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Investigation on the factors influencing the thickness distribution of superplastic-formed components*

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Abstract: In the superplastic sheet forming process, the uniformity of the sheet's final thickness distribution is vital for ensuring the good mechanical quality of the formed components. The influences of the component shape and the contact friction on the final thickness distribution were investigated in this work by using finite element method on a series of axisymmetric models. It was concluded that shape optimization and friction elimination are required to get uniform thickness distribution, and eventually to improve the mechanical quality of the formed components. The constitutive equation of the Ti-6Al-4V superplastic material was also determined on the basis of experimental data.

Key words: Thickness distribution, Component shape, Contact friction, SPF, Ti-6Al-4V
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INTRODUCTION

The superplastic forming (SPF) process involves a combination of large displacements, large strains and frictional contact over large areas between the sheet and mould (Yu and Zhang, 1995). For such a complex mechanical process, numerical analysis is preferably used because of its very flexible application to various materials, structures and boundary conditions (Sedaghi and Pursell, 1994). In the review of the numerical analysis of superplastic forming (Wood and Bonet, 1996), it was pointed out that a great number of simulations have been carried out mainly about strain rate control to ensure steady superplastic deformation in the sheet forming process. However, certain factors influencing the final thickness distribution of the sheet have not been fully investigated yet.

Keeping the final thickness distribution uniform is important in sheet forming because nonuniformity weakens the mechanical performance of the thin-sheet components. In practice, the relatively thin regions in the components always cause stress concentration and impair the mechanical strength. The phenomenon is of great importance, particularly for complex shape components bearing crucial loading (Kleinermann and Ponthot, 2003).

In this work, the FE simulation of the SPF process was done to investigate the distinct influences of component shape and contact friction on the thickness distribution of the formed components. The constitutive relation of the Ti-6Al-4V superplastic material was deduced first and then determined on the basis of experimental data. A series of axisymmetric models with different local shapes were simulated to show the effect of component shape on the thickness distribution, and then, the effects of contact friction

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on the minimum thickness and forming parameters were analyzed.

FINITE ELEMENT MODELLING

Model description

Axisymmetric models were used to determine the influences of various factors on the thickness distribution (Comstock *et al*., 2001). The geometrical configuration of the model is shown in Fig.1. There is a protuberant wall inside the mould. Points 1 to 6 denote key points. The path from point 1 to point 6 is defined as "contour line" representing the shape of the formed components.

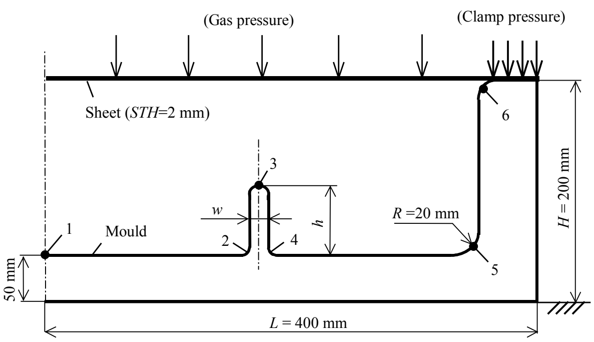

Fig.1 Illustration of an axisymmetric model of superplastic sheet forming

Axisymmetric membrane element was adopted for the sheet. The sheet is "clamped" to the mould at the outer boundary by node constraint equations. Although certain deformation exists in the mould because of high-temperature heat transfer, it has little effect on the studied sheet's thickness distribution. So, the mould can be considered as rigid surface in FE meshing to save much of the computer time in the simulation. Then the FE model becomes simple. But it is indispensable to define a fine and compatible mesh for the contact surfaces of the sheet and mould to ensure that there is no penetration when contact occurs (Garriga-Majo and Curtis, 2001). The argon gas pressure required for sheet forming was 1.0 MPa and the maximum stress induced by it was about 10 MPa.

