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Evaluation of the porous material plasticity when direct extruded

This article deals with results received after the investigation of caked porous metal plasticity from stabilized copper powder by the direct extrusion. To describe the plasticity dependence on the scheme of tense condition the surface of contiguous deformations was used, which describes the dependence of the accumulated to the destruction moment degree of the material base deformation on two indices of tense condition. In the process of investigation the surface of contiguous deformations for caked porous material on the basis of stabilized copper powder was received. The article suggests the assessment criteria of probability of porous solids destruction by high plastic deformations in which the history of loading is defined by spatial trajectories in coordinates: the accumulated deformation of the material base, inflexibility exponent of its tense condition, the parameter of Nadai-Lode, and the plasticity dependence on the scheme of tense condition is described by the surface of contiguous deformations. To denote the loading trajectories of free points of plastic field in the chosen space of the tense condition indices, it's necessary to have the information about the tense condition and about the low of its changing in any point of deforming billet. To denote the stress field, the method experimental-calculation was used, in which the components of speed deformations tensor was defined by visioplasticity method. The offered method of porous solids plasticity evaluation gave the possibility to increase the calculation precision of the used plasticity resource and establish the influence of the main parameters of the process of direct extrusion on the regularity of damage accumulation of the porous metal compression.

***Keywords:** plasticity; porosity; stress; deformation; failure; direct extrusion.*

Actuality of theme. In the technological process of obtaining billets and articles from the powder materials the process of the cold plastic deformation of the sintering materials possess a special place. The cold deformation processes permit to obtain the articles forms and shapes corresponding the task with the necessary accuracy. This provides high material utilization efficiency. By the rational selection of the plastic deformation conditions that provide the necessary trajectories of loading small porous articles of higher difficulty can be produced. The processes of the cold plastic deformation in the porous sintering billets have advantages in cases when it is necessary to obtain high mechanical strength as well as high quality and accuracy of the finished articles size [1, 2]. The given paper deals with the results of the investigation of the direct extrusion of the stabilized copper powder billets process.

Analysis of the latest research and publications on which the authors rely. By the direct extrusion the non-uniformed irregular compression laid over rather considerable shifts takes place. This deformation scheme facilitates to the decrease of porosity in the outlet billet and increases its physical-mechanical properties. However, in the plastic deformation of the porous bodies under the all-round compression conditions along with the process of the pore healing at the same time the processes of plastic dilatation occur. That is why it is important to choose the proper compression rate and matrix geometry for the processes of healing, i.e. porosity decreasing to prevail over the plastic deformation. The investigation analysis fulfilled in the papers [1, 2] shows that by the compression more that 60 per cent in the separate volumes of the billet extruded, especially on the axis and in the instrument contact zone porosity can increase and the zones where porosity exceeds the outlet one occur in the extruded billet.

The value of the angle α of the matrix cone canal, i.e. the angle formed by the generatrix of the canal and its axis effects the ratio between compressing and tangenting stresses as well as non-uniformity of their distribution. In the big angles $\alpha = 90^\circ$ the biggest distribution non-uniformity occur. However, by decreasing the angle α non-uniformity of the deformation distribution decreases only to the certain value. In case of the small angles $\alpha < 30^\circ$ due to the growth of the contact surface deformation non-uniformity increases again. In this case the friction forces have a considerable effect, the more these are, the more in non-uniformity. This is the evidence of existing the optimum value of the angle α where the deformation non-uniformity is minimal. By this angle the extrusion effort is to be minimal. On the ground of the analysis of the papers [1–3] the angle $\alpha = 60^\circ$ and compression 43 per cent have been adapted.

The purpose of this work is to increase the accuracy of calculations of the values of the used plasticity resource and establish the influence of the main parameters of the direct extrusion process on the patterns of damage accumulation and the efficiency of compaction of the porous material.

To achieve the set goal, the dependence of plasticity on the stress state scheme was described using the surface of limit deformations. The surface of limit deformations describes the dependence of the degree of deformation of the base material accumulated up to the moment of failure on two indicators of the stress state. In the proposed criterion for assessing the probability of the destruction of porous bodies with large plastic deformations, the load history is given by spatial trajectories. Load trajectories are specified in the space of dimensionless indicators: the accumulated deformation of the base material, the stiffness index of the stress state of the base material, the Nadai-Lode parameter.

On the basis of the conducted research, a methodology for estimating the amount of the used plasticity resource was developed for the first time, and the influence of the parameters of the direct extrusion process on the patterns of accumulation of damage and the features of compaction of the porous material was determined.

