is no grain fragmentation in the coherent scattering region (CSR = 112.3 \text{ nm}, i.e. commensurate with the grain size), the structural defect is due to the distortion of the crystal lattice. The FCC phase, which is formed with the predominant
content of the more ductile element of copper, naturally has a less distorted crystal lattice in comparison with the FCC lattice with a harder nickel base. This conclusion is confirmed by microhardness measurements: a FCC structure with a crystal lattice parameter \( a = 0.36098 \) nm has a microhardness of 5.5 GPa, a structure with a lattice parameter \( a = 0.35877 \) nm has a microhardness of 7.3 GPa.

The most intense line (110) of the structure with a BCC lattice on the x-ray spectrum of the sample is indicated by a line of weak intensity, which indicates a small amount in the sample alloy. In addition to line (110), we can consider the line (211) belonging to the BCC structure as a weak diffuse reflex. Line (220) is almost overlapped with the background. The diffuse character of the BCC reflections is due to the distortion of the crystal lattice, which is confirmed by the quantitative characteristics of the line structure elements. So the value of the regions of coherent scattering is 50.0 nm (probably somewhat overestimated as a result of overlapping of the part of the profile from the side of the small angle by the line of the FCC lattice (110)), microdistortions equal to 175.87 \( \times 10^{-3} \), the dislocation density is \( p = 62.0 \times 10^{11} \text{ cm}^{-2} \). The results on the distortion of the crystal lattice of the BCC phase are the largest for all the emerging highly entropic phases. The phase with the BCC structure is formed upon mutual dissolution of iron and chromium, has the parameter \( a_{\text{BCC}} = 0.2858 \) nm, has so small a grain that it was impossible to measure the microhardness.

It was pointed out that on the XRD pattern of the alloy, in addition to a series of phase lines of FCC and BCC structures, a number of reflections belonging to TiC and Cr7C3 carbides. The TiC lattice parameter is 0.4311 nm, hence, the TiC phase is present in the alloy with an atomic carbon to titanium ratio of 0.58. However, in the sintered alloy, the atomic ratio of carbon to titanium is 0.74.

The microstructure of the sintered and forged alloys consists mainly of two structural regions. According to micro-X-ray spectral analysis, the light phase has an increased content of Cu, Fe, and Cr. The darker phase is the result of the maximum interdiffusion of all elements of the alloy and has an increased concentration of Ni, Ti and C. Consequently, the dark phase contains TiC. In the forged alloy, a much greater dispersion of the structural elements is observed compared to the sintered alloy, as well as the presence of two carbides – TiC and Cr7C3, which is explained by the influence of hot forging.

![Fig. 4. Microstructures of sintered (a) and forged (b) equiatomic TiCrFeNiCuC alloys](image)

Analysis of the processes of structure formation of high entropy phases formed in alloys of TiCrFeNiCuC composition, inclusions of various compounds showed a significant increase in the defectiveness of crystal structures and, accordingly, an increase in the microhardness of both individual structural components and hardness of the alloy as a whole, using preliminary hot forging of porous blanks. In the sintered alloy, the hardness is 30 HRC, in the alloy with the preliminary hot forging, the hardness increased to 42 HRC (Table 1).

<table>
<thead>
<tr>
<th>№</th>
<th>Production method</th>
<th>Density, g/cm³</th>
<th>Porosity, %</th>
<th>Hardness, HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sintering</td>
<td>6.28</td>
<td>4.0</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>Hot forging and annealing</td>
<td>6.40</td>
<td>2.2</td>
<td>42</td>
</tr>
</tbody>
</table>

3. Conclusions

Thus, preliminary hot forging during the formation of a high entropy alloy intensifies the processes of structure formation, causes redistribution of carbon (with the formation of chromium carbide Cr72, titanium carbide TiC is formed with a smaller carbon content in TiC to 0.58), and also provides processes that lead to significant distortion of the crystalline lattice of the forming phases, which contributes to the strength of the alloys.

