SIMULATION OF CYLINDRICAL UPSETTING OF POROUS MATERIALS BY FINITE ELEMENT METHOD[①]

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ABSTRACT An important concern in forging of metal material is whether the desired deformation can be accomplished without failure of the work materials. In this paper, based on the plastic theory of porous metal materials, the compressible rigid plastic finite element method(FEM) was used to simulate the deformation processes of cylindrical upsetting of porous metal materials with full account of contact friction boundary conditions(m), the height to diameter ratio(H/D) and the initial relative density(R_0). Furthermore, combining the simulation results with the ductile fracture criterion, which is a strain-based criterion obtained by Lee and Kuhn, the critical technological parameters were predicted. This study revealed that larger height to diameter ratio and less friction factor can delay the local strain locus to intersect with the Lee-Kuhn's fracture line, delaying the occurence of the surface crack. Meanwhile, it revealed that the initial relative density affects little on the forming of the crack. And the results of the finite element method agreed well with the experiment results of Lee and Kuhn.

Key words porous metal materials the critical technological parameters defects

1 INTRODUCTION

Powder metallurgy (P/M) forging is a craft with no or little cutting, which is developed by combining the traditional P/M technology with the precise forging. It has widely application for its unique advantages such as high efficiency, high quality, low cost and energy consume etc. However, there are lots of voids in porous metal materials, so surface fracture or interior crack always occurs during plastic deformation if the technology or die design is unreasonable. These defects will affect the successive processes and utilization. If we have known the metal flow patterns and the critical conditions at which defects don't occur, we can take some measures to avoid defects, so as to assure the quality of products and raise the economy benefits.

Over the last few years, many papers[1-4,8] on defects prediction for full dense materials during the plastic deformation were published. However, only few papers studying defects of porous materials were publicly reported so far. This paper uses the compressible rigid-plastic finite element method (FEM) to simulate the deformation processes of cylindrical upsetting of porous metal materials. The surface defects are studied and the critical technological parameters are predicted in terms of the local strain criterion obtained by Lee-Kuhn's experiments.

2 BASIC THEORY AND FEM FORMULATION

The most difference between porous materials and full dense materials is that the volume of porous materials is changed during plastic deformation. In the constitutive relation, it is as-

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sumed that the porous material is continuous and isotropic and that the deformation does not produce anisotropy. This paper adopts the yield function for porous materials proposed by Doraivelu *et al*[6]. It is further assumed that the yield function of the porous materials can be represented by the following expression:

$$f = AJ'_2 + BJ_1^2 = Y_R^2 = \delta Y_0^2 \quad (1)$$

where $A = R^2 + 2$, $B = 1 - A/3$ and $\delta = (R^2 - R_c^2)/(1 - R_c^2)$ are functions of the relative density R; R_c is the critical relative density, at which the material loses its strength. Y_R denotes the yield stress of porous materials in uniaxial compression, and Y_0 denotes the yield stress of fully dense materials, J'_2 and J_1 are stress invariant.

Based on the yield function given in equation (1) and the plasticity theory of porous materials, we have

$$\sigma_{ij} = \frac{\bar{\sigma}_R}{\dot{\bar{\varepsilon}}_R}\left[\frac{2}{A}\dot{\varepsilon}_{ij} + \frac{\delta_{ij}}{3(3-A)}\dot{\varepsilon}_{kk}\right] \quad (2)$$

where $\dot{\varepsilon}_{ij} = (v_{ij} + v_{ji})/2$ is a strain rate component, $\bar{\sigma}_R = \sqrt{3(AJ'_2 + BJ_1^2)}$ is the effective stress and $\dot{\bar{\varepsilon}}_R = \sqrt{\frac{2}{A}\dot{\varepsilon}'_{ij}\dot{\varepsilon}'_{ij} + \frac{1}{3(3-A)}\dot{\varepsilon}_{kk}}$ is the effective strain rate.

Because porous materials is compressible during the plastic deformation, this paper adopts the compressible rigid-plastic finite element method to simulate the plastic deformation. For this problem, the only difference between porous materials and von Mises materials is that effective stress and strain include the hydrostatic stress component and the volumetric rate. Therefore, this paper utilize the discretization theory similar to the von Mises materials, only except the limit of incompressible condition.

The variational form of equilibrium equation for porous medium is

$$\delta\pi = \int_V Y_R \delta\dot{\bar{\varepsilon}}_R \mathrm{d}V - \int_S T_i \delta v_i \mathrm{d}S = 0 \quad (3)$$

The variational function can be converted to non-linear algebraic equation by utilizing the FEM discretization procedure. The solution of the non-linear simultaneous equations can be obtained by Newton-Raphson method.

