PLASTIC DEFORMATION AND DENSIFICATION FOR SINTERED POWDER MATERIALS①

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ABSTRACT

Equivalent yield strength of sintered powder materials is determined by experiments, and the following yield condition is constructed based on it. Experiments on uniaxial compression, and plane strain, closed die upsetting have been done using sintered copper, and the relation between the deformation resistance and compactness of the prefabricated preform is analysed. A design principle for the prefabricated preform density is proposed, and the effectiveness of shear plastic deformation to densification is pointed out.

Key words: sintered materials plasticity theory densification

1 INTRODUCTION

Sintered powder materials are made from metal or nonmetal powders and metal oxide powder by a process of blending, compacting and sintering. There is about 20% porosity in the materials. With the development of the powder metallurgy industry, sintered powder materials such as structural enginering materials with super properties, sintered hard alloys, sintered friction or antifriction materials, sintered metallic magnet, refractory materials, filter material and new types of superconduc- tor etc. are increasingly employed. The related plastic working technologies such as forging, extrusion, rolling, isostatic pressing etc. are gradually becoming important in the production of sintered powder parts. Some researchers have probed the plasticity theory[1-4] of sintered powder materials and have provided a basic theory for technology design, quality analysis of sintered powder parts. In this paper, the deformation and densification of sintered powder materials for basic forming process are researched deeply.

2 FOUNDATION OF PLASTICITY THEORY

2.1 *Constant Mass Condition*

In plastic working of sintered powder material, the volume of sintered powder material decreases, and the density of the material increases. The density increase due to the plastic deformation of sintered powder materials is called as densification, and is the essential reason plastic working can improve the mechanical and physical properties of sintered powder material. Because densification occurs during plastic deformation of the material, the plasticity theory of traditional full density metal based on the constant volume condition can not be used to analyse the deformation of sintered powder material. In the plastic deformation of sintered powder material, the constant mass condition[1-4] is obeyed. The constant

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mass condition can be expressed as follows

$$\left.\begin{aligned} & d\varepsilon_v + d\varepsilon_\rho = 0 \\ \text{or} \quad & d\varepsilon_1 + d\varepsilon_2 + d\varepsilon_3 + d\rho / \rho = 0 \end{aligned}\right\} \quad (1)$$

where $d\varepsilon_v$, $d\varepsilon_\rho$—volume strain increasement and density strain increasement respectively; $d\varepsilon_1$, $d\varepsilon_2$, $d\varepsilon_3$— the principal strain increasements respectively; $d\rho$, ρ— relative density increasement and relative density respectively of the sintered powder material.

For the preform of a sintered powder material, if the volume strain ε_v in plastic working is obtained, then we can calculate its relative density from the integral of equation (1)

$$\rho = \rho_o \exp(-\varepsilon_v),\ d = d_o \exp(-\varepsilon_v) \quad (2)$$

where ρ_o, d_o— initial relative and absolute densities respectively of the preform; ρ, d—relative and absolute densities respectively in the plastic deformation.

2.2 *Transverse Deformation*

Transverse deformation can be measured by means of uniaxial compression of cylindrical specimens. For fully dense materials the transverse strain is half the axial strain, i. e. Poisson's ratio $\nu = 0.5$. For a sintered powder material, the axial deformation can not be split thoroughly into two transverse deformations, and its transverse deformation is less than that of fully dense materials, i. e. its Poisson's ratio is less than 0.5. Experiments demonstrate that Poisson's ratio for sintered powder material in plastic deformation is not related to chemical composition and initial density, but it is a function[1, 3] of the instant relative density during plastic deformation. The function is $\nu = 0.5\rho^a$. In hot deformation a = 2, in cold deformation a = 1.92. After analyzing the expression for Poisson's ratio, the authors point out that assuming a = 2 both in hot and cold deformation can simplify the calculation, the calculation error is small[4], i. e. Poisson's ratio can be expressed as follows