References

FATIGUE ANALYSIS APPROACHES FOR VEHICLE COMPONENTS MADE OF RUBBER

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Abstract: Generally, the most frequently used structural materials are metals which have high strength and stiffness. However, there are many cases, when other important properties come to the fore as well as high deformation by elastic behavior, high viscosity namely good damping effect. Vehicle components made of rubber usually exhibit large deformations. One of the most important properties of rubber is the ability to withstand large strains without permanent fractures. This feature makes it ideal for many engineering applications. On the other hand, the task becomes more complicated because of some features of rubber parts. The temperature of rubber increases significantly after deformations. Material properties of rubber change after these above mentioned temperature changes. Thus it is necessary to understand the mechanics underlying the failure process. This paper summarizes the applied equations and the basic physical laws which are responsible for the theoretical background of the strain and temperature changes and the analysis approaches that are available for predicting fatigue life in rubber, especially in vehicle components made of rubber.

Keywords: RUBBER, HIGH DEFORMATIONS, THERMODYNAMICS, FATIGUE ANALYSIS

1. Introduction
Rubber can be classified as a so-called hyperelastic polymer which has a typical geometrical and material nonlinear behavior. It means that the relationship between displacements and internal forces can be described by functions whose order is higher than linear. The geometrical nonlinearity is easy to handle mathematically, however the material nonlinearity is only described approximately [1], [2]. Independently of the experimental investigations which deal with the material behavior of rubber, a number of theoretical works treated rubber as an ideally nonlinear elastic, in particular hyperelastic material. One of the properties of the constitutive equations of hyper-elastic material is that stresses are derived from stored elastic energy function. Hyper-elasticity can be described by particularly convenient constitutive equation given its simplicity and it constitutes the basis for more complex material models such as elastoplasticity, viscoplasticity, and viscoelasticity [3,4,5,6].

Furthermore, the task becomes more complicated because of some features of rubber parts. The temperature of rubber increases significantly. Therefore, the temperature- and displacement fields are coupled, and it means that special solving algorithms are required [7]. So the equations of mechanics and thermodynamics are coupled. As described above, the goals of this paper are the following:

It is necessary to summarize the applied equations and the basic physical laws which are responsible for the theoretical background [8,9]. Clarification of these relationships is essential because the material laws of rubber cannot violate those basic physical laws. It is necessary to extend these relationships like balance of linear momentum and balance of angular momentum, the first and second law of thermodynamics to high deformation of rubber and rubberlike polymers. An algorithm will be presented which allows to calculate strain changes and temperature changes of the rubber part of a vehicle component under certain conditions. The present numerical algorithm is the basis of the further fatigue and lifetime-calculations. After this, it will follow the literature survey which is responsible for predicting fatigue life.

2. Governing equations
2.1 Equilibrium of linear momentum
The differential formulation of the equilibrium of linear momentum in the current configuration is
\[ \rho \ddot{\mathbf{v}} = \mathbf{\sigma} : \nabla \mathbf{v} + \mathbf{f} \]
(1)
where \( \rho \) is the mass density, \( \mathbf{v} \) is the velocity, \( \mathbf{\sigma} \) is the Cauchy stress, \( \mathbf{f} \) is the volume force.

2.2 Equilibrium of angular momentum
The next equality shows the differential form of the balance of the moments.
\[ \mathbf{\sigma} = \alpha \mathbf{\omega} \]
(2)

2.3 First law of thermodynamics
When deformations repeatedly occur, significant increase in temperature can be observed. The differential form of the first law of thermodynamics is in the current configuration
\[ \dot{e}_{\rho} = -\nabla \cdot \mathbf{q} + h + \mathbf{f} \cdot \mathbf{V}^T \]
(3)
where \( \dot{e}_{\rho} \) is the internal energy per unit mass, \( \mathbf{q} \) is the heat flux, \( h \) is the heat source, \( 
\mathbf{V} \)
is the velocity gradient, \( I_1 = \mathbf{F}^T \mathbf{F} \), \( I_2 = \mathbf{\tau} \cdot \nabla \mathbf{\tau} \).

2.4 Second law of thermodynamics
The behaviour of viscoelastic materials is described by the second law of thermodynamics. The second law of thermodynamics in the current configuration can be written as
\[ \eta \mathbf{T} \rho \geq -\nabla \cdot \mathbf{q} + \frac{1}{\rho} \mathbf{V}^T + h \]
(4)
where \( \eta \) is the entropy per unit mass and \( T \) is the absolute temperature. It will be practical to change the variable from entropy per unit mass to temperature by applying the Legendre-transformation and by using the Helmholtz-free energy
\[ \psi = e - \eta T \]
(5)
Substitute the Eqn. (5) into the Eqn. (3) and subtract Eqn. (3) from Eqn. (4) the following expression will be generated
\[ -\left( \psi + \eta T \right) + \alpha \cdot \mathbf{V}^T - \frac{1}{\rho} \mathbf{V} \]
(6)
which is known as Clausius-Duhem inequality [2].

