Study of Workability Limits of Porous Materials under Different Upsetting Conditions by Compressible Rigid Plastic Finite Element Method

X.Q. Zhang, Y.H. Peng, M.Q, Li, S.C. Wu, and X.Y. Ruan

(Submitted 27 January 1999; in revised form 5 November 1999)

Workability limits must be considered when designing powder metallurgy (PM) forging processes. This research successfully applied the general upsetting experiment method to the deformation of porous materials. Based on the plastic theory of porous materials, the compressible rigid plastic finite element method is used to simulate the deformation processes of cold upsetting of disks and rings for porous metal materials with a full account of contact friction boundary conditions, the height-to-diameter ratio, the initial relative density, and the die and workpiece geometry. Furthermore, a successful analysis of the cold forging process results in the prediction of the stress, the strain, and the density field. By coupling with the ductile fracture criterion, which is a strain-based criterion obtained by Lee and Kuhn, possible defects leading to material failure have been checked. This research reveals that larger height to diameter and a lesser friction factor can delay the local strain locus to intersect with the Lee and Kuhn's fracture line and restrain formation of the surface crack. Meanwhile, it reveals that the initial relative density has only a very small influence on the strain to fracture in compression, and it shows the forming behavior of the ring and disk with the curved die. According to Lee and Kuhn's results, the calculated results agree well with the experimental results.

Keywords finite element method prediction, porous materials, relative density, workability limit

1. Introduction

Powder metallurgy (PM) parts has been widely applied in industry, mainly because of their economical and technical advantages; it is possible to make near final shape components of extremely complex geometry and components of high strength. Generally, one way of producing a PM component is described in two steps: cold compaction of powder and subsequent sintering. A known limitation of this route is the residual porosity left in components after sintering. This adversely affects mechanical properties of such components and reduces the usage scope. To obtain more reliable PM products, many secondary processes are applied to PM preforms, among which powder forging is particularly attractive because it allows the cost and material saving advantages of conventional PM, as well as the high production rates and property enhancement of forging. So powder forging is now a viable method for the fabrication of high-strength parts. Meanwhile, along with the increased use of forging operation in industry, there is a need to use modern analytical techniques to assist in the design of process to reduce die development time, to improve the quality of the forging, and to reduce costs. However, there are no general programs to analyze the deformation process of porous metals. So, the finite element program has been developed to analyze the processes at all kinds of conditions in this research.

In the past few years, the finite element method has been used because of its wide applicability and high computational accuracy. Many papers[1-5] on defect prediction for conventional materials during the plastic deformation were published. However, few systematic attempts have been made so far to study the deformation characteristics and fracture mechanics of porous materials using the finite element method. This research develops a finite element procedure to analytically determine the strain path similar to those determined by experimental studies. Meanwhile, the influence of lubrication, height-to-diameter ratio, initial relative density, die, and preform shape on the forming limit of parts is investigated. Because we investigate the cold forging processes, the temperature and strain rate effects are not considered. The locus strains are then calculated and possible defects leading to material failure have been checked. And the calculated and experimental results are compared.

2. Basic Theory for Porous Material and Finite Element Method Formulation

The plastic deformation of powder material is similar to that of conventional materials but is more complicated due to the substantial volume fraction of voids. Although various theories and analysis methods have been developed for analyzing problems in conventional metal forming process, they cannot be applied to PM working directly. For porous materials, not only does the deviation stress cause yielding, but so does the hydrostatic component. Hence, the yielding criterion must depend on both the second invariant of the deviation stress tensor and the first

---

X.Q. Zhang, Y.H. Peng, and **X.Y. Ruan,** National Die and Mold CAD Engineering Research Center, Shanghai Jiao Tong University, Shanghai 200030, People's Republic of China; and **M.Q. Li** and **S.C. Wu,** School of Material Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, People's Republic of China.

invariant of the deviation stress tensor. Therefore, the appropriate yield criterion should take the effect of pores into account. In this research, the criterion provided by Doraivelu and Gegel[6] is adopted, which can be expressed as the following expression:

$$
\begin{aligned}
f &= AJ_2' + BJ_1^2 = Y_R^2 = \delta Y_0^2 \\
A &= R^2 + 2 \\
B &= 1 - A/3 \\
\delta &= (R^2 - R_c^2)/(1 - R_c^2)
\end{aligned}
\qquad \text{(Eq 1)}
$$