$$\nu = 0.5\rho^2 \quad (3)$$

2.3 *Yield Condition*

That the yield of sintered powder material is related not only to the stress derivation but also to hydrostatic pressure is verified by the production of sintered powder parts. The basic expression of the yield condition[1-3] is as follows

$$1/2[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] + (\alpha\sigma_m)^2 = (\beta\sigma^o_{0.2})^2 \quad (4)$$

where σ_1, σ_2, σ_3— there principal stresses respectively; σ_m—the hydrostatic pressure, and $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$; $\sigma^o_{0.2}$—the yield strength of of matrix material; α, β—the yield coefficients of hydrostatic pressure and porosity respectively, both related to the relative density of the sintered powder material.

In cold plastic deformation, the yield strength of the matrix of sintered powder material is a variable because of deformation hardening. Therefore, expression (4) can only analyse the initial yield of a sintered powder material, and it is not easy to analyse the following yield and deformation law in plastic deformation. So, the authors proposed that $(\beta\sigma^o_{0.2})$ can be substituted by the following equivalent yield strength $\sigma^0_{0.2}$. Then we have

$$1/2[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] + (\alpha\sigma_m)^2 = \sigma^2 \quad (5)$$

From plastic potential theory and expression (5) for the gield, we can derive the following stress-strain relations

$$\left.\begin{aligned} d\varepsilon_1 &= d\lambda[\sigma_1 - (1 - 2/9\alpha^2)\sigma_m] \\ d\varepsilon_2 &= d\lambda[\sigma_2 - (1 - 2/9\alpha^2)\sigma_m] \\ d\varepsilon_3 &= d\lambda[\sigma_3 - (1 - 2/9\alpha^2)\sigma_m] \end{aligned}\right\} \quad (6)$$

where $d\lambda$—non-negative constant.

3 DETERMINATION OF THE EQUIVALENT YIELD STRENGTH

The equivalent yield strength can be determined by means of uniaxial compression of cylindrical sintered specimens. If orthogonal coordinates 1, 2, 3 express radial, azimuthal and axial directions respectively, then stress and strain components in uniaxial compresion are as follows

$$\sigma_1 = \sigma_2 = 0, \quad \sigma_3 = -\sigma \tag{7}$$

$$d\varepsilon_1 = d\varepsilon_2 = -\nu d\varepsilon_3, \quad d\varepsilon_3 = -d\varepsilon \tag{8}$$

Substituting the stress components of expression (7) into the yield condition (5) and stress strain relation (6), considering Poisson's ratio $\nu = -d\varepsilon_2 / d\varepsilon_3 = 0.5\rho^2$, and rearranging the equation, we find

$$\sigma^0_{0.2} = \sqrt{1 + 1/9\alpha^2}\ \sigma \tag{9}$$

$$\alpha = 3\sqrt{(1-\rho^2)/(2+\rho^2)} \tag{10}$$

The yield stress σ of a sintered powder material in uniaxial compression is related to its chemical composition, instant density, deformation temperature, initial density, etc. In order to determine σ and the equivalent yield strength $\sigma^0_{0.2}$, uniaxial compression experiment were done with sintered copper. Specimens were made from electroytic powder copper (purity of Cu$\geqslant$99.9%) by a process of blending, compacting and sintering. The sintering atmosphere was cracked ammonium. The sintering temperature was 920±10℃. The sintering time was 2 h. The compression test was conducted on a WI–60 type materials test machine at room temperature. Specimens used in uniaxial compression were cylinders of sintered copper. In order to minimize friction between the interfaces of specimens and tool, the contact surfaces of specimens and tool were ground and polished and smeared with a lubricating zinc stearate-alcohol paste. Each specimen was compressed ten times. The pressure and specimen dimensions were measured and recorded each time. Therefore, the true stress σ and strain ε are obtained. According to the form of the experimental σ–ε curve, an experimental σ–ε equation is derived by means of curve fitting and relation analysis. The initial paramet- ers and experiment equations are shown in Table 1. From Table 1 we find that the plastic coefficient A and strengthening exponent n of each sintered specimen vary with its initial relative density. The functions relating A and n to ρ_o, can be derived by means of curve fitting and relation analysis as mentioned above

$$\left.\begin{aligned} A &= -196.81 + 656.69\rho_o \\ n &= 0.9301 - 0.6171\rho_o \end{aligned}\right\} \tag{11}$$