Research materials and methods. Investigating the kinematics of the porous body plastic deformation the coordinate grid method has been used. Experimental research on the direct extrusion was fulfilled on the samples of the sintering porous material from the stabilized copper powder the outlet billets had the initial porosity $\theta_0 = 0.2$ and parameters: $h_0 = 60$ mm, $d_0 = 20$ mm. The samples were cut into halves and on the meridional cross-section of one of them the grid with a pitch of 0.7 mm with the help of the DPC milling machine has been drawn. The extrusion has been held on the hydraulic press with a force of 125 tons with the help of the special construction device. The outer diameter of the billet, i.e. diameter after the pressing out in the container equals d_0=20mm and the outer diameter of the pressed rod equals $d = 15.08$ mm.

The coordinates of the outlet grid units z_0, r_0 have been measured on the instrumental microscope, then the halves have been joined and the sample extruded. At the stationary stage the force P magnitude and the punch v_0 velocity have been determined, then the deformation has been discontinued and the sample pressed out from the matrix. The coordinates of the deformed grid units z, r were measured on the instrumental microscope. So the experimental functions of Eiler coordinates from Lagrange ones $z = z\ (z_0,\ r_0)$, $r = r\ (z_0,\ r_0)$ or Lagrange coordinates from Eiler ones $z_0 = z_0\ (z,\ r)$, $r_0 = r_0\ (z,\ r)$ have been obtained.

It is known [4] that the velocity of flow of the material particles v_z, v_r in the stationary deformation can be calculated due to the formulas

$$v_z = v_0 \frac{\partial z}{\partial z_0}, \tag{1}$$

$$v_r = v_0 \frac{\partial r}{\partial z_0}, \tag{2}$$

$$v_z = \frac{v_0}{\Delta} \frac{\partial r_0}{\partial r}, \tag{3}$$

$$v_r = -\frac{v_0}{\Delta} \frac{\partial r_0}{\partial z}, \tag{4}$$

where $\Delta = \frac{\partial z_0}{\partial z} \frac{\partial r_0}{\partial r} - \frac{\partial z_0}{\partial r} \frac{\partial r_0}{\partial z}$.

As the stress calculations are suitable to calculate in the system of Eiler coordinates, so cinematics should be calculated in the Eiler coordinates: this excludes the necessity of transition into another system of coordinates and, besides allows to represent, the calculation results more clearly. That is why in determining velocities formulas (3), (4) have been used. Functions of the Lagrange coordinates from Eiler coordinates $z_0\ (z,\ r)$, r_0 (z, r) were obtained with the help of approximation of the experimental data by the cubic splines. The components of tensor and deformation velocity deviator intensity have been determined by the known formulas

$$\dot{e}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right), \tag{5}$$

$$\dot{\gamma} = \sqrt{\left(\dot{e}_{ij} - \frac{1}{3}\dot{e}\delta_{ij}\right)\left(\dot{e}_{ij} - \frac{1}{3}\dot{e}\delta_{ij}\right)}. \tag{6}$$

The intensity of the deformation rate in the material of the base $\dot{\gamma}_0$ was determined according to the formula (7) [1]. The functions of porosity were expressed by dependences (8) [5, 6, 9, 10]

$$\dot{\gamma}_0^2 = \frac{\psi(\theta)\dot{e}^2}{1-\theta} + \frac{\varphi(\theta)\dot{\gamma}^2}{1-\theta}, \tag{7}$$

$$\varphi(\theta) = (1-\theta)^{4.7},$$
$$\psi(\theta) = 0.64\frac{(1-\theta)^{5.67}}{\theta^{0.97}}. \tag{8}$$

For the calculations of the porosity distribution the ratio [5, 6] has been used

$$\theta = 1 - (1-\theta_0)\frac{r_0}{r}\left(\frac{\partial r_0}{\partial r}\frac{\partial z_0}{\partial z} - \frac{\partial r_0}{\partial z}\frac{\partial z_0}{\partial z}\right), \tag{9}$$

where θ_0 (z_0 (z, r), r_0 (z, r)) – the initial porosity of the sample, z_0 (z, r), r_0 (z, r) – functions of the initial (Lagrange) variables from the current (Eiler).