3 LOCAL CRITICAL STRAIN CRITERION

Lee-Kuhn[5, 7] put forward a practical technique judging the workability limit during some technological conditions, which successfully applied the conventional upsetting experiments into the porous materials. In their experiments, they used little grids to mark and measure the axial and circumferencial strain at the equator surface of the cylindrical disk. These strains can be changed through changing the friction and the height to diameter ratio. The regression curve from the obtained surface strains is a line, which slope is 1/2 in the coordinate system consists of the axial and circumferential strain. The criterion is expressed as

$$\varepsilon_{\theta c} = a - \frac{1}{2}\varepsilon_{zc} \quad (4)$$

where subscript c represents the value at cracking. The intercept had been believed to depend on the properties of the materials, and be constant for each materials. $\varepsilon_{\theta c}$ and ε_{zc} are the circumferencial and axial strains.

For even compressive process with no friction, the fracture line is through the original point, and the circumferencial strain is zero, which never cause surface defects. However, when there exists friction, the slope of the fracture line is also 1/2, but the intercept with the y axis is not zero. Different material has different intercept. For example, the intercept of 601AB aluminum alloy powder is 0.14. For each material, the crack will occur when local strain locus at the equator intercepts with the fracture line during plastic deformation at the constant height to diameter ratio and friction.

4 RESULTS AND ANALYSIS

This paper develops the corresponding FEM software to analyze plastic deformation of porous materials. In order to study the critical conditions of causing the defects, this paper realizes the tracking technique to obtain the local circumferencial and axial strains at equator area. At last, combing the Lee-Kuhn's criterion and the strain locus, the critical technological parameters are obtained.

4.1 FEM analysis

At different height to diameter ratio (H/D), friction factor(m) and initial relative density(R_0), the plastic deformation of 601AB have been simulated. Fig. 1 shows its initial grids and the deformed grids when the H, D, m and R are 20, 20, 0.3 and 0.85, respectively.

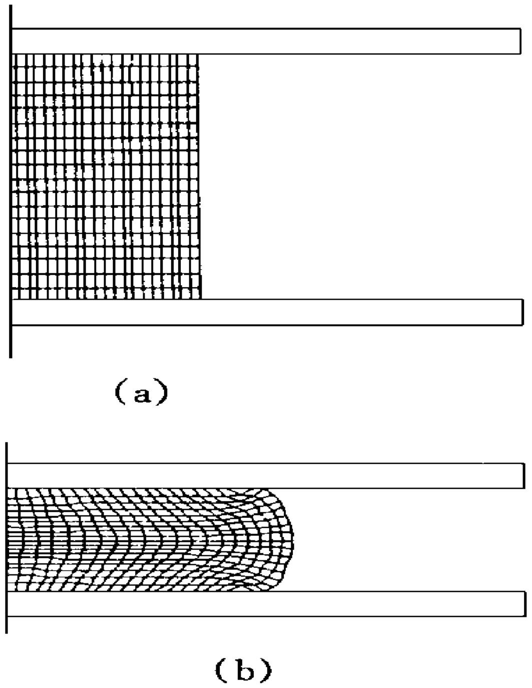

Fig. 1 Grid before and after deformation of deforming body
(a) —Initial grid;
(b) —Deformed grid at 50% relative compressive deformation

Fig. 2 shows the distribution of relative density and effective strain of deforming body at 50% relative compressive deformation. The relative density and effection strain distribute unevenly. The nearer the surface, the lower the relative density. The reason is that the metal at equator area is in the state of tensile strain due to friction. The lower the relative density, the more the void, which results in crack.

4.2 Effect of friction

Friction affects a lot on the plastic deformation, so it is very important and meaningful to study the effect on the defects forming. Fig. 3 shows the effect of friction on the strain path and the critical strains.

Fig. 3 shows that $d\varepsilon_\theta/d\varepsilon_z$ gets deeper as the friction factor increases, leading to a lower critical strain. These agree with the results of Lee-Kuhn's experiments. As the friction factor increases, the bulging phenomenon becomes more prominent and the distribution of the relative density is more uneven. In the bulging area, the

