scratch geometry ultimately observed on specimens is formed and disturbances in continuity take place leading to the formation of a brittle damage zone. The lower the degree of plasticity of a material, the smaller is its capacity for stress relaxation in its microvolumes under an indenter, the more pronounced is the elastic aftereffect, the higher are the buildups, and the larger is the zone of brittle damage.

The data obtained on the phenomena of surface deformation and disintegration of carbides can be useful in investigations into the kinetics of various processes of contact reaction, such as friction, wear, and abrasive machining, involving refractory compounds.

LITERATURE CITED

1. Yu. G. Tkachenko and V. I. Kovtun, "An instrument for testing materials by friction and sclerometry methods," Zavod. Lab., 41, No. 12, 1517-1519 (1975).
2. V. F. Berdikov, A. V. Babanin, and Yu. I. Artem'eva, "Determination of Young's moduli of various abrasive materials by a micropenetration method," Zavod. Lab., 41, No. 8, 1014-1019 (1975).
3. G. V. Samsonov, Yu. G. Tkachenko, V. F. Berdikov, and G. A. Bovkun, "Microhardness, microbrittleness, and brittle microstrength of transition metal carbides," in: Carbides and Carbide-Base Alloys [in Russian], Nauk, Dumka, Kiev (1976), pp. 98-103.
4. M. D. Katrich, E. S. Berkovich, M. B. Reifman, and M. P. Shaskol'skaya, "Investigation of the hardness of silicon carbide single crystals by a scratching method," in: Sclerometry [in Russian], Nauka, Moscow (1968), pp. 167-172.
5. V. P. Alekhin and A. P. Ternovskii, "Structural and kinetic characteristics of changes in shape of materials during micropenetration," in: New Developments in the Field of Microhardness Testing [in Russian], Nauka, Moscow (1974), pp. 29-52.

IRREVERSIBLE DEFORMATION OF A SINTERED POROUS BODY OF A WORK-HARDENING PLASTIC METAL II. EXPERIMENTAL PART

V. V. Skorokhod, I. F. Martynova, and V. P. Shklyarenko

UDC 621.762.5:621.792.8

In Part I [1] models and methods of calculation were chosen with the aid of which it is possible to describe the curve of strain densification of a porous body sintered from a plastic metal powder for a given type of stressed state. The object of the work described below was to compare results of calculations with experimentally obtained densification curves. Experiments were carried out on specimens, with $h/d \approx 1$, pressed from an electrolytic nickel powder and sintered for 1 h at 1000°C in a hydrogen atmosphere. The specimens had porosities (θ) of 0.51, 0.37, and 0.31. Isostatic volume compression of specimens was performed in a high-pressure chamber (using glycerin as the working fluid). To insulate them from the working fluid, the specimens were placed in a rubber bag. Single-ended compression was effected by densifying specimens in a die of the same diameter as in the compaction.

In Fig. 1 are shown experimentally constructed densification curves for sintered nickel specimens of various porosities in uniform isostatic compression (1) and results of calculations made with the aid of a spherically symmetrical model of a porous body (2) and concepts of rms strains and stresses in a porous body (3) with allowance for the strain strengthening of the matrix material. It will be seen that the experimental data for all the cases examined (different starting porosities and pressures) lie well below the calculated results. The difference between the two sets of data grows with increase in starting porosity. The resistance to deformation of a body with a matrix structure is higher than that of a porous body with the structure of a statistical mixture.

Institute of Materials Science, Academy of Sciences of the Ukrainian SSR. Institute of Metal Physics, Academy of Sciences of the Ukrainian SSR.

Translated from Poroshkovaya Metallurgiya, No. 5(173), pp. 62-69, May, 1977. Original article submitted July 16, 1976.

