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Finite element simulation of aluminum alloy cross valve forming by multi-way loading

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Abstract: Deformation behavior, temperature evolution and coupled effects have a significant influence on forming process and quality of component formed, which are very complex in forming process of aluminum alloy 7075 cross valve under multi-way loading due to the complexity of loading path and the multiplicity of associated processing parameters. A model of the process was developed under DFEORM-3D environment based on the coupled thermo-mechanical finite element method. The comparison between two process models, the conventional isothermal process model and the non-isothermal process model developed in this study, was carried out, and the results indicate that the thermal events play an important role in the aluminum alloy forming process under multi-way loading. The distributions and evolutions of the temperature field and strain filed are obtained by non-isothermal process simulation. The plastic zone and its extension in forming process of cross valve were analyzed. The results may provide guidelines for the determination of multi-way loading forming scheme and loading conditions of the forming cross valve components.

Key words: bulk forming; multi-way loading; cross valve; aluminum alloy; finite element simulation

1 Introduction

With the rapid development of aerospace, automotive and military industries, integral, light weight, complex components by "green manufacturing" are more and more widely used[1−3]. Complex integral components with light materials such as the cross valve body components of aluminum alloy 7075 can meet these requirements[4], and thus more attention is paid to it. But the plasticity of aluminum alloy 7075 is poor and the resistance to deformation is large[5]. Furthermore, the components with cavity or flange in multi-direction are hard to form integrally in one working cycle by means of conventional plastic forming process. Through multi-way loading, dies could be loaded in multi-direction at the same time or in sequential time, so it provides a new approach to form multi-ported valves in one working cycle. However, the metal flow is complex due to the complexity of loading path, which is easy to lead to the occurrence of forming defects such as folding. The heat transfer process is complex due to the complex deformation behavior, which results in temperature gradient affecting plasticity of billet especially for material which is sensitive to deformation temperature such as aluminum alloy. It is important to study the deformation behavior and distribution of temperature coupled deformation under multi-way loading to actualize forming process and control mechanical properties of component formed.

Physical experiment (lead is used as experimental material) of forming process of valve drop forging with three cavities has been done by GONTARZ[6], which provides a verification for finite element modeling. GONTARZ[6] also carried out a numerical simulation of the physical experiment process, and found that the magnitude of strain has significant influence on forming quality and work done.

With extensive progresses in computer aided engineering and computer technology, the finite element method (FEM) has become a powerful approach for solving and analyzing the problems of plastic forming

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processes[7]. XU[8] investigated the multi-ram forging of equal diameter tees by means of 2D finite element modeling, and obtained the metal flow law for equal diameter tees forming. HU et al[9] presented the 2D simulation of the multi-ram forging process of triple valve by using the FEM program developed under ANAYSY5.0a environment, and found that horizontal rams are forced unbalanceably. However, the 2D model is difficult to describe the deformation behavior accurately, and the influence of heat transfer and heat generated from the plastic deformation is ignored in all presented studies. Furthermore, little has been reported in the literature on integral forging of cross valves, besides some research on bulge forming of cross-joint[10].

Therefore, a coupled thermo-mechanical FE model of the process of multi-way loading for cross valve was developed under DFEORM-3D environment. Using the model, the influence of position of billet, sequence of loading, and heat transfer on forming process are investigated, and an attempt was made to analyze the yield of material in different locations and extensions of plastic zone in forming process. The results may provide a basis for research and application of multi-way actively loading forming process.

2 Finite element modeling

2.1 Geometric model and meshing

Dimensions of cross valve forging are shown in Fig.1. The thickness of wad in the hole of the forging is only 4 mm. The cross valve under multi-way loading is formed by six dies, including two female dies and four male dies. During the multi-way loading process, upper and lower (z axis) female dies are closed firstly; then the male dies in the plane (x and y axis) are loaded at the same time or in sequential time until cross valve is