2.4 Constitutive model
The property of an elastic element is that the total mechanical energy is reversible. The free energy of the body is the function of the strain and temperature. Dissipation comes only from heat conduction.

In order to make the further calculations easier it is necessary to split the Eq. (5) to temperature-dependent and temperature-independent parts. Based on known functions \( \psi_e(\mathbf{C}) \) and \( \epsilon_s(\mathbf{C}) \) for the free energy and the internal energy at a given reference temperature and the given heat capacity at a reference temperature, one obtains the following general structure for the thermoelastic free energy from the Eq. (5):
where $\mathbf{C}$ is the right Cauchy-Green strain tensor [2]. In the following section we are going to investigate the isotropic materials and we are going to apply the Neo-Hookean material law. It means that which is used in free energy depends on the scalar invariant of the right Cauchy-Green strain tensor. The internal energy is zero applying the entropic theory and the heat capacity is constant with good approximation.

2.5 Equation of heat conduction

Starting from the first law of thermodynamics and introducing the internal energy and changing the variable from entropy to temperature, the equation will have the next form:

$$\rho_0 c_T \frac{\partial \psi}{\partial T} = \frac{1}{2} \frac{\partial}{\partial T} \left( \frac{\partial \psi}{\partial \mathbf{C}} \right) + \rho_0 c_T \frac{\partial \psi}{\partial \mathbf{C}} \cdot \mathbf{C}^T - q_0 \nabla \cdot \mathbf{h} + h_0$$

(8)

where $\left( \frac{\partial}{\partial T} \right) \psi \frac{\partial}{\partial \mathbf{C}}$ is the non-recoverable part of the mechanical power, which is zero in the case of a pure elastic element [1], [2]. In this case the rheological model is regarded to be a pure elastic element. So the free energy of the body is characterized by the deformation and temperature. Furthermore, we are assuming that there are not heat sources in the rubber and the temperature field shows homogeneous distribution. Thus, the equation of the heat conduction is the following:

$$c_T = T \frac{\partial \psi}{\partial T} \mathbf{C}$$

(9)

2.6 Example

Let us consider the mechanical model of a silent block, thus the A, B, C axisymmetric bodies (see Fig.2). The A and C bodies are rigid bodies, and B is a deformable one. Regarding the structure of the silent block it consists of two metal elements whose are connected by the rubber which is vulcanized between them. The inside rubber part provides a non-linear elastic connection between the two metal elements in the following way: it transfers loads however filters out the harmful vibrations, i.e. it has damping effect. All three bodies are axisymmetric and their symmetry axes are the same.

The external body (A) is fixed and the internal one is imposed by a given rotation.

Further assumptions:

3. Literature survey: types of fatigue analysis approaches of rubber

The facility of rubber is the resistance finite strains without permanent deformation makes it ideal for engineering applications e.g. vehicle components made of rubber, as can be seen in the first figure. These loading cases impose large static and time-varying strains over a long period. The fatigue failure analysis have two distinct sections. The first section is a time during which cracks nucleate in regions. The second section is a time during nucleated cracks grow to the point of failure. Two further models for predicting fatigue life in rubber have to be considered. One theory occupies with the predicting crack nucleation life, given the history of quantities like stress and strain in the current configuration. The other theory derives from fracture mechanics, focuses on prediction of the growth of each cracks. Some of the information described in this paper has been reviewed previously [10-15]. Another paper summarizes factors that influence the fatigue life of rubber [16]. These factors are the effects of the mechanical loading history, environmental effects, rubber formulation, and effects due to dissipative aspects of the constitutive response of rubber.

3.1 Models for predicting crack nucleation life

Let us consider fatigue crack nucleation life which is defined as the number of cycles required to cause the appearance of a crack or cracks. The first study of this was Wöhler’s work in the 1860’s [17]. The maximum principal strain and the strain energy density...
are the two widely used fatigue life parameters for crack nucleation approach in rubber. Strain can be directly determined from displacements, which can be measured in rubber. The strain energy density can be estimated from a hyperelastic strain energy density function, which can be defined in terms of strains. The alternating and mean values of maximal principal strain predict nucleation life.