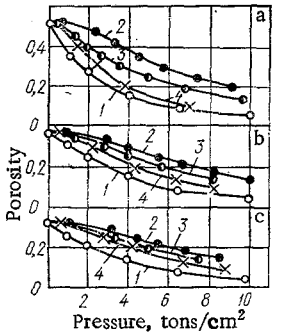

Fig. 1

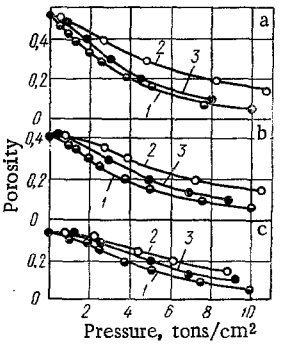

Fig. 2

Fig. 1. Variation of porosity with pressure in uniform isostatic compression for electrolytic nickel sintered for 1 h at 1000°C to porosities of 0.51 (a), 0.37 (b), and 0.31 (c): 1) experimental curve; 2) curve calculated using spherically symmetrical model; 3) curve calculated using rms stresses and strains, with allowance for strain strengthening; 4) as for 3 but with allowance for macrodefectiveness of structure.

Fig. 2. Variation of porosity with pressure in single-ended compression for electrolytic nickel sintered for 1 h at 1000°C to porosities of 0.51 (a), 0.42 (b), and 0.33 (c): 1) experimental curve; 2) curve calculated using rms stresses and strains, with allowance for strain strengthening; 3) as for 2 but with allowance for macrodefectiveness of structure.

The deformation of a porous body is, of course, accompanied by the formation of new particle contacts. Our earlier investigations [2-4], based on measurements of changes in physical and mechanical properties, have shown that during the deformation of a porous body satisfactorily sintered from a plastic metal powder no rupture of the contacts produced during sintering occurs, and that the macroscopical picture of the deformation of a porous body involves essentially deformation of the pores, in the course of which they become "flattened" and transformed into quasi-two-dimensional macrodefects. In [5] a quantitative measure of macrodefectiveness, θ_S, is proposed, representing the relative fraction of the free surface in a disperse system. It is expressed as the ratio of the free surface in a porous body to the total surface of the separate elements forming the body.

Let us attempt to describe the densification of a porous body under conditions of uniform isostatic compression within the framework of concepts of rms strains and stresses and with allowance for the formation of macrodefects in the course of deformation. To do this, it is necessary to know the quantitative relationship between the shear viscosity η of the porous body and the quantity θ_S. As we are using the hydrodynamic analogy of the theory of elasticity, the expression $\eta = f(\theta_S, \theta)$ will be analogous to the function of the elastic modulus $E = f(\theta_S, \theta)$. To derive such a relationship, resort is made to a device, described in [5], for calculating the electrical conductivity of a porous body with imperfect contacts.

Let us consider a cube of edge length a, porosity θ, and relative fraction of imperfect contacts θ_S subjected to uniform triaxial compression by a force P. When the displacement is equal to Δa, the linear strain of the cube is

$$\varepsilon = \frac{\Delta a}{a} = \frac{P}{a^2 E}, \qquad \text{(II-1)}$$

where E is the elastic modulus of a porous body of porosity θ.

We will imagine that the body grows in size uniformly in all three directions while the number of its perfect contacts remains unchanged, until θ becomes equal to θ_S. As the "compact" cross section of the body will not change during this growth, clearly the linear displacement in such a hypothetical body under the action of the force P will be the same, i.e., Δa. Under these conditions the linear strain will be

$$\varepsilon_h = \frac{\Delta a}{a_h} = \frac{P}{a^2 E_h} \qquad \text{(II-2)}$$

where a_h is the linear dimension of the hypothetical cube, related to a by the expression

$$\frac{a}{a_h} = \frac{(1-\theta_s)^{1/3}}{(1-\theta)^{1/3}}. \tag{II-3}$$

Equating the expressions for Δa from Eqs. (II-1) and (II-2) and taking into account Eq. (II-3), we obtain

$$\frac{E}{E_h} = \frac{a_h}{a}. \tag{II-4}$$

Now E_h represents the elastic modulus of a body of porosity θ_s without contact imperfections. Consequently, if the porosity dependence of the elastic modulus of such a body is expressed by a power function with an exponent m [5],

$$E = E_0 (1-\theta)^m, \tag{II-5}$$

where E_0 is the elastic modulus of the material, then

$$E_h = E_0 (1-\theta_s)^m. \tag{II-6}$$

Substituting Eqs. (II-3) and (II-6) into Eq. (II-4), we get

$$E = E_0 (1-\theta_s)^{m-1/3} (1-\theta)^{1/3}. \tag{II-7}$$

It can be taken, with reasonable accuracy, that m = 2. Then, by analogy, we obtain the following expression for the shear viscosity of the body:

