

DEVELOPMENT OF THE THEORY AND PRODUCTION TECHNOLOGY OF MACHINE-BUILDING PARTS FROM POWDER MATERIALS

Full Prof. Dr. Eng. Ryabicheva L.

Department of Material Science – Volodymyr Dahl East Ukrainian National University, Lugansk, 91034, Ukraine

Abstract: The possibility of production of structural powder materials with given structure and physico-mechanical properties established. The modelling of stress-strain state at the secondary technological operations has performed on a basis of new regularities of plasticity theory of porous bodies. The deforming force was determined using the modelling results. The various production technologies have presented for manufacturing of different machine parts from powder materials that are including pressing of billet from the powder mixture, sintering, second compaction at different temperature and strain rate conditions, heat treatment.

Keywords: POWDER MATERIAL, STRUCTURE, PHYSICO-MECHANICAL PROPERTIES, PRESSING, SINTERING, SECOND COMPACTION, HEAT TREATMENT.

1. Introduction

Resource-saving technologies for manufacturing of products from powder materials are developing in two interrelated ways that allowing combination of fundamental research with production technologies of materials and products for industry. A computer simulation is an important component in fundamental research of structure and properties of materials resulting in prediction of new materials, development of processing methods for manufacturing of materials and products directed to improvement the products' quality without high expenses.

The powder metallurgy plays an important role in development of new materials for different purposes and allowing purposeful design the structure and properties of materials, production of details with minimal amount of wastes and solving of many environmental problems.

The functional powder materials with given physico-mechanical properties are among the most promising materials, which are determined by operating conditions of products. The required set of mechanical properties ensured by optimization the content of various components in the material for a given porosity value, which can be obtained by various types of processing. Creating of new multi-component powder materials with given properties, ensuring the high dimensional accuracy and surface quality of finished products is impossible without a detailed analysis of phenomena occurring during powders' compaction. It requires a comparative analysis of physical and mechanical properties of many similar materials with different contents of components and different porosity. The particle-in-cell method, boundary element method and finite element method (FEM) are widely used for solving of such problems.

The improved method of modelling physical and mechanical properties of multi-component powder materials by finite element method developed [1, 2]. The mathematical model is presented by system of governing equations characterizing physical and mechanical properties of components and allows with taking into account their interaction. The elastic-plastic model is applied to all components and tested for prediction of physico-mechanical properties of copper-nickel powder material of 10-30% porosity and nickel content of 10-30% in the compression tests. The density, Young's modulus, Poisson's ratio, yield strength and tensile strength were evaluated during mathematical experiment. The flow curves obtained using results of numerical simulation and compression tests are well concordant to each other. The relative error was not exceeded 10%.

One of the important problems of metal forming is studying the deformation and fracture processes. The problem of estimating the plasticity resource of metal at high-temperature loading have solved by mathematical modelling using a finite element method [3, 4]. The Lyapunov function has implemented for investigation of plastic equilibrium stability, which allows estimating the growth of stress

intensity after reaching a maximum degree of deformation in dangerous sections of detail.

2. Mathematical models

Powder materials have a more complex structure than compact metals. Their properties are formed both by a composition of components and under the influence of technological parameters of production and processing of material. Implementation of high-energy methods of their manufacture ensures the required level of mechanical and performance properties. The plasticity theory of porous bodies has further developed by accounting of rate sensitivity. The micromechanical and phenomenological models for plastic flow of porous bodies that are making possible estimation rate sensitivity of material parameters of porous body and rheological properties of hard phase were developed [5]. These models have applied to solving technological problems of manufacturing compact material from powder billet by compression into a mould and radial compressing in the matrix with smooth walls [6]. The concept for obtaining of high-density material at high strain rates and lower degrees of deformation established.