Constitutive equation of Ti-6Al-4V

Among various superplastic materials, titanium alloy is most widely used in the aerospace industry because of its advantages of small specific gravity, high strength, heat resistance and erosion resistance. A typical titanium alloy, Ti-6Al-4V, was used in this study. For superplastic materials, the flow stress can be written as:

$$\sigma_{\mathrm{f}} = K(\dot{\varepsilon}_{\mathrm{eq}}^{\mathrm{p}})^{m}(\varepsilon_{\mathrm{eq}}^{\mathrm{p}})^{r} \tag{1}$$

where $\varepsilon_{\mathrm{eq}}^{\mathrm{p}}$ is equivalent plastic strain and $\dot{\varepsilon}_{\mathrm{eq}}^{\mathrm{p}}$ is equivalent plastic strain rate. The strength coefficient K, the strain sensitivity index r, and the strain rate sensitivity index m, are material parameters determined by experiment (Ghosh and Hamilton, 1982). These material parameters mainly depend on the grain size evolution dominated by temperature, so they were dominated by temperature too. Because the forming temperature during the sheet forming process is always kept at a given value, these material parameters can be considered as constants.

For small forming strain rate (controlled at 3.0×10^{-4} s^{-1} or so), there is little hardening effect during superplastic forming and no residual stress after forming due to the excellent relaxing behavior of superplastic materials. Eq.(1) can be rewritten as the power-law creep model after ignoring the strain-hardening effect, i.e.

$$\dot{\varepsilon}_{\mathrm{eq}}^{\mathrm{cr}} = A\sigma_{\mathrm{eq}}{}^{n} \tag{2}$$

where $\dot{\varepsilon}_{\mathrm{eq}}^{\mathrm{cr}}$ is the uniaxial equivalent creep strain rate, σ_{eq} is the Mises equivalent stress in the isotropic case. For Ti-6Al-4V, the material parameters A=2.2734E-6 and n=1.754 are determined from the strain measurement described below.

A thin-sheet Ti-6Al-4V specimen was placed in a high temperature environment like the actual forming temperature 900 °C~950 °C, and tested under uniaxial tension loading. The Poisson ratio of the material was 0.29 and the Young's Modulus at 900 °C was 1.0 GPa. The material's strain evolution was measured for different magnitudes of tension loading. A group of fitting curves of strain versus time at 900 °C was then obtained corresponding to different stress levels, which are shown in Fig.2. It is obvious that there is no time-hardening effect. By virtue of the differential forms of these curves, the relations of strain rate versus time for different stress levels could be obtained. The relation between strain rate and stress was then obtained without time variable, so that the parameters A and n can be determined respectively from this relation by a curve-fitting method. The experimental results were verified by comparison with the results of Cope and Ridley (1986).

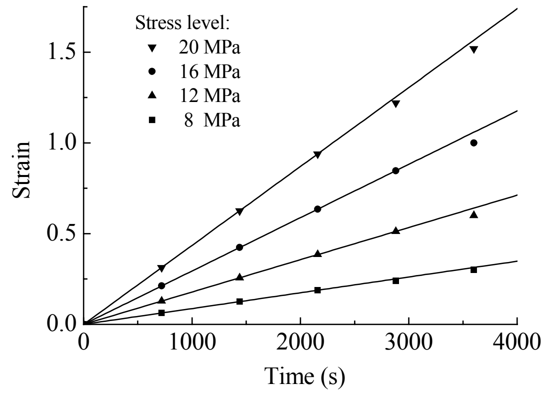

Fig.2 Strain versus time relation under different stress levels at 900 °C

NUMERICAL ANALYSIS OF FACTORS INFLUENCING THICKNESS DISTRIBUTION

Effect of component shape on final thickness distribution

It was found that the final thickness distribution was affected especially by the inside shape of the mould, namely, the shape of the formed component. To investigate the effect of the component shape, the SPF process was simulated with a series of axisymmetric models with different dimensions h and w for the inside protuberant wall (as shown in Fig.1). The final thickness distributions of the sheet along the "contour line" for these models are compared with each other in Fig.3. The numbers 1 to 6 stand for key points defined before.