$$\eta = \eta_0 (1-\theta_s)^{5/3} (1-\theta)^{1/3}. \tag{II-8}$$

Next, we use the method of calculating rms stresses and strains proposed in [5], which consists in equating expressions for energy dissipation during deformation in terms of squares of true rates of deformation and viscosities of the material, on the one hand, and in terms of macroscopic rates of deformation and viscosities of the porous body as a whole, on the other hand. If the assumption is made that the local deformation of some arbitrarily selected element is reduced to simple compression [5] and k = 3/2, then for the case of uniform isostatic compression the expression for the rms rate of deformation is

$$\bar{\dot{U}} = \frac{\sigma \sqrt{\theta}}{2\eta_0 (1-\theta) \sqrt{(1-\theta)^{1/3}(1-\theta_s)^{5/3}}}. \tag{II-9}$$

Using the kinetic formula for uniform isostatic compression derived in [5],

$$\frac{d\theta}{dt} = -\frac{3}{4}\frac{\sigma}{\eta}\theta, \tag{II-10}$$

we obtain the following differential equation for rms strains:

$$\frac{d\bar{U}}{dt} = -\frac{2}{3\sqrt{\theta}}\left(\frac{1-\theta_s}{1-\theta}\right)^{5/6} d\theta. \tag{II-11}$$

Assuming, with adequate accuracy for all practical purposes, that

$$\left(\frac{1-\theta_s}{1-\theta}\right)^{5/6} \approx \frac{1-\theta_s}{1-\theta}, \tag{II-12}$$

we finally have

$$\bar{U} = -\frac{2}{3}\int_{\theta_0}^{\theta} \frac{1-\theta_0}{\sqrt{\theta}(1-\theta)}\, d\theta. \tag{II-13}$$

Judging by data on changes in mechanical properties [4], the mechanical strength of contacts forming during the deformation process is negligible, and because of this the freshly formed contact surface can be regarded as free. At the same time, it has been shown that contacts forming during high-temperature sintering do not rupture. Thus, to a first approximation the free surface does not change during deformation and hence $\theta_S = 0$.

Performing a simple substitution of variables and integrating Eq. (II-13), we obtain an expression for rms strains,

$$\bar{U} = \frac{2}{3}(1-\theta_0)\ln\frac{(1+\sqrt{\theta_0})(1-\sqrt{\theta})}{(1+\sqrt{\theta})(1-\sqrt{\theta_0})}. \tag{II-14}$$

True rms viscous stresses are given by the expression

$$\bar{P} = 3\bar{\dot{U}}\eta_0 = \frac{3\sigma\sqrt{\theta}}{2(1-\theta)\sqrt{(1-\theta)^{1/3}(1-\theta_0)^{5/3}}}. \tag{II-15}$$

Neglecting the term $(1-\theta)^{1/6}$ as small compared with $(1-\theta)$ and assuming, to an approximation, that

$$(1-\theta_0)^{5/6} \approx (1-\theta_0),$$

we finally obtain a formula relating the yield stress of the porous body σ to the yield stress of the material σ_y,

$$\sigma = \frac{2(1-\theta)(1-\theta_0)}{3\sqrt{\theta}}\sigma_y. \tag{II-16}$$

Using this equation, it is possible to construct a densification curve for a porous body subjected to uniform isostatic compression in the same way as was done in Part I (Fig. 1, curve 4). The case considered constitutes the best approximation to experimental by calculated data, the degree of approximation being the higher the more porous the starting specimen.