In the above equation, J_2' and J_1 are the quadratic stress deviator invariant and the linear stress invariant, respectively. The term Y_R denotes the yield stress of porous materials with a relative density R, and Y_0 is the yield stress of $R = 1$. For work-hardening materials, Y_0 and Y_R are the flow stresses of nonporous and porous metals, respectively. The parameter R_c is an experimental parameter, which can be interpreted as a critical relative density, where the yield stress of porous metal becomes zero. Since for nonporous metals $R = 1$ and $Y_R = Y_0$, Eq 1 becomes the Von Mises yield criterion, namely, $3J_2' = Y_0^2$.

Under the assumption of continuous, isotropic hardening and isothermal conditions, and based on the yield function in Eq 1 and the plasticity theory of porous materials, we have

$$
\begin{aligned}
\sigma_{ij} &= \frac{\bar{\sigma}_R}{\dot{\bar{\varepsilon}}_R}\left[\frac{2}{A}\dot{\varepsilon}_{ij} + \frac{\delta_{ij}}{3(3-A)}\dot{\varepsilon}_{kk}\right] \\
\dot{\varepsilon}_{ij} &= (v_{i,j} + v_{j,i})/2 \\
\bar{\sigma}_R &= \sqrt{3(AJ_2' + BJ_1^2)} \\
\dot{\bar{\varepsilon}}_R &= \sqrt{\frac{2}{A}\dot{\varepsilon}_{ij}'\dot{\varepsilon}_{ij}' + \frac{1}{3(3-A)}\dot{\varepsilon}_{kk}}
\end{aligned}
\qquad \text{(Eq 2)}
$$

Because porous material is compressible in forging, this paper uses the compressible rigid-plastic finite element method to simulate the plastic deformation. For this problem, the difference between porous materials and conventional materials is that effective stress and strain include the hydrostatic stress component and the volumetric rate. Therefore, the discretization theory similar to the Von Mises materials is used in this paper, except for the limit of incompressible condition.

The variational form of the equilibrium equation for porous medium is

$$
\delta\pi = \int_V Y_R \delta\dot{\bar{\varepsilon}}_R \, dV - \int_S T_i \delta V_i dS = 0 \qquad \text{(Eq 3)}
$$

The variational function can be converted to a nonlinear algebraic equation by using the finite element method discretization procedure. The nonlinear simultaneous equations can be solved using the Newton-Raphson method.

3. The Local Critical Strain Criterion

Historically, workability criteria are based on an experiment that uses deformation processes that can be related to actual industrial application. The criteria used in this research are those performed by Lee and Kuhn.[7,8] They have resulted in the determination of forming limits in terms of local strain. The forming limit is based on a plot of tensile strain vs compressive strain and can be used for any process that results in both strains. The fracture strains for a given material lie on a straight line and have a slope of one-half. Therefore, the criterion is expressed as

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

where the subscript c represents the value at cracking. The intercept is believed to depend on the properties of the materials and to be considered as constant for each material. The terms $\epsilon_{\vartheta c}$ and ϵ_{zc} are the tensile and compressive strain, respectively.

For the tested materials, the fracture loci have been observed to have a slope of one-half and to be parallel to the strain path for homogeneous (frictionless) compression. For homogeneous compression with no friction, the freespreading cylindrical surfaces remain straight (no bulging), the circumferencial stress is zero, and surface defects never form under this condition. However, any strain path that curves upward from that path of homogeneous compression will lead to fracture, and the intercept with the fracture line with the ordinate varies with the material and its condition. For example, the intercept of 601AB aluminum alloy powder is 0.14.

4. Results and Analysis

The corresponding finite element method software was developed to study the plastic deformation of porous materials. Axisymmtric upsetting of porous 601AB aluminum alloy with and without friction are simulated in order to examine the effect of the friction, the initial relative density and die shaping. And ring upsetting is also simulated to study the effect of preform shape. The entire initial conditions for calculation is in Table 1. Meanwhile, it assumes homogeneous initial relative density distribution in preform.