The earliest fatigue studies in rubber occupied with the developing of the description of the number of cycles to failure as a function of strain. Cadwell et al. [18] considered unfilled rubber and investigated minimum engineering strains and strain amplitudes in a determined range. They stated that, for constant strain amplitude, the fatigue life of rubber improves with extending minimum strain, up to a high strain level, and the additional minimum strain decreased the life. Generally, in the case of strain crystallized rubbers, by increasing the minimum strain of the strain cycle can significantly elongate the fatigue life.

The strain energy density is the second most important parameter which can be used for prediction of fatigue crack initiation. The energy release rate is proportional to the product of strain energy density in certain conditions and the crack size [19, 20]. Several paper can be mentioned in which researchers investigated strain energy density as a fatigue life parameter in rubber. According to the research of Roberts and Benzies [21], and Roach [22], the equibiaxial tension fatigue life of natural rubber is longer than simple tension fatigue life, in the case of using equal strain energy density. Furthermore, Roach gave the best correlation between simple and equibiaxial tension fatigue data, i.e. Roach proposed – in the case simple tension – that all of the strain energy density is available for flaw growth.

3.2 Models by using crack growth approach

The pre-existing cracks or flaws are in the focus of the crack growth approaches. The two main bases of this type of approach are the works which were published by Inglis and later Griffith [23]. Griffith offered a fracture criterion based on energy balance including both the mechanical energy of a cracked body, and the energy associated with the crack surfaces. This approach was further developed by for the case of rubber by Thomas, Lake, Mullins, Lindley and Rivlin. The original application of this approach in the case of rubber was predict to static strength, and later Thomas extended it to the analysis of the growth of the cracks under cyclic loadings in natural rubber. Thomas discovered a square-law context between energy release rate and crack growth rate in the case of unfilled natural rubber. According to Griffith’s hypothesis the crack growth is due to the conversion of the stored potential energy to surface energy is in connection with new crack surfaces. He presented that the surface energy associated with the crack faces of a broken glass cane was equal to the elastic energy caused by the fracture. The potential energy (in rubber) released from surrounding material is spent on both reversible and irreversible changes to create the new surfaces. The energy release rate is simply the change in the stored mechanical energy $\partial u$, per unit change in crack surface area $\partial A$. This quantity is often called tearing energy $T$ in rubber literature.

$$ T = \frac{\partial u}{\partial A} $$

The energy release rate was first applied to the analysis of rubber specimens under static loading, and the above mentioned concept also applied to crack growth under cyclic loading. The experience was that the maximum energy release rate achieved during a cycle determined the crack growth rate, for $R=0$ cycles [24].

4. Summary

An algorithm was presented which allows to calculate strain changes and temperature changes of the rubber part of a vehicle component under certain conditions. In the future I would like to develop a solving computer program in order to apply it as a thermodynamically consistent description. The present numerical algorithm is the basis of the further fatigue and lifetime calculations. The literature survey will be used to create the connection with the calculations.

5. Acknowledgement

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References


Abstract: Nowadays, only a small percentage of waste tires are being landfilled in Albania. The large environmental impact has made the government to support some companies for building up the recycling industry of the waste tire in Albania. The Recycled Tire Rubber have been used in many fields such as agricultural uses, sport applications, civil engineering, rubber modified asphalt applications etc. Therefore, different parts of the world have used rubber modified asphalts where the benefits were being more widely experienced and recognized. Based on it, our paper will be focused on the asphalt mixtures produced with Recycled Tire Rubber Modified Bitumen’s (RTR-MBs). Our proposal can reduce environmental impact from the waste tires and improving the quality of the road constructions in Albania.

Keywords: RTR-MBs, ROAD CONSTRUCTIONS, ASPHALT APPLICATION, WASTE TIRES, ENVIRONMENTAL IMPACT.

1. Introduction

In recent decades, the worldwide growth of the automobile industry and the increasing use of vehicles as the main means of transport have tremendously boosted tire production [1]. This has generated massive stockpiles of used tires [1, 2]. Extensive research works were carried out on how to use used tires in different applications [2]. Furthermore, some of the fields are linked with agricultural uses, sport applications, civil engineering, rubber modified asphalt applications which have used Recycled Tire Rubber.

The increasing use of vehicles and traffic intensity on the roads has pushed Albanian government to speed up the quality policies on the road constructions and to reduce the environmental impact caused from the waste tires. The quality of the road constructions and the large environmental impact has made also the government to support some companies for improving the paving industry and building up the recycling industry through the waste tires. The use of rubber is of interest to the paving industry because of the additional elasticity imparted to the binder and enhanced safety related to improved roadway skid resistance [3].