Let us now calculate the densification of a porous sintered specimen in a die with the aid of concepts of rms strains and stresses and with allowance for strain strengthening. In the calculation use is made of the quantitative characteristic of macrodefectiveness of material θ_S. Resorting to the same device as in the case of uniform isostatic compression, we can obtain the following expression for the elastic modulus of the porous body, measured in the direction of compression in the die

$$E_{\parallel} = E_0(1-\theta_s)^5(1-\theta)^{-1}. \tag{II-17}$$

Following the same procedure as in the previous case, we arrive at an expression for rms stresses,

$$\sigma = \frac{2(1-\theta_0)^{3/2}}{3\sqrt{\theta}}\sigma. \tag{II-18}$$

The rms rate of deformation is given by the formula

$$\bar{\dot{U}} = \frac{\sigma\sqrt{\theta}}{2\eta_0(1-\theta_0)^{3/2}}. \tag{II-19}$$

Using the kinetic function of porosity variation during single-ended compression and performing a simple integration, we get an expression for rms viscous strains,

$$\bar{U} = \frac{3}{3(1-\theta_0)^{3/2}}\left[(\theta_0^{1/2}-\theta^{1/2}) - \frac{1}{3}(\theta_0^{3/2}-\theta^{3/2})\right]. \tag{II-20}$$

In Fig. 2 are shown experimental and calculated densification curves for sintered porous nickel. As in the case of uniform isostatic compreesion, the best approximation to experimental results is afforded by data calculated with the aid of concepts of rms strains and stresses and with allowance for strain strengthening and pore nonisometry in the deformation of a sintered body. Physically, the contribution from pore nonisometry consists in enabling material to move tangentially along the pore surfaces without loss of continuity.

It should be noted that for all the cases investigated there is a quantitative difference between the experimental and theoretical curves. The difference is generally slight, but rather more marked at small values of pressure. Calculation yields larger values of pressure required for the attainment of a given porosity than are needed in practice. Let us try to discover what brings about this difference. First of all let us examine the role of nonuniformity of strain, which is characteristic of the deformation of a porous body. There exist several types of nonuniformity of strain, having different causes:

I. Macroscopic nonuniformity, which is linked with differences in relative magnitude between different forces (axial and lateral pressures) acting on any given volume within a porous body and manifests itself in porosity variations within a compact.

II. Medium-scale nonuniformity of strain, resulting from the plastic deformation process gradually extending to new volumes of a porous body, the mean stress acting in each such volume being equal to the effective yield stress.

III. Small-scale nonuniformity of strain, brought about by the variation of stress in any given direction resulting from changes in effective cross section.

Apart from these types, as in the deformation of nonporous metal, there is also nonuniformity of strain on the scale of individual grains and coherent scattering regions.

Nonuniformity of strain of type I was first observed a long time ago, in experimental investigations into the pressing of powder [6-9] which showed that the mean porosity of a specimen may differ from the porosities of volumes cut from various parts of the specimen (periphery, center, various heights) by up to 20%. It would appear that phenomena of the same character occur also during the re-pressing of a sintered porous body, because, as has been demonstrated by the present authors in [10], the compressibility of such a body is virtually independent of the degree of cohesion between its component elements. As is well known, nonuniformity of this type can be substantially reduced by pressing specimens from both ends and, as was done in the present work, using small-sized specimens.

On the other hand, attempts – such as that made in Part I – to allow for nonuniformity of type III with the aid of Green's spherical model [11] fail to yield results close to experimental data.

In the authors' opinion, the most appropriate for describing the process of deformation of a porous solid is allowance for nonuniformity of strain of type II. If we divide a whole porous body into equal-sized volumes of linear sizes of the order of several pore sizes and measure the porosity of each such volume, then clearly we shall have a certain porosity distribution of the numbers of volumes of the same porosity, and the mean of this distribution, μ, will be equal to the mean porosity of the specimen.

Let us try to assess very roughly the effect of the existence of such a distribution on the position of the compressibility curve of a sintered porous body pressed in a closed volume. To do this, we must make some simple assumptions. We will regard the porosity distribution of the numbers of volumes of the same porosity as rectangular. We will further assume that the type of distribution, like the pore size distribution assumed and then experimentally confirmed by Bockstiegel [12], does not change in the course of deformation. The choice of distribution and its parameters in this case is entirely arbitrary. Our task will be merely to ascertain in principle what contribution nonuniformity of strain of this type makes to the process of densification of a sintered porous body.