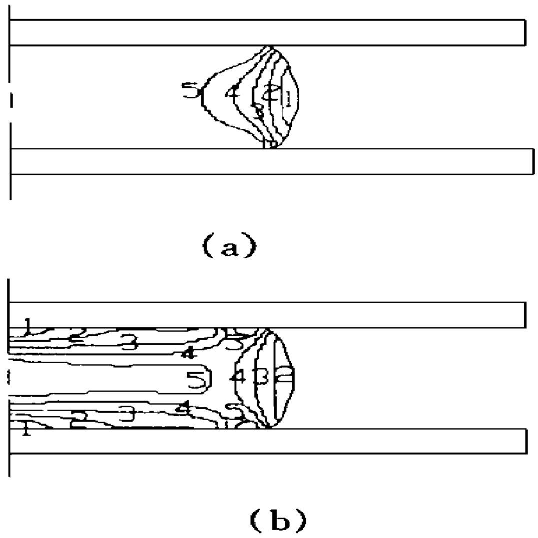

Fig. 2 Distribution of relative density and effective strain at 50% relative compressive deformation
(a) —Relative density
1 —0.913586; 2 —0.930389;
3 —0.963996; 4 —0.98079; 5 —0.99760
(b) —Effective strain
1 —0.66756; 2 —0.79267; 3 —0.91777;
4 —1.04288; 5 —1.16798

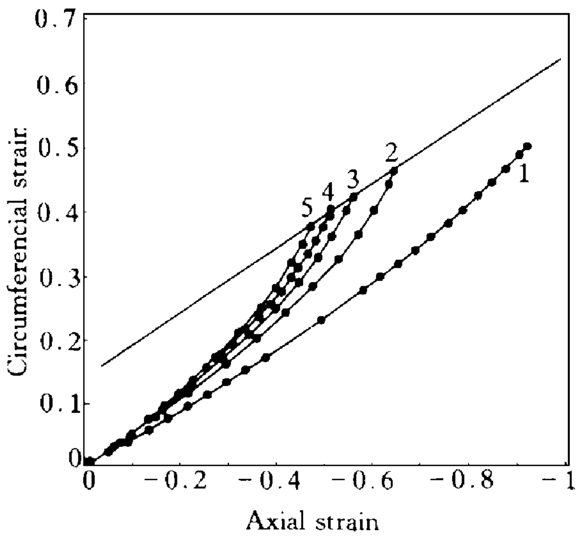

Fig. 3 Effect of friction on the strain path
1 —m = 0.1; 2 —m = 0.3; 3 —m = 0.4;
4 —m = 0.5; 5 —m = 0.6

less the relative density is and the more the void is, in which defects occur at first. Therefore, larger friction factor results in defects early and easily, and the defects could be decreased by improving the lubrication conditions.

4.3 Effect of the height to diameter ratio

This paper has studied the effect of the height to diameter ratio between 0.4~ 1.5 on the strain path and the critical strain. (shown in Fig. 4)

Fig. 4 shows that $d\varepsilon_\theta/d\varepsilon_z$ gets gentler as the height to diameter ratio increases, which causes the strain paths to intersect the fracture line later than those with a lower H/D, so the critical strain is larger.

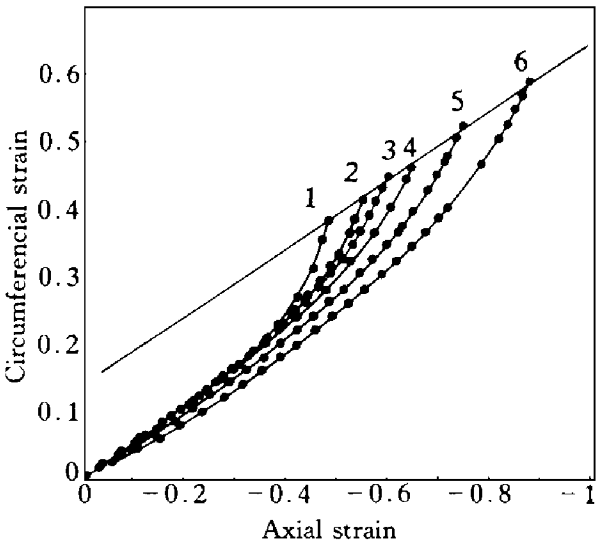

Fig. 4 Effect of the height to diameter ratio on the strain path

1—H/D= 0.4; 2—H/D= 0.6; 3—H/D= 0.8; 4—H/D= 1.0; 5—H/D= 1.25; 6—H/D= 1.5

4.4 Effect of initial relative density

This paper selects three initial relative density(R_0= 0.85~ 0.90) to simulate the plastic deformation. Fig. 5 shows the effect of initial relative density on the strain path and the critical strain.