Then the stress-strain relation of sintered copper in uniaxial compression is

$$\sigma = A\varepsilon^n \tag{12}$$

Table 1 Initial parameters of specimens for uniaxial compression and experimental σ–ε equations

No	weight /g	height /mm	diameter /mm	relative density	σ / MPa
1	253.0	44.80	29.88	0.9049	$\sigma = 391.26\varepsilon^{0.3645}$
2	238.8	45.08	29.74	0.8568	$\sigma = 384.78\varepsilon^{0.4215}$
3	225.0	44.68	29.62	0.8211	$\sigma = 343.62\varepsilon^{0.4061}$
4	252.8	45.28	29.72	0.9043	$\sigma = 395.71\varepsilon^{0.3733}$
5	224.8	44.48	29.35	0.8393	$\sigma = 344.39\varepsilon^{0.4072}$
6	239.1	45.08	29.65	0.8631	$\sigma = 337.97\varepsilon^{0.3771}$
7	209.9	40.68	29.08	0.8729	$\sigma = 398.91\varepsilon^{0.4273}$
8	209.8	40.60	29.22	0.8658	$\sigma = 372.09\varepsilon^{0.3895}$
9	220.3	43.30	29.15	0.8566	$\sigma = 379.04\varepsilon^{0.4304}$
10	219.6	43.44	29.20	0.8482	$\sigma = 353.26\varepsilon^{0.4051}$

Substituting the strain components of expression (8) in uniaxial compression into the constant mass condition expression (1), and considering Poisson's ratio $\nu = 0.5\rho^2$, we have

$$d\varepsilon = d\rho / \rho(1-\rho^2)$$

Integrating the equation above, we have

$$\varepsilon = \ln(\rho/\rho_o\sqrt{(1-\rho_o^2)/(1-\rho^2)}) \tag{13}$$

The relation between axial strain and relative density for sintered powder material in uniaxial compression is determined by equation (13). Substituting equation (13) into equation (12), we find the following relation between the axial stress and relative density of sintered powder materials in uniaxial compression

$$\sigma = A[\ln\rho/\rho_o\sqrt{(1-\rho_o^2)/(1-\rho^2)}]^n \tag{14}$$

Substituting equation (14) into equation (9), we have the following equivalent yield strength of sintered powder materials

$$\sigma_{0.2} = \sqrt{1 + 1/9\alpha^2}\, A[\ln \rho / \rho_o \sqrt{(1-\rho_o^2)/(1-\rho^2)}]^n \qquad (15)$$

If the initial relative density of a sintered copper preform is equal to the loose relative density, i. e. $\rho_o \approx 0.3$, then the preform corresponding to this density will have no mechanical strength. Substituting $\rho_o = 0.3$ into equation (11), we have $A = 0$, $\sigma = 0$, which demonstrate experimental equation (11) is correct to the minimum relative density. If the initial relative density of a sintered copper preform $\rho_o = 1$, i. e. sintered copper is changed into fully dense copper, then from equation (11) we have $A = 460$ MPa, $n = 0.313$, the plastic coefficient 448 MPa and strengthening exponent 0.443 of full dense copper respectively. This demonstrates experimental equation (11) is correct to the maximum relative density.