Using values of rms strains and stresses with allowance for strain strengthening and macrodefectiveness, we can calculate and construct a nomogram of compressibility curves for various starting porosities θ_{0i} on the assumption that the distribution considered above is in the form of a delta function, i.e., that all volumes have the same porosity, equal to the mean specimen porosity, or, in other words, that there is no nonuniformity of strain of type II. The volume of a porous body at a given pressure can be found by summating the volumes obtained at this pressure for various starting porosities, multiplied by the statistical weight $f(\theta_i)$ in the distribution of volumes having a given starting porosity. Then the total porosity at a given pressure is

$$\bar{\theta} = \sum \frac{\theta_{0i} - \theta_i}{1 - \theta_i} f(\theta_i). \qquad \text{(II-21)}$$

In the case of rectangular distribution $f(\theta_i) = 1/(b - a)$, where a and b are distribution intervals; in our case $b - a = 2\mu$. Then

$$\bar{\theta} = 2\mu \sum_i \frac{\theta_{0i} - \theta_i}{1 - \theta_i}. \qquad \text{(II-22)}$$

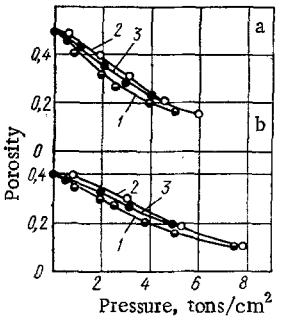

Fig. 3

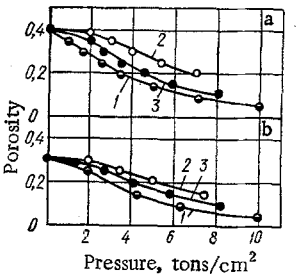

Fig. 4

Fig. 3. Compressibility curves for electrolytic nickel sintered for 1 h at 1000 °C to porosities of 0.5 (a) and 0.4 (b): 1) constructed experimentally; 2) calculated using rms strains and stresses, with allowance for strain strengthening and macrodefectiveness of structure; 3) as for 2 but with allowance for nonuniformity of strain.

Fig. 4. Compressibility curves for sintered iron powder specimens with starting porosities of 0.39 (a) and 0.30 (b): 1) constructed using experimental data [9] (APZhM powder sintered for 3 h at 1200°C); 2) calculated using rms strains and stresses, with allowance for strain strengthening (data taken from [10]); 3) as for 2 but with allowance for macrodefectiveness of structure.

In Fig. 3 are shown compressibility curves constructed experimentally and calculated both without allowance for nonuniformity of strain of type II and taking such nonuniformity into account as described above (μ was taken to be 0.15). At the two starting porosities considered (θ = 0.5 and 0.4) nonuniformity of strain can be seen to manifest itself at small values of pressure, and it can be concluded that allowing for it enables theoretical results to be obtained approximating more closely to experimental data.

The method of calculation based on the use of rms strains and stresses and on allowance for strain strengthening and macrodefectiveness of structure was employed for processing published compressibility curves for sintered porous iron deformed in a constraining shell [13]. The specimens, from APZhM iron powder, had been presintered for 3 h at 1200°C in a converted natural gas atmosphere. Data on the strain strengthening of nonporous iron necessary for the calculation were taken from [14]. The experimental and calculated data are shown in Fig. 4. The results are analogous to those obtained for nickel: The experimental data are in good agreement with data calculated using rms strains and stresses, with allowance for strain strengthening and imperfection of particle contacts forming during deformation.

Thus, the proposed method of constructing theoretical porosity vs pressure curves can be used with porous materials of any plastic metal for which the law of strengthening in the nonporous conditions is known.

CONCLUSIONS

1. An analysis is made of various methods of calculating compressibility curves for porous bodies sintered from plastic metal powders. It is shown that the best approximation to experimental results is given by the method based on the use of rms viscous stresses and strains and on allowance for strain strengthening and macrodefectiveness of structure.

2. Taking into account the nonuniformity of strain due to density variations in compacts enables calculated results to be brought closer to experimental data obtained at low pressures.

LITERATURE CITED

1. V. V. Skorokhod and I. F. Martynova, "Irreversible deformation of a sintered porous body of a work-hardening plastic metal (Part I)," Poroshk. Metall., No. 4, 70-74 (1977).
2. I. F. Martynova, V. V. Skorokhod, and S. M. Solonin, "Physicomechanical properties of volume-strained sintered porous nickel (Part I)," Poroshk. Metall., No. 8, 79-83 (1975).
3. I. F. Martynova, V. V. Skorokhod, S. M. Solonin, and G. R. Fridman, "Physicomechanical properties of volume-strained sintered porous nickel (Part II)," Poroshk. Metall., No. 9, 72-76 (1975).