Results and discussion. The accumulated deformation of the material base was calculated according to the formula

$$\Gamma_0(z,r) = \int_0^t \dot{\gamma}_0 dt, \tag{10}$$

along the trajectories of the material particles (along the line of the reference grid). When determining deformation time t it has been taken into account that the arbitrary particle moves to the next position of the reference grid for the same time interval

$$\Delta t = \frac{\Delta z_0}{v_0}, \tag{11}$$

where Δz_0 – the reference grid pitch in the non-deformed zone.

The stress tensor components in the axial-symmetrical deformation should satisfy the differential equation of equilibrium

$$\begin{aligned} &\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\varphi}{\partial r} = 0, \\ &\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r} = 0 \end{aligned} \tag{12}$$

and limiting conditions that for the extrusion process were taken in the integral form on the elastic and plastic zone boundary in the inlet G_1 and G_2 in the matrix outlet

$$P_n = 2\pi \int_{G_n} r(\sigma_z \nu_z + \tau_{rz}\nu_z) dG, \tag{13}$$

where $P_n(n = 1.2)$ – the force on the G_n boundary,

ν_z, ν_r – components of the outer normal vector to G_n.

The P_n force magnitude have been determined experimentally. The stress tensor components have been calculated according to the formulae

$$\dot{e}_{ij} - \frac{1}{3}\dot{e}\delta_{ij} = \frac{\dot{\gamma}}{\tau}\left(\sigma_{ij} - p\delta_{ij}\right), \tag{14}$$

$$p\varphi(\theta)\dot{\gamma} = \tau\psi(\theta)\dot{e}, \tag{15}$$

using the ratio of the cinematic and static magnitude connection [5, 6, 9, 10]

$$\tau = \tau_0 \varphi(\theta)\frac{\dot{\gamma}}{\dot{\gamma}_0}, \tag{16}$$

$$p = \tau_0 \varphi(\theta)\frac{\dot{e}}{\dot{\gamma}_0}. \tag{17}$$

The stress intensity value in the material of the base τ_0 has been determined on the curve of flow of the material base

$$\tau_0 = 110 + 513.6\Gamma_0^{0.902}, \quad (\Gamma_0 \geq 0.01). \tag{18}$$

It is necessary to note that the average stress magnitude p for the porous material can be determined according to (17), that’s why the limiting conditions programming in the form of (13) isn’t necessary, because p is determined from (17). In this case, limiting conditions (13) can be used for the checking the accuracy of the results obtained.

η_0 value is calculated from the formula [7]

$$\eta_0 = \eta\sqrt{\frac{\varphi(\theta)}{(1-\theta)(\alpha\eta^2 + 1)}} \tag{19}$$

and Nadai-Lode parameters according to the formula

$$\mu_\sigma = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}. \tag{20}$$

As in the process of the direct extrusion the axial-symmetrical deformation takes place, one of the main stresses was equal to σ_φ and for determining two other stresses formula (21) has been used.

$$\sigma_{\substack{\max \\ \min}} = \frac{\sigma_z + \sigma_r}{2} \pm \frac{1}{2}\sqrt{(\sigma_z - \sigma_r)^2 + 4\tau_{rz}^2}. \tag{21}$$

Porosity in the plastic area has been calculated on the formula (9). The analysis of the porosity distribution on the cross-section shows that at the beginning of the extrusion process the packing has taken place practically on the whole sample volume and porosity decreases from $\theta_0 = 0.2$ to $\theta = 0.14$ on the inlet to the cone part. Although more intensive packing takes place in the cone part of the matrix where all-round compression is putting on the relatively big deformation of shift. All this leads to the decrease of porosity to 0.04…0.08 in the outlet of the matrix. That is due to the direct extrusion the outlet billet porosity decreases in 2.5 times. By the chosen compression and the geometry of the matrix the non-uniformity of the porosity distribution over the radius of the obtained billet does not exceed $\Delta\theta/\Delta r = 0.015$ mm^{-1}.

The used plasticity resource has been determined according to the criteria [8] that for the porous body has been recorded as follows

$$\psi = 3\psi_0^2 \exp\left(2c\int_0^{\Gamma_0} \eta_0 d\Gamma_0^* / |\eta_0| \Gamma_{0p}(\eta_0, \mu_\sigma)\right) + \sqrt{\psi_{ij}\psi_{ij}} \tag{22}$$

where

$$\psi_{ij} = \int_0^{\Gamma_0} \left(1 - a + 2a\frac{\Gamma_0^*(\eta_0, \mu_\sigma)}{\Gamma_{0p}(\eta_0, \mu_\sigma)}\right)\beta_{ij}\frac{d\Gamma_0}{\Gamma_{0p}(\eta_0, \mu_\sigma)} - \tag{23}$$

the components of the compass adjuster of the damage tensor,

$\beta_{ij} = \dfrac{de_{ij}}{d\Gamma_0}$ – components of the path tensor of the deformation gain,