4 DEFORMATION PRESSURE AND DENSIFICATION

In plastic deformation of sintered powder material, if the density of the preform is increased to a certain value, then the deformation pressure needed to density is not only related to its forming process, but also to its initial density. Because the initial density of tpreform can greatly influence the compacting and plastic working process, the relation between the deformation pressure and densification for sintered powder materials in uniaxial compression, plane strain and closed die upsetting (see Fig. 1) was investigated. The specimens manufacture and experimental conditions were the same as above. The initial parameters for specimens subjected to uniaxial compression are shown in Table 1. Rectangular specimens made from sintered copper were used in plane strain, and the initial parameters of the specimens are shown in Table 2. Cylindrical specimens made from sintered copper were used in closed die upsetting, and their initial parameters are shown in Table 3. Die diagram and experimental results are shown in Figs. 2–4 respectively.

From an analysis of experimental results shown in Fig. 2–4, we can induce the characteristics for deformation and densification of sintered powder materials as follows.

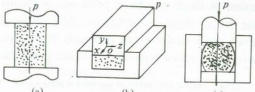

Fig. 1 Experimental Scheme

(a)—uniaxial compression; (b)—plane deformation; (c)—closed die uppsetting

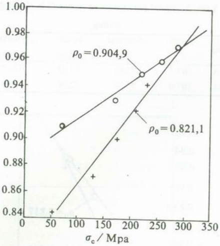

Fig. 2 Experimental results for uniaxial compression

σ_c—deformation resistance; ρ—density of the preform

(1) With the increase of preform density in plastic deformation, the deformation pressure increases rapidly. The form of the deformation pressure-relative density curve in uniaxial compression is similar to the form of the curve in plane strain, and these two curves are

apparently different from the curve in closed die upsetting. Comparing these three curves, we know that with the increase of deformation pressure the relative density of the preform in plastic deformation increases much more rapidly along the curves of uniaxial compression and plane strain than along the curve of closed die upsetting. The causes are that there is large shear strain in plastic deformation by uniaxial compression and plane strain, and the densification in these two basic processes is mainly due to of shear deformation. Also there is small shear strain which is mainly concentrated in the corners of the preform in plastic

Table 2 Initial parameters of specimen in plane strain

No	weight / g	length / mm	width / mm	height / mm	relative density
11	134.3	44.11	15.11	29.82	0.743
12	142.6	44.55	14.98	29.39	0.817

Table 3 Initial parameters of specimen in closed die upsetting

No	weight / g	diameter / mm	height / mm	relative density
13	107.1	23.62	32.22	0.827
14	107.0	23.36	32.96	0.849

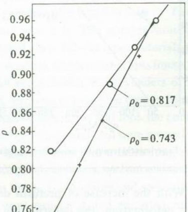

Fig. 3 Experimental results for plane strain

deformation of closed die upsetting and densification in this process is mainly due to repressing deformation. Therefore, the densification efficiency of shear deformation is much higher than that of repressing deformation.

(2) The value of the tamgemt pressure-relative density curve increases with the decrease of initial relative density of the preform. That is a preform with low a relative density has a high densification speed in plastic deformation;

(3) If plastic deformation is used to densify a preform near full density, then a preform with low initial density has to be employed, and it must be deformed by means of a large shear deformation. A low density pre- form is not only easy to compact but also easy to deform and densify in plastic working. But one has to be centain that low density preform has low plasticity.

5 CONCLUSIONS

(1) Equation (14) gives the relationship between stress and relatives density for sintered copper subjected to uniaxial compression;

(2) The equivalent yield strength for sintered powder materials is given by equation (15);

(3) The deformation pressure and the law of densification for sintered copper were investigated by means of uniaxial compression, plane strain and closed die upsetting. It is

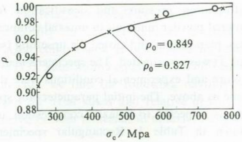

Fig. 4 Experimental results for closed die upsetting

noted that shear deformation is effective in the densification by plastic working of sintered powder mater- ials. On the condition of meeting the need of forming plasticity, low density preform can be used in the production of sintered powder parts.

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for a general sheet is such one every peak of which meets equations (15) and (24).

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