The scalar defining equations of plastic yielding with taking into account a strain rate sensitivity of porous medium have implemented for calculation of stress-strain state parameters of porous powder billets using the equation of loading surface [5]:

$$(1), \quad \frac{p^2}{1+\nu} + \frac{\tau^2}{3(1-2\nu)\phi} = (1-\theta)\sigma_0^2,$$

$$(2), \text{ the equivalent strain rate: } W = \frac{\partial \omega}{\partial t} = \frac{1}{\sqrt{1-\theta}} \sqrt{\phi \gamma^2 + \frac{1}{3} \phi \frac{1+\nu}{1-2\nu} \dot{\alpha}^2}.$$

In such conditions, porosity functions with taking into account the strain rate sensitivity may be written in the following way [6]:

$$(3), \quad \phi = \frac{(1-k_2\theta)^2}{1-(1+\frac{1}{3}k_1)\theta} (1-\theta), \quad \psi = \frac{1}{2} \frac{(1-\theta)(1-k_2\theta)^2}{k_1\theta};$$

$$(4), \text{ the plastic Poisson's ratio: } \nu = \frac{1}{2} \left(1 - k_1 \frac{\theta}{1-\theta} \right).$$

where p – is the hydrostatic pressure;

τ – is the intensity of shear stresses;

σ_0 – is the yielding stress of hard phase;

θ – is the porosity;

ϕ, ψ – are porosity functions that accounting a rate sensitivity;

k_1 – is the densification intensity coefficient;

k_2 – is the coefficient that describes the intensity of hardening process of hard phase;

γ, e – are shape and volume changing rate respectively;

ω – is the equivalent deformation of porous body.

Generally, at biaxial deformations the parameters in expressions (1-4) defined through components of stress tensor and strain rate tensor as follows [5]:

$$(5), \quad \gamma = \sqrt{\frac{2}{3}}|e_z - e_r|, \quad p = \frac{1}{3}(\sigma_z + 2\sigma_r), \quad \tau = \sqrt{\frac{2}{3}}|\sigma_r - \sigma_z|,$$

$$(6), \quad \text{thus for a cylindrical sample: } e_z = \frac{\dot{h}}{h}, \quad e_r = \frac{\dot{R}}{R}, \quad e = \frac{\dot{\theta}}{1-\theta},$$

where h and R - are current height and radius of cylindrical sample, respectively.

We are suppose, that deformation process happens in lack of exterior friction. It ensures homogeneity of density allocation and other properties of deformable porous body. The presence of rigid wall defined by expression: $e_r = 0$. According to [5], the plastic yielding has determined by equations, that coupling strain rates and stresses as follows [6]:

$$(7), \quad \sigma_{ij} = \phi \frac{\sigma_0}{W} \left(e_{ij} + \frac{\nu}{1-2\nu} \nu e \delta_{ij} \right), \quad e_{ij} = \frac{1}{\phi} \frac{W}{\sigma_0} \left(\sigma_{ij} - 3 \frac{\nu}{1+\nu} p \delta_{ij} \right)$$

At biaxial deformations, the equations (7) with taking into account (5) become [6]:

$$(8), \quad e_r = \frac{1}{3\nu(1-2\nu)} \frac{W}{\sigma_0} ((1-\nu)\sigma_r - \nu\sigma_z), \quad e_z = \frac{1}{3\nu(1-2\nu)} \frac{W}{\sigma_0} (\sigma_z - 2\nu\sigma_r),$$

$$(9), \quad \sigma_r = \frac{\phi}{1-2\nu} \frac{\sigma_0}{W} (e_r - \nu e_z), \quad \sigma_z = \frac{\phi}{1-2\nu} \frac{\sigma_0}{W} ((1-\nu)e_z - 2\nu e_r).$$

Solving the equations (1-4) together with (5) allows write expressions for determination of the yield stress for a hard phase σ_0 and for the equivalent strain rate W in the form:

$$(10), \quad \sigma_0 = \frac{1}{\sqrt{\phi(1-2\nu)}} \sqrt{\sigma_z^2 - 4\nu\sigma_r\sigma_z + 2(1-\nu)\sigma_r^2},$$

$$(11), \quad W = \sqrt{\frac{\phi}{1-2\nu}} \sqrt{(1-\nu)e_z^2 + 4\nu e_r e_z + 2e_r^2}.$$

The further problem is determination of pressure necessary to obtain the given density and dimensions of initial billet. In case of radial pressing $e_z = 0$, from expression (10) follows, that [5]:

$$(12), \quad \sigma_z = 2\nu\sigma_r.$$

Solving the set of equations (9) and (12) becomes to following expressions for axial σ_z and radial σ_r stresses [6]:

$$(13), \quad \sigma_z = -\sqrt{\phi} \frac{2}{\sqrt{3}} \frac{\nu}{\sqrt{1-2\nu}} \sigma_{0z}, \quad \sigma_r = -\sqrt{\phi} \frac{1}{\sqrt{3}} \frac{1}{\sqrt{1-2\nu}} \sigma_{0z},$$

or in variables ϕ and ψ [7]:

$$(14), \quad \sigma_z = -\frac{2}{\sqrt{3}} \frac{\psi - \frac{\phi}{3}}{\sqrt{2\psi + \frac{\phi}{3}}} \sigma_{0z}, \quad \sigma_r = -\frac{1}{\sqrt{3}} \sqrt{2\psi + \frac{\phi}{3}} \sigma_{0z}.$$