ψ_0 – depends on the initial porosity and is determined by the formula [8]

$$\psi_0 = \frac{\Gamma_{0p} - \Gamma_{0p}^*}{\Gamma_{0p}}, \tag{24}$$

where Γ_{0p} – limiting deformation for the extention of the sample with the initial porosity $\theta_0 = 0\ldots0.03$,
Γ_{0p}^* – limiting deformation for the extention of the sample with the given porosity.

For $\theta_0 = 0.2$ for ψ_0 the value $\psi_0 = 0.08$ has been obtained. The constant c equals $c = 0.5$ and the constant $a = 0.1$.

The trajectories of tension $\Gamma_0(\eta_0, \mu_\sigma)$ in every particle of the plastic zone were determined according to the results of the calculations of the stressed-deformed conditions and the values of the accumulated base material deformation Γ_0, hardness index of the base material tension condition η_0 and Nadai-Lode parameter μ_σ. For the boundary surface of plasticity the approximation [8] has been used.

$$\Gamma_{op}(\eta_0, \mu_\sigma) = \frac{0.45e^{-0.47\eta_0}}{1 - 0.4\mu_\sigma + 0.02\mu_\sigma^2}.$$

Figure 1 shows the meridional section of a porous sample with the location of points and levels for calculating the value of the used plasticity resource. Figure 2 shows the trajectories of the material particles on the axis ($r = 0$), in the middle part ($r = R/2$) and on the surface of the billet ($r = R$). As it can be seen from fig. 2 in the most unfavorable conditions the particles of the axial zone are deformed.

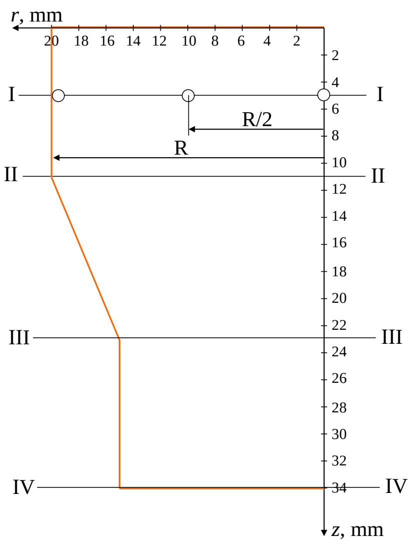

Fig. 1. Meridional section of a porous sample

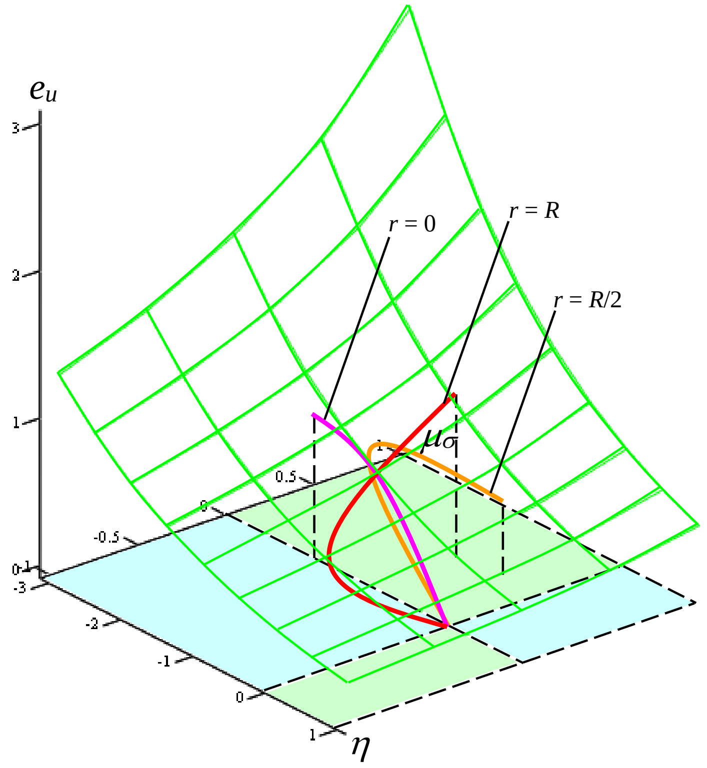

Fig. 2. The limiting plasticity surface for the porous billets on the copper base and the trajectories of the material particles loading that are on the axis of the billet (r = 0), in the middle (r = R/2) and on the surface (r = R)

Figure 3 shows the results of calculating the used plasticity resource after direct extrusion of a cylindrical workpiece from sintered porous copper-based material.