For the basic model with no wall (i.e. h=0), the numerical results showed that the thinnest position of the formed component lies at its axisymmetric center. The final minimum thickness was about half of the initial thickness (2 mm). The thickness was almost equally distributed within the base of the component but increases rapidly along the outside wall from the inner fillet to the upper fillet. Thus, the nonuniformity of the thickness distribution was mainly concentrated along the outside wall of the component.

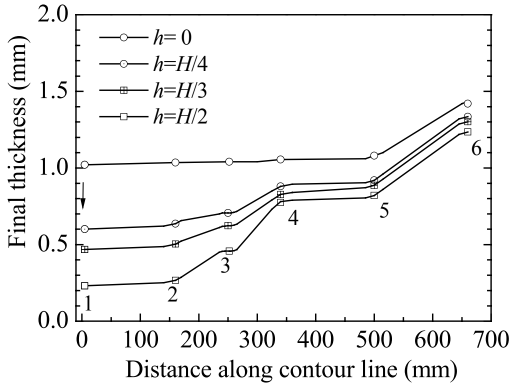

Fig.3 The final thickness distribution of the sheet along the contour line (The distance in *x* coordinate starts from the axisymmetric centre; *h* is height of the inside wall; *H* is height of the mould)

For other models that have an inside wall, the final thickness decreases as a whole with the increase of the inside wall's height. In particular, the thickness around the inside wall was reduced dramatically. As a result, the maximum final thickness difference increases considerably between points 1 and 6 and reaches up to 1.05 mm. The mechanical properties of components will be badly impaired by so great a thickness difference. Furthermore, it was noticed that the thickness distribution was sensitive to the height (but not width) of the inside wall.

On the other hand, the influence of component shape on the thickness distribution was revealed by the different thickness evolutions of certain nodes in the sheet. In Fig.4, the thickness evolutions of the sheet's nodes, which correspond to the critical positions on the mould's surface, are given based on the basic model with no wall. The final thickness difference mainly lies between the nodes corresponding to points 5 and 6, and was determined by the depth of the component. The final thickness difference between the nodes corresponding to points 1 and 5 was closely related to the radius of the component. Besides, the thickness evolution was approximately linear in view of the material's steady deformation, which was ensured by optimal strain rate control.

Since the component shape influences the final thickness distribution remarkably, the proper design shape of a component is vital to its robust mechanical properties. Local sharp protuberance should be avoided if possible. In addition, it was shown that very high pressure and long time were needed to shape the inner fillet at the end of the forming process. So the curvature radius of the concave surfaces should not be too small if cost saving is considered.

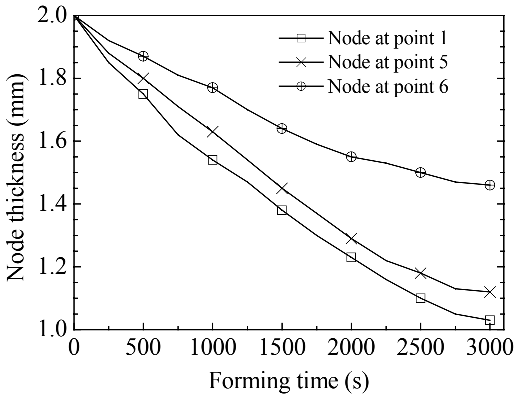

Fig.4 Evolution of thickness at the critical nodes of the sheet

Effect of contact friction on final thickness distribution

The friction force was computed in ABAQUS with the use of the Coulomb friction law. The standard Coulomb friction model assumes that no relative motion occurs if the equivalent frictional stress is less than the critical frictional stress. In the rough friction model for non-slipping case, it can be further assumed that there seems to be no relative motion as long as the two surfaces are in contact. A penalty contact algorithm in the Lagrangian multiplier method was adopted to remove the relative motion by dividing the friction force by the penalty stiffness.