Expressed through the porosity and rate sensitivity parameters, these components have written as [6]:

$$(15), \quad \sigma_z = -\frac{1}{\sqrt{3}} \frac{(1-k_2\theta)(1-\theta-k_1\theta)}{\sqrt{k_1\theta\left(1-\theta-\frac{k_1\theta}{3}\right)}} \sigma_{0z},$$

$$(16), \quad \sigma_r = -\frac{1}{\sqrt{3}} \frac{(1-k_2\theta)(1-\theta)}{\sqrt{k_1\theta\left(1-\theta-\frac{k_1\theta}{3}\right)}} \sigma_{0z}.$$

We may determine a strain rate of hard phase by using the expression (11), where it is necessary to define $e_z = 0$ and having introduced porosity functions with accounting of rate sensitivity [5]:

$$(17), \quad W = \frac{(1-\theta)(1-k_2\theta)}{\sqrt{k_1\theta\left(1-\theta-\frac{k_1\theta}{3}\right)}} \sqrt{2}|e_r|.$$

The equation of accumulated deformation of hard phase may be written as [6]:

$$(18), \quad \omega = \frac{1}{\sqrt{2}} \int_{\theta_0}^{\theta} \frac{(1-k_2\theta)}{\sqrt{k_1\theta\left(1-\theta-\frac{k_1\theta}{3}\right)}} d\theta.$$

The solution of this integral is following to expression [6, 7]:

$$(19), \quad \omega = \frac{1}{\sqrt{2}} \left[\frac{\sqrt{3}\theta \left(A + \frac{(6+2k_1-3k_2)}{(3+k_1)^{3/2}} B \right)}{C} + \frac{\sqrt{3}\theta_0 \left(A_0 + \frac{(6+2k_1-3k_2)}{(3+k_1)^{3/2}} B_0 \right)}{C_0} \right].$$

In expression (19) it is necessary to define:

$$(20), \quad A = \frac{k_2\sqrt{\theta}((3+k_1)\theta-3)}{3+k_1}, \quad A_0 = \frac{k_2\sqrt{\theta_0}((3+k_1)\theta_0-3)}{3+k_1},$$

$$B = \sqrt{3-(3+k_1)\theta} \text{Arc sin} \left[\frac{\sqrt{3+k_1}\sqrt{\theta}}{\sqrt{3}} \right],$$

$$B_0 = \sqrt{3-(3+k_1)\theta_0} \text{Arc sin} \left[\frac{\sqrt{3+k_1}\sqrt{\theta_0}}{\sqrt{3}} \right],$$

$$C = \sqrt{-k_1\theta}((3+k_1)\theta-3), \quad C_0 = \sqrt{-k_1\theta_0}((3+k_1)\theta_0-3).$$

During radial compression in conditions of longitudinal strain limitation by rigid dies, the constraint equation of the initial and final dimensions with a porosity of billet exists [5, 7]:

$$(20), \quad S = S_0 \frac{(1-\theta)}{(1-\theta_0)} \frac{h}{h_0}.$$

Taking into account the law of porosity change as $\theta = \theta_0 e^{-k_1 e_z}$, the expression (19) is possible to write in the following way [6]:

$$(21), \quad S_0 = S \frac{\left(1 - \frac{\theta}{e^{-k_1 e_z}}\right) h_0}{(1-\theta) h}.$$

The compaction pressure in this case is σ_r , i.e. q_s related to the area of its application. However, it is necessary to take into account, that for densification and obtaining of necessary dimensions of porous billet, the following condition is necessary $\sigma_z > \sigma_r$, i.e. the response of rigid dies should exceed the applied pressure. Considering the law of hardening in the Ludwick's form [5] and expression (15) for side pressure gives:

$$(22), \quad q_s = -\frac{1}{\sqrt{3}} \frac{(1-k_2\theta)(1-\theta)}{\sqrt{k_1\theta\left(1-\theta-\frac{k_1\theta}{3}\right)}} (\sigma_{0r} + N\omega^n) S_s,$$

where S_s - is the pressure application area.