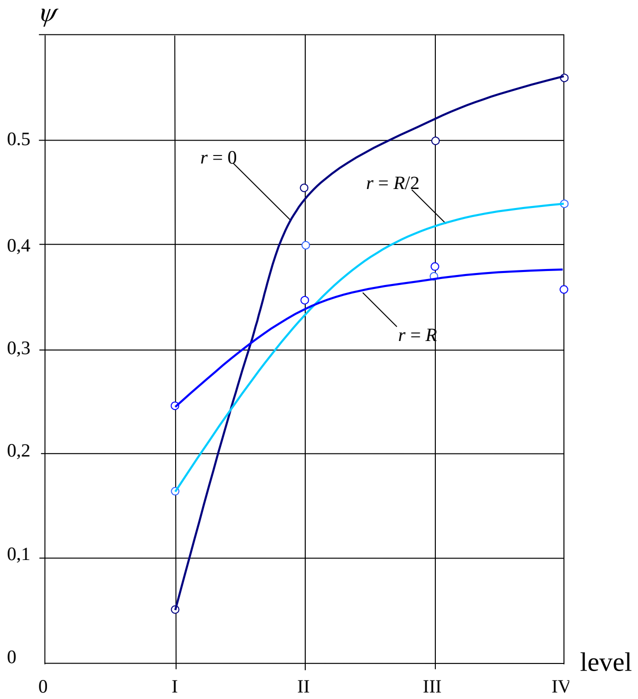

Fig. 3. Distribution of the used plasticity resource ψ on the meridian cross-section during the direct extrusion of the porous billet

Conclusions and prospects for further research. The results of the used plasticity resource calculations after the direct extrusion are shown in the fig. 3. The maximum value ψ has on to axis of the billet ($\psi = 0.56$) and decreases within the radius r increase. In the zone of the contact $\psi = 0.36$. So non-uniformity of distribution of the used plasticity resource upon the radius in the matrix outlet is $\Delta\psi/\Delta r = 0.03$ мм$^{-1}$. The obtained distribution of ψ (fig. 3) can be considered as optimum because within different parameters of the direct extrusion process the values of the used plasticity resource and non-uniformity of its distribution increase greatly. This work is a continuation of research in the field of plasticity of sintered porous material. In the future, these studies will be improved by clarifying methods for calculating the stress-strain state, clarifying experimental research methods, and quantitatively assessing the intensity of damage accumulation.

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Оцінка пластичності пористого матеріалу при прямому осесиметричному видавлюванні циліндричної заготовки

У статті зазначено результати досліджень пластичності спеченого пористого матеріалу з мідного порошку ПМС-1 при прямому видавлюванні. При цьому для описання залежності пластичності від схеми напруженого стану використано поверхню граничних деформацій, яка описує залежність накопиченого до моменту руйнування ступеня деформації матеріалу основи від двох показників напруженого стану. В роботі отримана поверхня граничних деформацій для спеченого пористого матеріалу на основі мідного порошку ПМС-1. Запропоновано критерій оцінки ймовірності руйнування пористих тіл при великих пластичних деформаціях, в якому історія навантаження задається просторовими траєкторіями в координатах: накопичена деформація матеріалу основи, показник жорсткості напруженого стану матеріалу основи, параметр Надаі – Лоде, а залежність пластичності від схеми напруженого стану описується поверхнею граничних деформацій. Для визначення траєкторій навантаження довільних точок пластичної області в вибраному просторі показників напруженого стану необхідно мати інформацію про напружений стан та закон його зміни в будь-якій точці заготовки, що деформується. Для визначення поля напружень використано експериментально-розрахунковий метод, в якому компоненти тензора швидкостей деформацій визначали методом візіопластичності. Запропонований у цій роботі метод оцінки пластичності пористих тіл дозволив значно підвищити точність розрахунків значень використаного ресурсу пластичності та встановити вплив основних параметрів процесу прямого видавлювання на закономірності накопичення пошкоджень та ефективність ущільнення пористого матеріалу.

Ключові слова: пластичність; пористість; напруження; деформація; руйнування; пряме видавлювання.

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