The effects of friction on sheet forming are illustrated in this section. The basic model was simulated with different friction coefficients on the contact surfaces of the sheet and mould. The relation of final minimum thickness versus friction coefficient is given in Fig.5. Although the final minimum thickness was almost invariable when the friction coefficient was greater than 0.2, it decreased with friction for smaller friction coefficient. Fig.6 shows the relations of the final forming time and forming pressure versus the friction coefficient. Obviously, more forming time and forming pressure are required finally to shape a component if there is more friction. That is to say, the contact friction increases the forming cost. So it is necessary to make the contact friction as small as possible in the SPF process to eliminate its negative influence. However, for the protruding-die forming, certain contact friction may be needed to keep the uniformity of the thickness distribution by sticking the sheet on the moving die. Besides, with increase of friction, the position of maximal contact pressure moves from the post-formed part to the pre-formed part of the sheet.

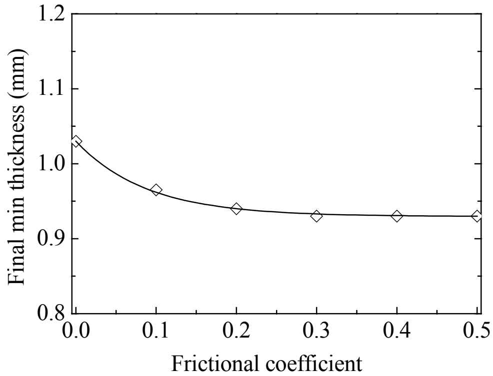

Fig.5 Effect of friction on the final minimum thickness of the sheet

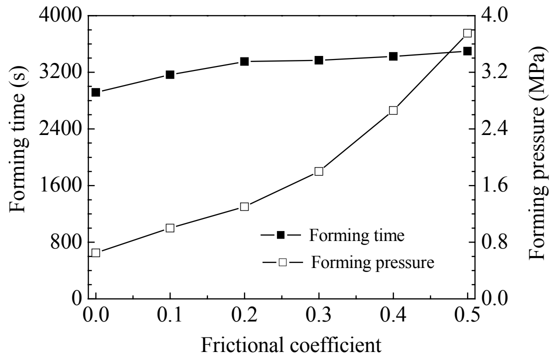

Fig.6 Effect of friction on the final forming time and pressure

CONCLUSION

In the superplastic sheet forming process of titanium alloys, the most concerned aspects of forming quality are the formed components' mechanical properties, which are closely related to the component thickness distribution. The thinnest regions may have the weakest mechanical strength. The numerical results in our work revealed that the thickness distribution is especially influenced by the characteristic of the component shape, indicating that close attention should be paid to the design shape of components, for example, blunting local sharp parts to avoid high surface curvature and making complex parts more concise if possible, especially for crucial load-bearing components. The contact friction also has negative influence on the thickness distribution. If less friction occurs during the forming process, the maximum thickness difference in components decreases and forming cost decreases too. Some effective technological methods, such as the diffusion barrier method (referred to as "stop off"), should be utilized to eliminate the contact friction.

References

Comstock, R.J., Kaiping, L., Wagoner, R.H., 2001. Simulation of axisymmetric sheet forming tests. *J. Mater. Proc. Tech.*, **117**:153-168.

Cope, M.T., Ridley, N., 1986. Superplastic deformation characteristic of micro-duplex Ti-6Al-4V alloy. *Mat. Sci. and Tech.*, **2**:140-145.

Garriga-Majo, D., Curtis, R.V., 2001. Geometric analysis of thinning during superplastic forming. *Mater. Sci. Forum*, **357-359**:213-218.

Ghosh, A.K., Hamilton, C.H., 1982. Influences of material properties and microstructure on superplastic forming. *Metall. Trans.*, **13A**:733-743.

Kleinermann, J.P., Ponthot, J.P., 2003. Parameter identification and shape/process optimization in metal forming simulation. *J. Mater. Proc. Tech.*, **139**(1-3):521-526.

Sedaghi, R.S., Pursell, Z.S., 1994. Finite element modelling of superplastic forming. *Mater. Sci. Forum*, **170-172**: 571-576.

Yu, T.X., Zhang, L.C., 1995. Plastic Bending: Theory and Applications. World Scientific Publishing Company, Singapore.

Wood, R.D., Bonet, J., 1996. A review of the numerical analysis of superplastic forming. *J. Mater. Proc. Tech.*, **60**:45-53.