Tire recycling is one of the most important processes in the industry [4-6]. The Fig. 1 depicts the technologies of the possible waste tire treatment routes.

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastomers</td>
<td>47</td>
</tr>
<tr>
<td>Carbons</td>
<td>21.5</td>
</tr>
<tr>
<td>Metals</td>
<td>16.5</td>
</tr>
<tr>
<td>Textile fibers</td>
<td>5.5</td>
</tr>
<tr>
<td>Zn-oxide</td>
<td>1</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1</td>
</tr>
<tr>
<td>Additive</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Through tire recycling process we can eliminate metal materials and fibrous with textile nature from inside the rubbers. Afterward, particle size of the rubbers would influence in the performance of the rubber modified asphalt. Non-regular sizes of the rubbers having a specific area of greater than regular size were more likely to react with bitumen at high temperature through wet process asphalt forming. In our research work, the wet process asphalt forming has been used to produce rubber modified asphalts, see Fig. 2.

The quantity of the Recycled Tire Rubber (RTR) in the mixture of the asphalt was 10%. Particles size of the rubbers varied from 0.85 mm to 2.36 mm and 1 mm to 4 mm. The modification of this material is carried out to reinforce the bitumen properties through the physical-chemical coupling between bitumen and rubber at high temperatures.
3. Summary Results

Addition of elastomeric rubber to the asphaltic bond, regardless of the method used for obtaining the final product, makes it possible to reinforce the properties of the asphalts which are as follows. The Fig. 3 depicts the comparisons of the crack levels during the years.

![Fig. 3 Comparisons of the cracks level during the years.](image)

The results have shown that the cracks level during the years were more lower in rubber modified asphalt than conventional asphalt. Another important analysis is focused on the comparisons of the penetration values between rubber modified asphalt and conventional asphalt, see Fig. 4.

![Fig. 4 Penetration value for rubber modified asphalt and conventional asphalt](image)

The results have shown that penetration value is lower for rubber modified asphalt in comparisons of the conventional asphalt.

4. Conclusions

The importance of the usage of Recycled Tire Rubber Modified Bitumens for improving the quality of properties of this material has been briefly described. This proposal have shown that rubber modified asphalts will reduce environmental impact by using recycling process and improve the quality of the road constructions in Albania. Further studies should be done to investigate long term performance of field test sections under various traffic conditions.

5. Acknowledgment

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6. References


SURFACE TREATMENTS AND COATINGS APPLICATION ON THE ALUMINUM PRODUCTS

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Abstract: The aim of this work is to present the influence of anodic surface treatment parameters on thickness and structure of an anodic layer formed on aluminum products.

The materials used in this study are the aluminum products from Alumil Company in Albania. The analyses of samples were performed using Optical Microscopy (Leica DMI 5000 M) for characterization of macrostructure of anodizing layer and Vickers micro-hardness (HMV-2 tester) of non-anodized aluminum products and anodized aluminum products. Aluminum product of the series A6060 are taken in Alumil Company in Albania. Comparing the results in this research (analyses) we have concluded the characteristics of anodizing layer in the aluminum product, which have improved and increase their surface and product performance.

Keywords: ALUMINUM ALLOY, MICRO-HV, OM, ANODAZING, MICROSTRUCTURE

1. Introduction

Surface treatments and coatings are applied to aluminum products to enhance their performance. In order to improve surface properties of final products, such as wear resistance, corrosion resistance - different types of surface treatments are applied. [1,2]

Anodizing is one the best technique for protective and decorative purposes is the most common method of superficial oxidation processes and is carried out through anodic oxidation. [1,2]

The usability of aluminum after anodizing depends mainly on the properties of oxide layers occurred during this process. [1,2]

Table one presents the chemical composition of A6060 [4]:

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6060</td>
<td>0.44</td>
<td>0.33</td>
<td>0.029</td>
<td>0.039</td>
<td>0.43</td>
<td>0.0095</td>
<td>0.053</td>
<td>0.016</td>
</tr>
</tbody>
</table>

Evaluation of the thickness of the oxide layer was carried out in the transverse section of the anodized profile, after polishing. Observations for thickness estimation of the oxide layer were performed on the 500x and 1000x metallographic microscope as well as the micro-hardness (Vickers) 400x magnification. [1,2,5]