4.1 Finite Element Method Analysis

The plastic deformation of 60lAB aluminum alloy has been simulated under different conditions. Figure 1 shows the Corresponding initial mesh and deformed mesh at all conditions. Because of symmetry, only one-half of the geometry is considered. Figures 1(b), (d), and (f) show the predicted grid distortions at 50% reduction in height. When an element is compressed in the axial direction, tensile deformation occurs in the radial direction in response to the imposed compressive stress. The value of plastic Poisson's ratio is less than 0.5 for solid metals because of densification. Since the initial density is homogeneous, the deformation of upper lower halves is symmetrical. The free surface barrels, and the part of the initial free

Table 1 Initial conditions for calculation

Problem considered	Working conditions
Cylindrical disk	$D = 20$, $H/D = 0.4 \sim 2.0$, $m = 0.1 \sim 0.8$
Disk, with curved die	$D = 20$, $H/D = 1$, no friction
Ring	$D = 24$, $D_0{:}D_i{:}H = 6{:}3{:}2$, $m = 0.3$

Notes: D—diameter; H—height and m—friction coefficient

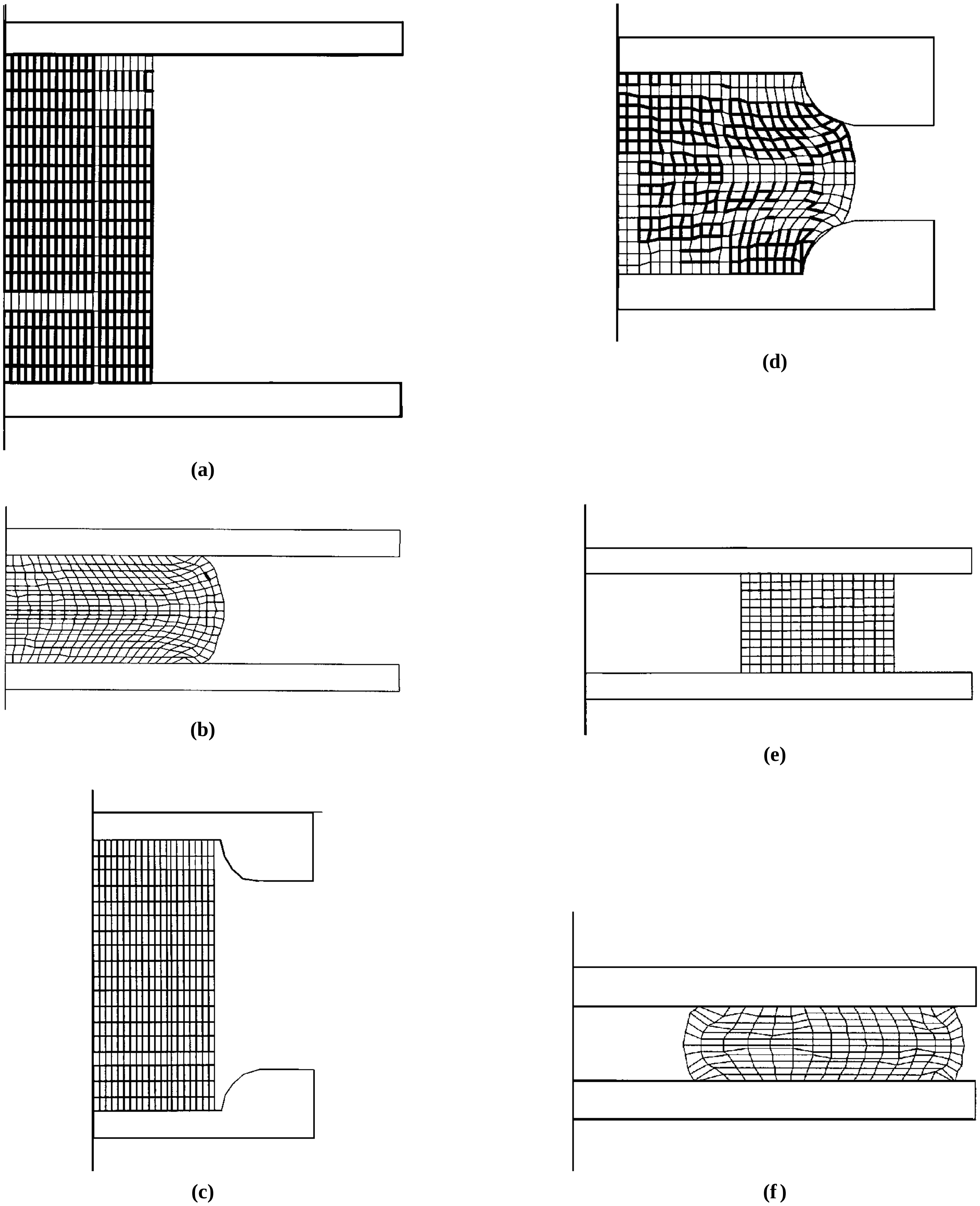
(a) (b) (c) (d) (e) (f)