From Fig. 5, it can be seen that the initial relative density affects little on the strain path and the fracture strain. When the initial relative density is less, the void degree is higher, so the ability of resisting fracture decreases. However, when the initial relative density decreases, the void degree lower, the Poisson ratio decreases and the ability side of extension decreases, so the bulging phenomenon becomes light and the circumferencial strain decrease. The initial relative density affects little on the total compressive strain. However, if the density of bulging area is less than R_c, the deforming body will lose its strength.

4.5 Critical technological parameters

According to a series of critical strains from the simulation at different condition, the critical locus can be obtained, showing in Fig. 6. The area below the locus is the safe area, and that above the locus is the fracture area. Furthermore, from Fig. 6, it can be seen that, larger H/D and less friction factor can delay the occurrence of the crack, however, the initial relative density affects it little. The figure shows that the FEM results agrees well with the experimental results[7] of Lee-Kuhn.

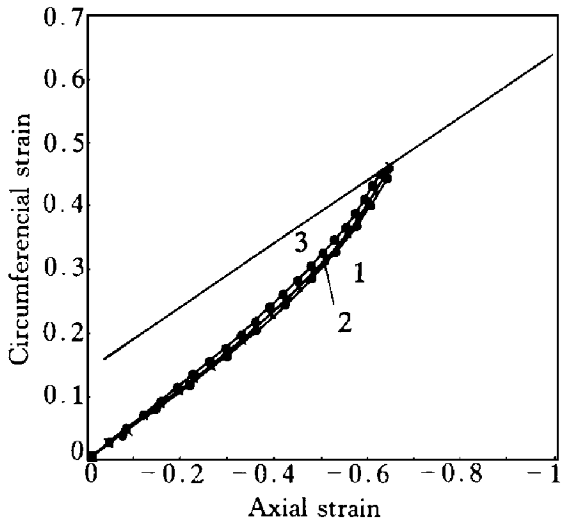

Fig. 5 Effect of the initial relative density on the strain path

1—R_0= 0.85; 2—R_0= 0.875; 3—R_0= 0.90

5 CONCLUSIONS

This paper regards the porous materials as the study object. The workability limits for upsetting disk have been predicted by using the compressible rigid - plastic finite element analysis

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4 CONCLUSIONS

(1) The electroreduction of Ni(II) in urea-NaBr-KBr melt is irreversible in one step and the nickel is deposited on the cathode.

(2) The transfer coefficient of the reaction Ni(II) + 2e= Ni is determined as about 0.4 and the exchange current density is determined as $1.1 \times 10^{-6} A \cdot cm^{-2}$ at 100 ℃.

(3) The electroreduction of Ti(IV) in urea-NaBr-KBr melt before the limit of the background is corresponding to the reaction Ti(IV) + e= Ti(III).

(4) The Ti-Ni alloy can be electrodeposited in the urea-NaBr-KBr-$NiCl_2$-$TiCl_4$ melt. The titanium content changed with the cathode potential and reached 59% (in mole) at − 0.90 V.

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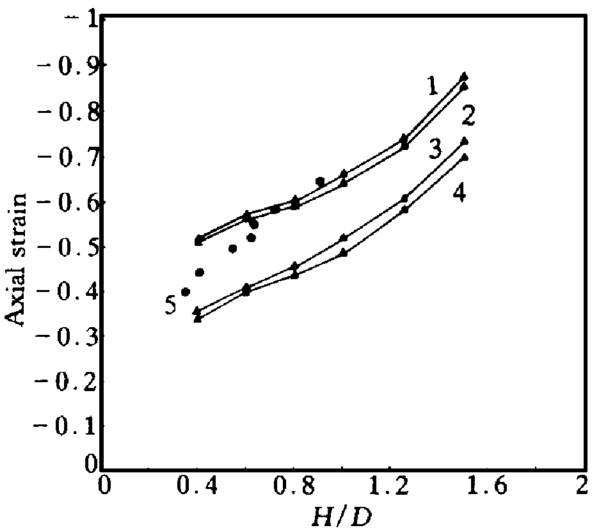

Fig. 6 The critical technological parameters

1 —m= 0.3, R_0= 0.85; 2 —m= 0.3, R_0= 0.90; 3 —m= 0.5, R_0= 0.85; 4 —m= 0.5, R_0= 0.90; 5 —Experiment

with full account of contact friction boundary conditions, the height to diameter ratio and the initial relative density, in combination with the Lee-Kuhn's fracture criterion. This discussion reveals the effect of height to diameter ratio, friction factor and initial relative density. From the work, the critical technological parameters were obtained, which can lead to choose the suitable technological parameters to avoid the occurence of fracture. It is very important to guide the practical production according to the critical locus.

Of course, for porous materials, if we want to know the details of defects forming, more work should be done.

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