4. S. I. Evlash, I. F. Martynova, V. V. Skorokhod, and S. M. Solonin, "Physicomechanical properties of volume-strained sintered porous nickel (Part III)," Poroshk. Metall., No. 11, 72-76 (1975).
5. V. V. Skorokhod, Rheological Principles of Sintering Theory [in Russian], Nauk. Dumka, Kiev (1972).
6. C. G. Goetzel, Treatise on Powder Metallurgy, Interscience Publishers, New York (1949).
7. H. Unckel, Arch. Eisenhuettenwesen, 18, 161-170 (1945).
8. P. Duwez and L. Zwell, J. Metals, Trans., 1, No. 2, 137-142 (1949).
9. M. Yu. Bal'shin, Metal Powder Science [in Russian], Metallurgizdat, Moscow (1948).
10. I. F. Martynova, V. V. Skorokhod, and S. M. Solonin, "Plastic deformation in the pressing of powders of ductile metals," Poroshk. Metall., No. 3, 40-46 (1974).
11. R. J. Green, "Theory of plasticity of porous bodies," in: Mechanics [Russian translation], Vol. 4 (1973), pp. 109-120.
12. G. Bockstiegel, "Relations between pore structure and densification mechanism in the compacting of iron powders (Communication II)," Intern. J. Powder Metall., 3, No. 1, 29-37 (1967).
13. A. Ya. Artamonov, Effect of Processing Parameters on the Physicomechanical Conditions of Sintered Materials [in Russian], Nauk. Dumka, Kiev (1965).
14. A. V. Tret'yakov and V. I. Zyuzin, Mechanical Properties of Metals and Alloys in Plastic Working [in Russian], Metallurgiya, Moscow (1973).

WEAR-RESISTANT COMPOSITE ELECTROLYTIC COATINGS BASED ON NICKEL AND IRON

I. M. Fedorchenko, V. A. Danilenko, and Yu. A. Guslienko

UDC 621.762

Composite materials and coatings with a heterogeneous structure consisting of a ductile matrix and hard, wear-resistant inclusions seem to hold considerable promise for the manufacture of components of frictional units of various machines and mechanisms. In many cases it is logical to make parts in low-cost cast materials and apply to their working surfaces wear-resistant composite electrolytic coatings. A process for the application of nickel- and iron-base coatings of this type has been developed at the Institute of Materials Science, Academy of Sciences of the Ukrainian SSR. Essentially, it consists of two key operations: 1) electrolytic codeposition of a metal (nickel or iron) and fine powders of a metal (nickel or iron) and fine powders of materials (metals and nonmetals) acting as solid lubricants or alloying additions; 2) heat treatment of the coatings (annealing and sintering). A detailed study has already been carried out at the Institute of Materials Science of the deposition of two- and three-component nickel and iron coatings wtih inclusions of fine boron, tungsten carbide, and calcium fluoride powder particles.

Procedure for the Application and Heat Treatment of Coatings

The deposition of coatings is performed in standard nickel- and iron-plating tanks from sulfate and chloride electrolytes at current densities of 20-30 A/dm^2, ensuring coating deposition rates of 100-150 μ/h. It may be mentioned for comparison that in factory plating shops and laboratories, for example at the Volga Automobile Factory, nickel coatings are deposited at current densities not exceeding 10 A/dm^2, as at higher current densities passivation phenomena are observed and poor quality coatings are obtained, as a result of which a high proportion of plated articles must be scrapped. In the process under consideration the presence in the electrolyte of a considerable quantity of dispersed particles (30-100 g/liter) and intense agitation of the electrolyte (necessary to maintain the particles being codeposited in suspension) enable good-quality deposits to be obtained at much higher current densities.

The annealing of coatings deposited by this process is performed in a vacuum or in nonoxidizing atmos-

Institute of Materials Science, Academy of Sciences of the Ukrainian SSR. Translated from Poroshkovaya Metallurgiya, No. 5(173), pp. 70-72, May, 1977. Original article submitted September 28, 1975.