Fig. 1 Initial and deformed mesh of porous 601AB aluminum alloy, where the reduction in height is 50%. In **(a), (b), (e),** and **(f),** the friction coefficient is 0.3; in **(c)** and **(d),** the friction coefficient is 0.

surface that is close to the die surface comes into contact with the die (the folding phenomenon).

Figures 2(a), (c), and (e) show the relative density distribution at 50% reduction in height. From the result predicted, it can be found that the relative density is lower the nearer it is to the exterior surface. Furthermore, for the ring, the density in the external surface is lower than that in the internal surface.

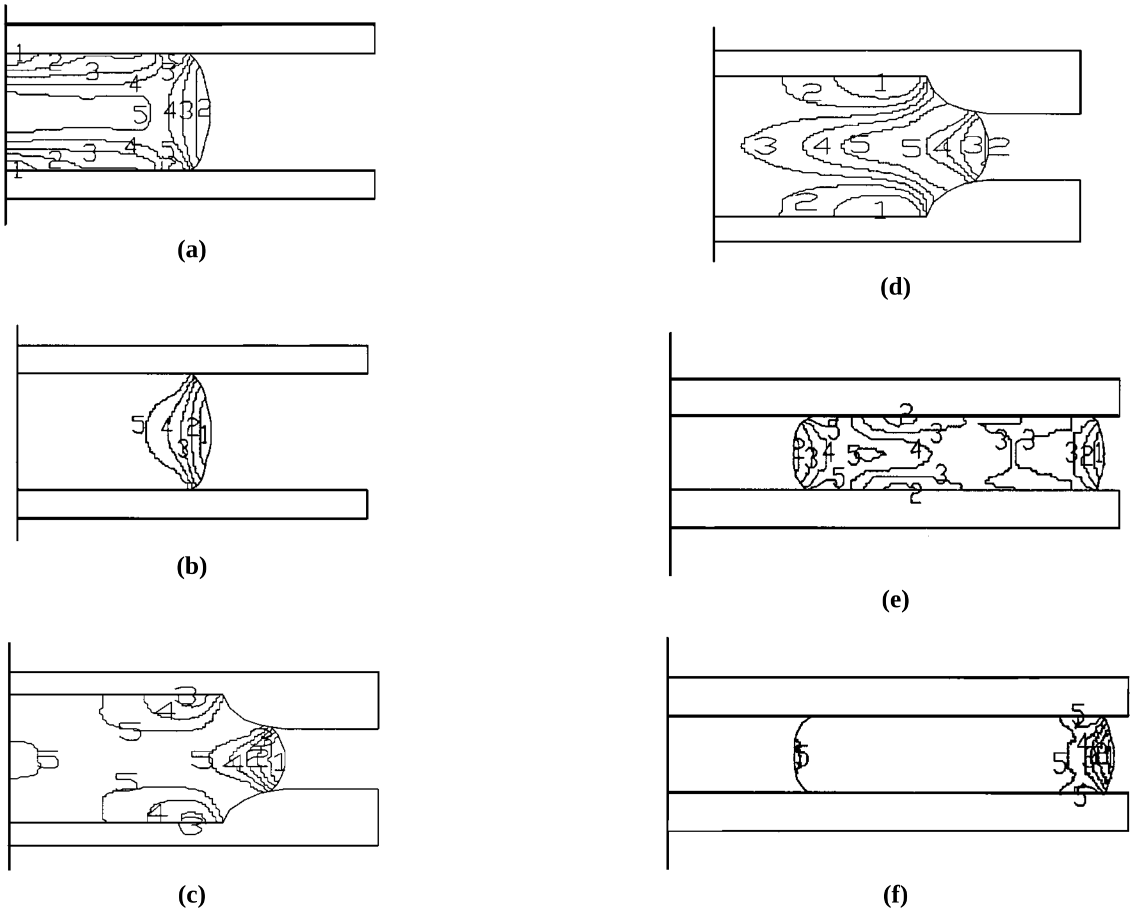

Fig. 2 **(a), (c)** and **(e)** show the relative density distribution at 50% reduction in height. From the result predicted, it can be found that the relative density is lower the nearer it is to the exterior surface. Furthermore, for the ring, the density in the external surface is lower than that in the internal surface. **(b), (d),** and **(f)** show the effective strain distribution at 50% reduction in height, where it distributes homogeneously and is symmetrical because of the effect of friction and die shape.

Figure 2(b), (d), and (f) show the effective strain distribution at 50% reduction in height, where it distributes inhomogeneously and is symmetrical because of the effect of friction and die shape.

4.2 Effect of Friction

Friction has a significant influence on the plastic deformation; in particular, it is very important to study the effect of friction on the type of defects that form during forming. Figure 3 shows the effect of friction on the strain path and forming limits.

Figure 3 shows that $d\epsilon_\vartheta / d\epsilon_z$ is larger as the friction factor increases, resulting in lower forming limits. These agree with the results of Lee and Kuhn's experiments, which depict that the intersection point also increases as the friction decreases. As the friction increases, the barreling phenomenon is more obvious and the distribution of the