The metallographic preparation of the samples and measurement are performed in Materials Science and Technology Laboratory, in Mechanical Engineering Faculty in Tirana-Albania. [1,2]

We focused the experimental part of our work on estimating the thickness of the anodized layer and its hardness. Performing Optical Microscopy using Leica DMI 5000 M software for characterization of macrostructure of anodizing layer and performing micro-hardness Vickers (HMV-2 tester) on aluminum products with anodizing treatment on the surface and also aluminum products without treatment. [1,2]

2. Discussion and Conclusions

- The A6060 products were coating with a layer anodizing and the level of strengthening was followed up and measured by micro-hardness test with 10gf, force applied for 10 sec in one indenter;
- The thickness of the anodized layer depends on the maintaining time in the anodizing bath;
- The A6060 products were coating with a layer anodizing and the level of strengthening was followed up and measured by micro-hardness test with 10gf, force applied for 10 sec in one indenter;
- In figure 1 it is shown the microstructure of sample from an aluminum profile products, taken from metallographic microscopy;
- The anodizing surface of aluminum products Based on the micro-hardness measurement results have higher hardness compared with the simple aluminum products without treatments in the surface;
- The micro - hardness of layer anodizing it is in the range between 420 – 560 HV comparing with the results of aluminum samples without treatments in the range between 55 – 70 HV.

Graph. 1. The results of micro-HV comparing the homogeneity of surface treatments
- Evaluation of micro-hardness of the oxide layer with thickness ~11microns determined with metallographic microscope by Leica Soft – provides the anodizing efficiency by increasing the hardness 8 times more versus aluminum products without treatments or coating on their surface.

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ИДЕНТИФИКАЦИЯ ПОЛИМЕРНОГО МАТЕРИАЛА TEKRONE

IDENTIFICATION OF TEKRONE POLYMER MATERIAL

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Abstract: Authentication of polymeric material of TEKRONE, that is used for making of dumps of ploughs, is conducted. Analogues are certain - superhigh molecular polymers PE- 500 and PE- 1000. Experimental standards are made. Their capacity is well-proven.

KEYWORDS: COMPOSITE MATERIALS,..

1. Вступление

В соответствии с принципами, разработанными Европейской комиссией по ключевым технологиям (European Commission Key Enabling Technologies) создание новых материалов являются приоритетными задачами.

Сельскохозяйственное машиностроение сегодня интенсивно внедряет инновационные решения. Машины и механизмы, которые используются для обработки почвы, оснащаются деталями и узлами из полимеров и полимерно-композитных материалов (ПКМ) на их основе, что позволяет существенно повысить надежность и долговечность машины, а также на сервис снизить затраты на сервис снизить стоимость одного отвала "TEKRONE" плуга ПЛН-3-35 составляет до 930 € [5].

2. Постановка проблемы

Несколько лет назад в Украине появились отвалы плугов из ПКМ марки "TEKRONE" (рис.1). Такие изделия являются надежными и долговечными деталями, которые при соответствующей эксплуатации могут работать и в полном объеме выполнить свои функции в течение длительного периода [4, 5]. Однако, этот материал производится в Европе и на их основе, что позволяет существенно повысить надежность и долговечность машины, а также на сервис снизить стоимость одного отвала "TEKRONE" плуга ПЛН-3-35 составляет до 930 € [5].

4. Решение рассматриваемой задачи

Результаты исследований показали, что ПКМ марки "TEKRONE" - это материал на основе термопластичного полимера с содержанием черного пигмента 0,5 ... 0,7 % масс. Кроме того, установлены свойства этого материала (табл. 1) близки к свойствам сверхвысокомолекулярных полизитиленов РЕ-500 и РЕ-1000. Из данных, приведенных в табл. 1 можно сделать вывод о том, что материалы на основе РЕ-500 и РЕ-1000 по своим свойствам соответствуют ПКМ марки "TEKRONE". Также установлено, что толщина отвалов составляет 12 мм, а это позволяет практичеески все агрегаты на 9%

Таблица 1 – Некоторые свойства исследуемых полимеров

<table>
<thead>
<tr>
<th>Марка полимера</th>
<th>Плотность, кг/м³</th>
<th>Предел текучести при сжатии, МПа</th>
<th>Термостойкость по Вика, °C</th>
<th>Ударная вязкость, кДж/м³</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEKRONE</td>
<td>954</td>
<td>17,9</td>
<td>95</td>
<td>44</td>
</tr>
<tr>
<td>РЕ 500</td>
<td>960</td>
<td>24</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>РЕ 1000</td>
<td>930</td>
<td>19</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

