THE EFFECT OF MICROSTRUCTURE OF COMMERCIALLY PURE COPPER ON TRIBOLOGICAL PROPERTIES

ВЛИЯНИЕ МИКРОСТРУКТУРЫ ТЕХНИЧЕСКИ ЧИСТОЙ МЕДИ НА ТРИБОЛОГИЧЕСКИЕ СВОЙСТВА

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Abstract: The paper reports the results of tribological investigations performed on commercially pure (CP) Cu in triboconjunction with the tool steel R18 and graphitiferous material. The investigated material was in two structural states: initial (annealed) state and state after severe plastic deformation (SPD) by equal-channel angular pressing (ECAP). As a result of the preliminary investigations it was established that in the whole investigated temperature range in case of grain size decrease there is a significant growth of normal stresses on the contact predetermined by the increase of strength of the investigated material (Cu) and a decrease of the full and adhesive component of friction coefficient. The lowest values of full friction coefficient and adhesive component of friction coefficient (strength of adhesive bonds) are demonstrated by material processed by ECAP. Consequently, the full friction coefficient, strength of adhesive bonds and the adhesive component of friction coefficient are structure sensitive parameters.

KEYWORDS: COMMERCIAL PURE COPPER, SEVERE PLASTIC DEFORMATION, EQUAL-CHANNEL ANGULAR PRESSING, MICROSTRUCTURE, FRICTION COEFFICIENT, ADHESIVE COMPONENT OF FRICTION COEFFICIENT.

1. Introduction

It is known that harder materials provide less wearing and friction coefficient [1]. For alloys in most cases there are various ways for increase of hardness by means of thermal treatment [2]. However for many pure metals and low-alloyed alloys thermal treatment with the view of hardness increase is inefficient. For such materials there are applied different ways of chemical-thermal [3] and surface plastic deformation [4], which allow increasing strength of the surface of processed materials. The drawback of such techniques is a relatively small depth of the strengthened surface layer that is why they can be applied only as finish treatment for relatively simple and low-loaded details of triboconjunctions.

There are known works on estimation of influence of structure condition on tribological properties of copper [5], and also of phase composition and microstructure of tool carbon steel on its tribological properties [6, 7]. In works, devoted to the studies of steels tribological studies were performed on materials with various ways of thermal treatment, which caused changes of microstructure and phase composition of the material.

As of today there is developed a technology of efficient and multiple increase of strength with retention of high technological ductility, based on the severe plastic deformation techniques (SPD), which allows producing high-strength bulk billets out of metallic materials [8]. One of the SPD techniques is equal channel angular pressing (ECAP) [9], effected in several deformation cycles. The essence of this technique of material strength increase is the maximum refinement of grain structure to submicrocrystalline and nano sizes [10].

SPD techniques allow considerably increasing the sphere of application of commercially pure and low-alloyed alloys. Therefore a great scientific and practical interest is attracted to complex comparative tribological studies of materials in various structure condition.

At present a great interest is given to complex studies of nanostructured copper and copper-based alloys [11]. One of the most promising spheres for innovation application of these materials is high-speed railways. Due to the increase of speeds of railway transport a big attention is given to studies of tribological parameters of a current collector with a contact wire [12].

2. Methods and materials of investigation

The object of investigations was commercially pure copper M1 in the annealed (coarse grained) and submicrocrystalline (SMC) conditions after 8 cycles of severe plastic deformation (SPD) by equal channel angular pressing (ECAP) at room temperature with rotation of the billet around the longitudinal axis by 90° after every cycle. The ECAP scheme [13, 14] is represented in fig. 1. The channel intersection angle made 90°.

For tribological studies there were used two schemes, represented in fig. 2. For calculation of the accumulated strain degree the following formula was used [13, 15]:

\[ \varepsilon = N \cdot \frac{2 \cdot \text{ctg} (\varphi / 2)}{\sqrt{3}} \]

where \( N \) – the number of cycles of deformation processing; \( \varphi \) – channel intersection angle.

For tribological studies there were used two schemes, represented in fig. 2.
The first scheme with reciprocal motion (fig. 2, a) was used for assessment of the friction coefficient in the couple “commercially pure copper – graphitiferous plate EK-40”. The testing conditions were the following: normal load \( P \) made 80 N, relative sliding speed – 0.1 m/s, time period of every test – 60 min. Normal load was chosen basing on the conditions of maximum force of holding of the contact wire to the graphitiferous current collector on a railway transport. The test speed regime was predetermined by the possibilities of the used tribometer. The time was set basing on the experience of performance of similar tests. The tests were performed at room temperature.

The second scheme (fig. 2, b) was used for assessment of shear strength of adhesion bonds and the molecular component of the friction coefficient in the contact couple “commercially pure copper – tool steel R18s”. With this view there were prepared disk-shaped samples with the diameter of 20 mm and a thickness of 5 mm out of commercially pure copper, and a spherical indenter with the sphere radius of 2.5 mm out of steel R18. The tests were performed at the temperatures of 20; 150; 250 and 450°C on a one-ball adhesion tester [16]. The basis of this technique was a physical model, which at a first approximation reflects the real conditions of friction on a local contact.

In accordance with this model, the spherical indenter 2 (imitating single asperity of the contact spot of the friction solid bodies), compressed by two plane-parallel samples 1 (with high precision and purity of contact surfaces) rotates under load around its own axis. The force \( F \), spent on the indenter rotation and applied to the cable 3, in the groove of the disk, is connected mainly with the shear strength \( \tau_s \) of adhesion bonds. With the view of application of this technique in conditions of increased temperatures of the contact there was developed and fabricated a special equipment, allowing performance of electrical contact heating of the contact zone (through conductor lines isolated by insulating spacers from the frame).