relative density is more nonuniform. In the barreling area, where circumferential tensile stress exists, the relative density decreases and void formation increases. Therefore, a larger friction coefficient leads to defects early and easily, and the defects could be avoided by improving the lubrication conditions.

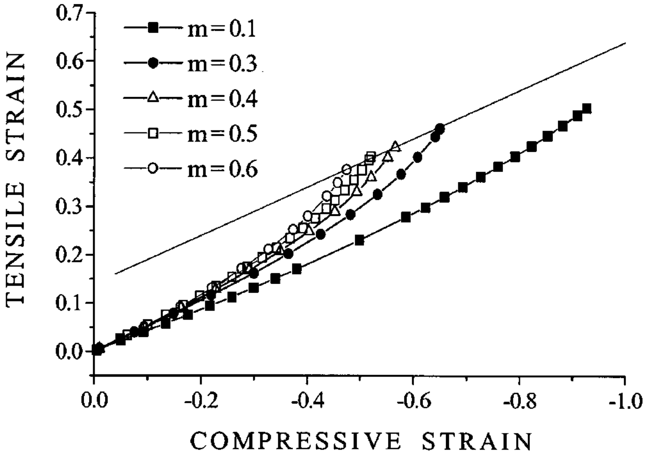

Fig. 3 Effect of friction on the forming limits; the height-to-diameter ratio is 1.0, and the initial relative density is 0.9.

4.3 Effect of Preform Shape and Die Shaping

This research has also studied the effect of the height-to-diameter ratio, preform shape, and die shaping on the strain path and forming limit, which are shown in Fig. 4 to 6.

The characteristics of strain path are also influenced by geometrical factors such as the height-to-diameter ratio, which is known to increase $d\epsilon_\vartheta/d\epsilon_z$ of the curve. Geometrical constraints could be a decisive factor even if the friction is absent. Consider for instance, the upsetting of a cylinder using a curved smooth die. As depicted in Fig. 5, the strain path starts with a slope of one-half, but the slope increases as the block contacts the curved die causing the strain path to diverge from the ideal frictionless straight line, promoting the conditions for free surface cracking. The fact that no friction was applied at all surfaces means that the anticipated fracture is only due to geometrical constraints imposed on the material during deformation. However, the curved die is favorable to densify the block.[8] For the ring case, the behavior is more complicated. The deformation behavior of the metal is different on the internal and external barreled surfaces. It is easier to cause surface cracking on the external diameter than on the internal one. Figure 6 shows the strain path to fracture.

4.4 Effect of Initial Relative Density

This paper selects three initial relative densities to simulate the plastic deformation. Fig. 7 shows the effect of initial relative density on the strain path and the forming limits.