Рисунок 1 – Отвал лемешного плуга, изготовленный из полимера "TEKRONE"
Проводя анализ рынка по продаже данных материалов можно сделать вывод, что материалы PE-500 и PE-1000 до 2 раз дешевле, чем ПКМ марки "TEKRONE", поэтому изделия из них тоже могут быть либо дешевле, либо рентабельность производства выше. Следует отметить, что материал PE-500 на 20% дешевле, чем PE 1000 (90 евро против 119 за 1 лист). Таким образом, было принято решение изготовить опытную партию отвалов плугов лемешных.

Для изготовления экспериментальных отвалов были закуплены полимерные материалы PE-500 и PE-1000 в виде листового профиля, выпускающихся промышленностью Бельгии. Геометрические размеры 3000 × 1500 × 12 мм.

Стоимость листа PE-500 - 90 €; PE-1000 - 119 €.

Рационально разместить проекции отвалов плугов, укомплектованных обычными культурными отвалами, получили 16 отвалов и 12 полевых досок (рис. 2). При этом наименьшее расстояние между заготовками составило 5 мм.

Рисунок 2 – Схема размещения заготовок отвалов.

Лист разрезали на отдельные заготовки. В дальнейшем их нагревали до температуры 120 °C и изгибали. Охлаждали до наименьшего расстояния. Полученные таким образом опытные отвалы были установлены на плуг ПЛН-3-35, производства ООО «Велес Агро» (г. Одесса).

Рисунок 3 – Плуг, укомплектованный экспериментальными отвалами: а) конструкция позволяет регулировать угол наклона отвала; б) визуализация размещения отвалов по маркам.

Обычный агрофон - стерня ранних зерновых колосовых, глубина обработки - 25 ... 27 см. Экстремальный агрофон - стерня подсолнечника - глубина обработки - до 30 см. При эксплуатационно-технологической оценке определили:
- производительность за час сменного времени;
- удельный расход топлива;
- количество обслуживающего персонала;
- качество обработки.

Эксплуатация агрегата проходила в штатном режиме, рабочая скорость - 8 ... 9 км / ч. В качестве эксперимента на отдельных участках выполнялась вспашка на повышенных скоростях - до 10 ... 11 км / ч.

Экспериментальным агрегатом была выполнена вспашка на площади 63,8 га, на таких агрофонах:
- стерня ранних зерновых колосовых - 42,4 га, глубина обработки - 25 ... 27 см;
- стерня подсолнечника после дискования - 21,4 га - глубина обработки - 27 ... 30 см.

Кратковременно, периодически выполнялась экстремальная вспашка на глубину 31 ... 32 см (общая площадь такой пахоты - не более 0,03 га).

Грунты - черноземы обычные среднечерноземные, класс - 3. Относительная влажность на период первых испытаний составила 26%, что является оптимальным показателем.

Результаты. В течение всего периода испытаний отказов, отклонений от агротехники, других осложнений, вызванных экспериментальными изделиями, не было. После первых проходов было отмечено инертную реакцию композитных отвалов в почву - налипание или минимальное, или отсутствует. В процессе дальнейших испытаний исчезла необходимость очистки отвалов от налипания почвы и растительных остатков. Как следствие - оперативное время агрегата в работе возросло.

При этом качество вспашки улучшалось.

5. Заключение

1. После выполнения наработки 63,8 га визуальный осмотр и диагностика технического состояния отвалов плугов показали отсутствие видимых признаков их износа, все параметры находятся в номинальных пределах, экспериментальные отвалы пригодны к дальнейшей эксплуатации.

2. Уменьшено расход горючего не менее, чем на 2 л / га с одновременным увеличением производительности агрегата МТЗ-82.1 + ПЛН-3-35ПЕ на 36 %.

3. Комплекс проведенных научных исследований и полученных результатов свидетельствует о целесообразности использования разработанного продукта для изготовления отвалов лемешных плугов.

6. Литература


4. Филія АТ «Промаґроматура» «Агротехсервіс». [Електронний ресурс]. Режим доступа от 03.01.2019: http://www.agroservice.dp.ua/