The initial roughness of contact surfaces of the tested samples and indenter in both testing schemes made 0.06 – 0.16 \( \mu \)m by the Ra scale. The roughness of copper samples was measured on a profilometer – profile recorder SE-3500K 2D-3D.

The shear strength of adhesion bonds \( \tau_s \) (MPa) was determined from the ratio:

\[
\tau_s = 0.75 \frac{M}{\pi \left( \frac{d_{1,2}}{2} \right)^2},
\]

where \( d_{1,2} \) – diameters of indents on the tested samples, \( mm \); \( M \) – moment at indenter rotation, \( N \ mm \).

The adhesion (molecular) component of the friction coefficient was determined as:

\[
f_M = \frac{\tau_s}{p_r},
\]

where \( p_r \) – normal pressure, MPa

\[
p_r = \frac{P}{\pi \left( \frac{d_{1,2}}{2} \right)^2}
\]

where \( P \) – compression force of samples, \( N \).

Prior to performance of tribological tests by the first scheme (fig. 2, a) and after them there were performed hardness measurements \( H\mu \) on the Micromet-5101 machine under the loading of 0.98 N with holding under the load for 15 s.

3. Investigation results and discussion

3.1. Investigation of structure and microhardness

As a result of the microstructure studies of copper samples in the annealed and deformed conditions (fig. 3) it was established that the average size of grains in the annealed commercially pure copper makes about 80 \( \mu \)m, and after 8 cycles of SPD by ECAP there is formed almost equiaxed SMC structure with the average grain size of 0.22 \( \mu \)m.

![a] and [b] - initial (annealed) structure of commercially pure copper in the as-received condition (average grain size 80 \( \mu \)m); b) – submicrocrystalline structure of commercially pure copper after SPD (TEM, average grain size 0.22 \( \mu \)m).

Microhardness measurements on samples with various microstructures before and after tribological tests are represented in table 1.

Table 1. Values of microhardness of the investigated material in the annealed and deformed conditions before and after tribological tests

<table>
<thead>
<tr>
<th>Material</th>
<th>Before test</th>
<th>After test</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (99.9% copper)</td>
<td>120.9</td>
<td>125.1</td>
</tr>
<tr>
<td>M1 (99.9% copper)</td>
<td>141.9</td>
<td>145.0</td>
</tr>
</tbody>
</table>

As it is seen from table 1, the deformed material has higher microhardness than the annealed one. Moreover, it was noted that after friction interaction the microhardness of the friction surface increases, though insignificantly, in both cases.

3.2. Tribological studies

3.2.1. Assessment of friction coefficient

The results of tribological tests by the first scheme (fig. 2, a) in the friction couple “commercially pure copper – graphitiferous plate EK-40” are represented in fig. 4.

![Graph of friction coefficient vs. sliding distance](image)

As it is seen in the represented graph, the friction coefficient values of the annealed samples (1), are higher than those of the samples with a SMC structure (2). Also it was noted that in samples with a coarse-grained structure the friction coefficient almost does not change during the whole testing period. The samples with a SMC
structure demonstrate a tendency for a slight decrease of friction coefficient. This fact can be explained by the increase of strength of the samples after deformation processing by means of grain structure refinement and the significant development of grain boundaries, which contributes to activation of grain boundaries and increase of diffusion interaction of copper with the carbon of the graphitiferous material. This assumption requires further investigation.

3.2.2. Assessment of shear strength of adhesive bonds and molecular component of the friction coefficient

On the basis of analysis of the obtained investigation results, represented in table 2, it was established that with the decrease of the grain size within the whole investigated temperature range there is observed a considerable growth of normal stresses on the contact, predetermined by the increase of strength of the investigated material (commercially pure copper), and also decrease of the adhesive component of the friction coefficient. The lowest values of shear strength of adhesive bonds and of the adhesive component of the friction coefficient $f_M$ is observed in the material with a SMC structure, subjected to SPD by ECAP technique.

Table 2.

<table>
<thead>
<tr>
<th>№</th>
<th>Material condition</th>
<th>Normal stresses on a contact, $p_r$, MPa</th>
<th>Adhesive component of the friction coefficient, $f_M$, Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cu (annealed)</td>
<td>1060 150 250 450</td>
<td>0,110 0,110 0,115 0,115</td>
</tr>
<tr>
<td>2</td>
<td>Cu (SMC)</td>
<td>1480 1360 1200 1140</td>
<td>0,085 0,085 0,090 0,090</td>
</tr>
</tbody>
</table>

4. Conclusion

There was established a dependence between the friction coefficient and the way of friction in the couple “graphitiferous material – tool steel R18” for a material in various structure conditions. From these dependencies it follows that tribological contact parameters are structurally sensitive characteristics. It was established that the investigated material with a SMC structure has lower values of both the friction coefficient and the molecular component.

6. References:


The performed studies prove the obtained earlier results [17]. In samples of commercially pure copper within the investigated temperature range the molecular component of the friction coefficient changes insignificantly in both structural conditions. In the annealed samples these values are slightly higher than in samples with a SMC structure. It follows that the strength of adhesive bonds and the adhesive component of the friction coefficient are structurally sensitive parameters. Table 2 represents results of tribological investigations of the commercially pure copper with various structure in contact with the tool steel R18.


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