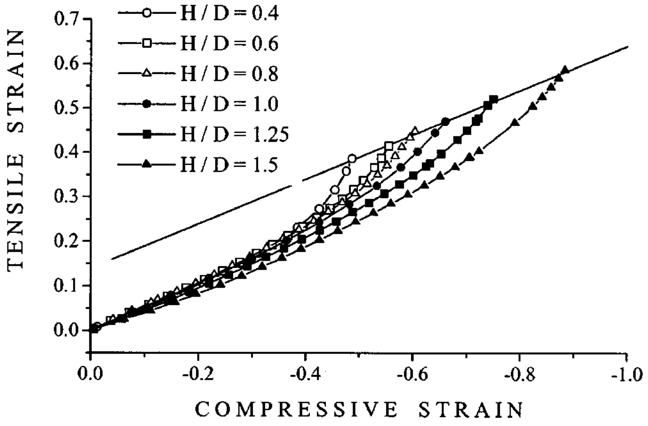

Fig. 4 Effect of the height, to diameter on the forming limits; the friction coefficient is 0.3, and the initial relative density is 0.90.

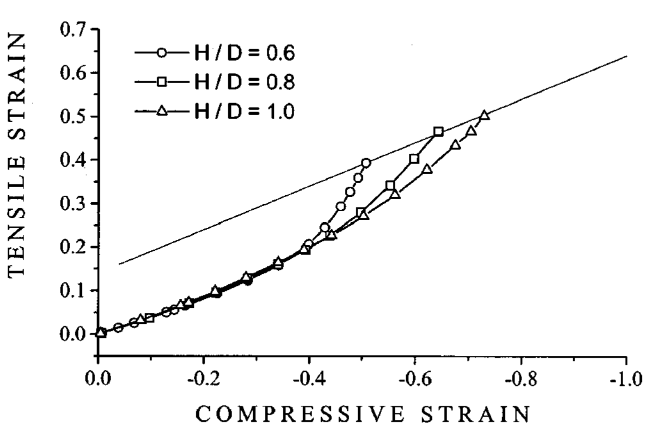

Fig. 5 Effect of the die geometry on the forming limits; the friction coefficient is 0.1, and the initial relative density is 0.9.

From Fig. 7, it can be seen that the initial relative density has only a very small influence on the strain to fracture in compression. This is suggested because fracture is dependent on two factors: the ductility of the material and the localized tensile stress at the barreled surface. For a lower initial density, on the one hand, increasing porosity leads to a decrease in ductility of the tested materials. On the other hand, increasing porosity also results in a decrease in the tensile stress generated, because the severity of barreling decreases. These two factors counteract and restrict each other. For the same reason, the same restriction exists for a larger initial relative density. Therefore, the initial relative density has a small influence on the total compressive strain. However, if the relative density of the barreling area is less than R_c, the forming body will lose its strength.

4.5 The Forming Limits

According to a series of critical strains from the simulation at different conditions, the forming limits can be obtained, and the

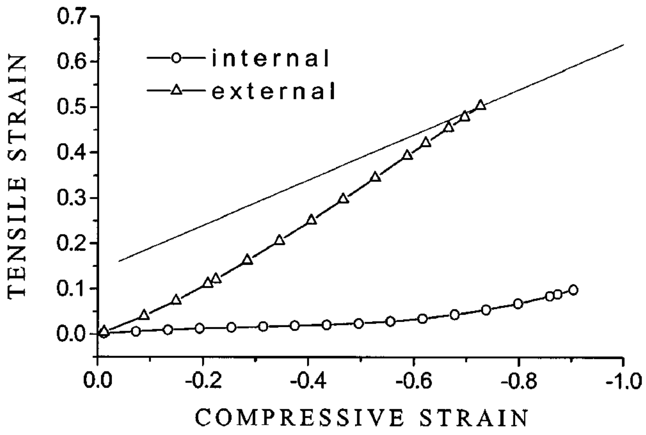

Fig. 6 The strain path on the internal and external barreled surfaces of the ring