The elasto-plastic model of material has applied to all components. Strain intensities ε_i and strain rates $\dot{\varepsilon}_i$ inside each element defined through projections of nodal displacements onto the coordinate axes. Taking into account the thermo-mechanical coefficients, the Cowper and Symonds equation for stress intensity σ_i inside a finite element looks like [2]:

$$(23), \quad \sigma_i = \left[1 + \left(\frac{\dot{\varepsilon}_i}{C} \right)^p \right] (\sigma_0 + \beta E \varepsilon_i),$$

where σ_0 – is the initial yield stress of a component;

E – is the Young modulus;

$\beta = k_1 k_v k_\varepsilon$ – is the hardening coefficient of a component;

C, p – are arbitrary constants.

The values of σ, ε, E , Poisson's ratio ν and density ρ in a given area of a sample expressed as follows [2]:

$$(24), \quad \sigma = \frac{\sum_{j=1}^n \sigma_j}{n}, \quad \varepsilon = \frac{\sum_{j=1}^n \varepsilon_j}{n}, \quad E = \frac{\sigma}{\varepsilon}, \quad \nu = \frac{\varepsilon_{xy}}{\varepsilon_z}, \quad \rho = \frac{\sum_{j=1}^n \rho_j}{n \sum_{i=1}^m \delta_i}.$$

where n – is the number of finite elements in a given area;

ε_{xy} – is the radial deformation;

ε_z – is the axial deformation;

m – is the number of components in the material;

δ_i – is the volume fraction of each component.

The following exponential functions were implemented on the basis of experimental data for describing dependences of back pressure p_{bp} from extrusion pressure p and relation of dimensions of detail h/b (where h – is the depth of hollow into the detail, b – is the wall thickness) [8]:

$$(25), \quad p_{bp}(p) = A \exp(K_1 p), \quad p_{bp} \left(\frac{h}{b} \right) = A \exp \left(K_2 \frac{h}{b} \right),$$

where $K_1 = (0,01 - 0,1)\eta$ – is the stiffness coefficient of stress state;

$\eta = \frac{\sqrt[3]{\sigma_1 \sigma_2 \sigma_3}}{\sigma_i}$ – is the stiffness exponent of stress state;

$K_2 = \frac{\varepsilon_i^{max}}{\varepsilon_i^{min}}$ – is the coefficient of non-uniformity of deformation.

The significant advantage of models mentioned above is that porosity is also a component of powder material and zero-element used for its modelling. The volume fraction of zero-elements is equal to porosity of powder material [2, 5].

3. Development of production technologies

Scientific research in the field of production and processing of materials are always valuable, if they are implementing by industry. The development of power engineering, chemical industry and other industries is impossible without creation of new materials, including fibrous porous materials used for filters. The combination of required physical and mechanical properties makes them widely used as filter elements, mixers, aerators, noise suppressors, heat exchangers and catalysts. A wide range of sizes and materials of fibres provides a filter material with a high retention capacity (up to 2-4 mm) and operating in aggressive environments and at elevated temperatures. The theory of deformation of sinusoidal shape fibres at profiling obtained further development, non-waste technology and equipment for production of fibrous materials for high-quality parts used in transport and chemical engineering. The maximum ultimate stress at a porosity of 40% varies from 57 MPa for fibrous material from copper to 118 MPa for nichrome. The maximum values of the hydraulic resistance coefficient make them suitable for operation at high differences of pressure [8, 9].

The oil filters made of highly porous fibrous materials based on copper M2 and stainless steel 03X18N9T are using during production of polyethylene (Fig. 1). The durability of filters is 3-5 times longer than wire mesh filters made in Germany. The catalyst carrier made of high-porous fibrous material 03H18N9T steel is implemented in the production of phthalic anhydride from orthoxylene. It makes possible to increase the oxidation rate of carbon monoxide and reduce a consumption of expensive catalyst components.