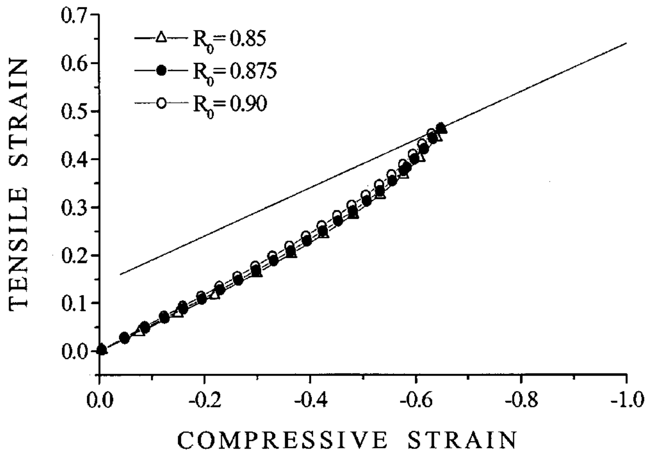

Fig. 7 Effect of the initial relative density on the forming limits; the friction coefficient is 0.3, and the height to diameter is 1.0.

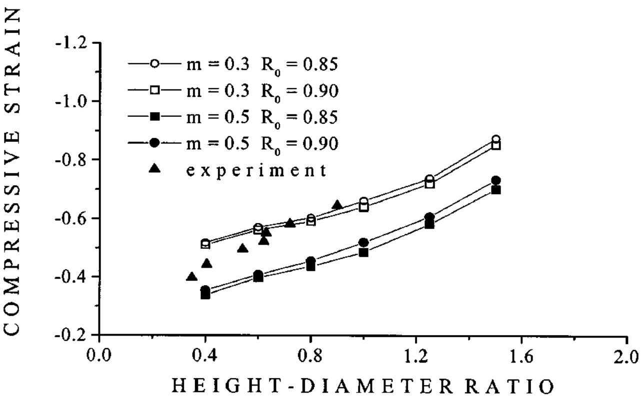

Fig. 8 The forming limit diagram for cylindrical upsetting

results are shown in Fig. 8. The area below the locus is safe, and that above the locus is the fracture area. Furthermore, it can be seen that from Fig. 8, the larger height-to-diameter ratio and lesser friction coefficient can delay the occurrence of the crack; however, the initial relative density has a very small influence on it. The figure also shows that the finite element method results agrees well with the experimental results of Lee and Kuhn.[8]

5. Conclusions

This research investigates the deformation behavior of porous materials during metal forming. The workability limits among the upsetting disks and ring have been predicted using the compressible rigid-plastic finite element in combination with the Lee-Kuhn's fracture criterion. This discussion reveals the effect of the height-to-diameter ratio, friction coefficient, initial relative density, die shape, and preform shaping. The forming limits were obtained from the work. This information can help technicians choose suitable process parameters and avoid the occurrence of fracture. It is very important to guide the production practice according to the forming limits. Of course, for porous materials, the details of defects forming will come from further research.

Acknowledgments

The authors wish to thank the Open Research Fund, National Key Laboratory of Powder Metallurgy, Central South University of Technology (Changsha, People's Republic of China), for its grant for the work on which this research is based.

References

1. Y.H. Peng and X.Y. Ruan: *J Mater. Proc. Technol.,* 1994, vol. 45, pp. 539.
2. M.Q. Li, S.C. Wu, and C.R. Tang: *Appl. Mathmatics Mech.,* 1998, vol. 11(8), pp. 733.
3. J.C. Gelin and J. Oudin: *Ann CIRP,* 1985, vol. 34(1), pp. 209.
4. L.F. John and R.P. Bruce: *J. Mater. Shaping Technol.,* vol. 7(1), pp. 57.
5. A.S. Wifi and A. Abdel-Hamid: *J. Mater. Proc. Technol.,* 1996, vol. 56(1), pp. 918.
6. S.M. Doraivelu and H.L. Gegel: *Int. J. Mech. Sci.,* 1984, vol. 26 (9-10), pp. 52.
7. P.W. Lee and H.A. Kuhn: *Metall. Trans.,* 1973, vol. 4, pp. 969.
8. P.W. Lee and H.A. Kuhn: *P/M Forging, in Powder Metallurgy,* vol. 7, 9th ed., Metals Handbook, American Society for Metals, 1984, pp. 410.