The annual growth of solid industrial wastes in the Ukraine is 1.4-1.5 billion tons. Piling up in dumps so many metallurgical wastes leads to exclusion of useful areas from economic turnover and environmental pollution. The largest fraction of wastes appeared on metallurgical enterprises are products of melting - steel slag and sludge. Existing methods of recycling such wastes based on the chemical and mechanical processes accompanied by the formation of dust and pollution of environment. The technology of recycling slag appeared during production of secondary aluminium briquettes for use in the metallurgical industry as a deoxidizer. The theory of deformation and interparticle bonds during pressing of heterogeneous mixture of metal oxides' particles by shear has created and the technology for briquetting of secondary aluminium production wastes and nickel-containing sludge developed on a basis of this theory. Application of pressing with shear allows increasing the strength of briquettes up to 2.4 times and fracture resistance up to 1.75 times [8-10].

The most promising materials are powder materials based on non-ferrous metals and alloys. Production of these materials makes a significant economic impact in various sectors of national economy [9, 11].

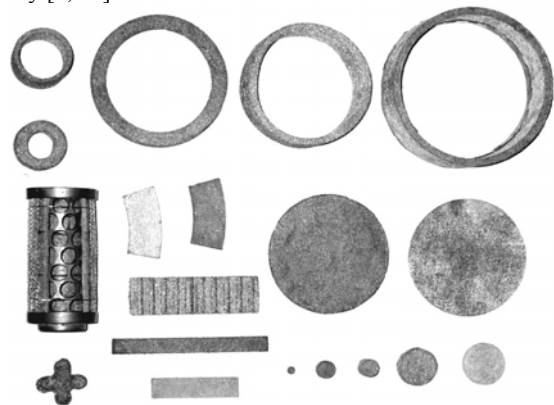


Fig. 1. The different parts made of fibrous materials

The technology for production of the copper powder from wastes of copper current conductors developed, physical and technological properties of the copper powder obtained from wastes investigated. The chemical composition of the powder, %: 99.7 Cu, 0.18 Fe, 0.10 O, 0.10 Si. The granulometric composition is less than 0.160 mm. The shape of copper powder particles is closed to spherical with a rough surface, which ensures its high compactibility [12]. The parts of plasma torch (Fig. 2) have manufactured from this copper powder. The copper powder also used for production of powder bronze. The wear rate for material with the density equal to 8.56 g/cm³ is 0.51·10⁻¹⁴ m/km at the sliding speed 1.1 m/s and pressure 2.25 MPa [13].



Fig. 2. Details made of copper powder produced from wastes of copper current conductors

The possibility of using copper fibres produced from wastes of current conductors for manufacturing of products with properties that are complied to properties of cast and deformed materials established. It has shown that application of uniform compression scheme allows manufacturing products with high physical-mechanical properties. The proposed technology for production of copper rod from fibres consists of the following operations: preparation of fibrous charge, cold compaction, heating to the temperature of 920°C and direct extrusion. The advantage of

proposed technology of direct extrusion is using an original fibrous pressing with a compensator, which eliminates the defects during extrusion. The diameter of rod is 5.8-6.0 mm with a tolerance for the normal precision drawn rods of 0.12 mm according to GOST 1535. The production technology of cold extrusion of copper tubes with inner diameter of 1.0 mm made it possible to produce tips for welding in carbon dioxide from fibrous charge (Fig. 3) [14].

Thermo-mechanical deformation modes for copper-titanium materials have developed on a basis of regularities of dynamic softening processes in hard phase of porous powder materials at the elevated temperatures at different strain rates [15]. By forging new modes of manufactured The details "welding roller" from a copper-titanium material with 0.5% of titanium, and "hub" of sliding bearing from copper powder material with 2% of titanium. Physical and mechanical properties of materials are meeting the requirements of drawings and providing the high performance of products.



Fig. 3. The details produced from fibrous copper

The research works directed on development structural heterogeneous iron-based powder materials for transport machinery parts are conducted (Fig. 4). The different schemes of deformation: radial forging, upsetting into the closed matrix by a punch not set into the cavity of matrix, and by a punch that is set into the cavity of matrix [16, 17].



Fig. 4. The details produced from structural heterogeneous iron-based powder materials

Powder materials obtained by hot and cold stamping density equal to compact material and demonstrating properties that are similar to materials with same chemical composition obtained by casting and metal forming.

4. Conclusion

The production technologies of machine-building products from porous and high-density powder materials developed on a basis of the plasticity theory of porous bodies using the finite element method have considered. The powder metallurgy facilities allowing production of details with desired physical and mechanical properties presented.

5. References

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