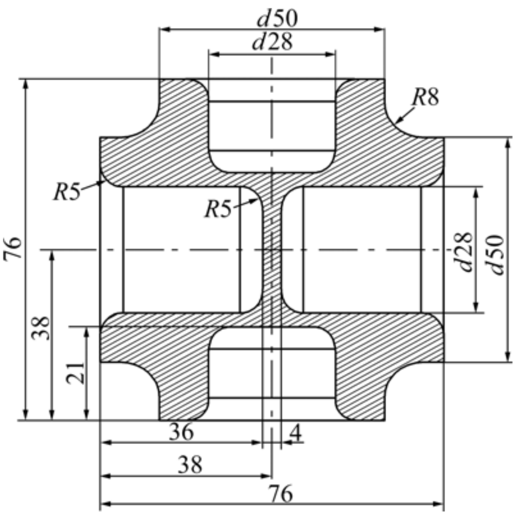

Fig.1 Dimensions of cross valve forging (Unit: mm)

formed. And the billet is a bar whose diameter is 50 mm and length is 75 mm according to volume constancy principle.

In order to reduce computational time and save storage capacity, the half of billet and male dies was modeled. The nodes at the symmetry plane were restrained in the normal direction of symmetry plane. The geometric models of billet and dies were built through CAD software UG, and then meshed and assembled through DEFORM. Local mesh densification and automatic remeshing technology were used to improve computational efficiency and avoid mesh distortion[11]. Meshes of billet and dies are shown in Fig.2.

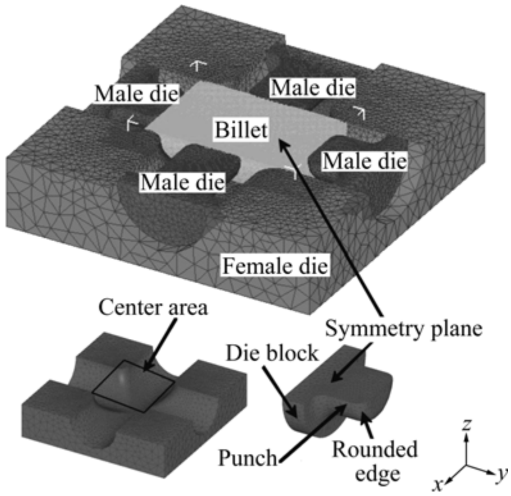

Fig.2 Meshes of billet and dies

2.2 Material parameters

The material of dies is H-13 hot die steel. The stress−strain relationships of aluminum alloy 7075 and hot die steel came from material library in DEFORM-3D, and their physical properties are shown in Table 1. In the simulation, the die was treated as a rigid body, while the billet as a rigid-plastic material.

2.3 Simulation parameters

The shear friction model widely used in hot plastic finite element simulation was employed to describe the friction at die/billet interface. According to the friction state between aluminum alloy and die steel, the friction factor m was set as 0.4[12].

The thermal conductivity of aluminum alloy is much greater than that of die steel, and aluminum alloy is very sensitive to deformation temperature[13]. So, the die was preheated up to close initial temperature of billet. According to handbooks[14] and the process characteristic of multi-way loading forming, the other processing parameters were selected. The parameters used in simulation are summarized in Table 2.

Table 1 Physical properties of material

Material	Coefficient of thermal expansion/K^{-1}	Thermal conductivity/($W\cdot m^{-1}\cdot K^{-1}$)	Heat capacity/($N\cdot mm^{-2}\cdot K^{-1}$)
Aluminum alloy 7075	2.2×10^{-5}	180	2.43
H-13 hot die steel	1.22×10^{-5} (200 ℃) 1.24×10^{-5} (315 ℃) 1.30×10^{-5} (425 ℃) 1.31×10^{-5} (480 ℃)	24.6 (215 ℃) 24.4 (350 ℃) 24.2 (475 ℃)	3.0 (200 ℃) 3.2 (315 ℃) 3.8 (425 ℃) 4.5 (530 ℃)
Material	Emissivity ratio	Heat transfer coefficient between workpiece/dies and air/($kW\cdot m^{-2}\cdot K^{-1}$)	Heat transfer coefficient between workpiece and dies/ ($kW\cdot m^{-2}\cdot K^{-1}$)
Aluminum alloy 7075	0.1	0.02	11
H-13 hot die steel	0.3	0.02	11

Table 2 Parameters in simulation

Room temperature/℃	Initial temperature of billet/℃	Initial temperature of die/℃	Friction factor	Loading speed of male die/($mm\cdot s^{-1}$)
20	450	400	0.4	10

2.4 Verification of model

Through changing geometric models of billet and dies, the finite element model established is also suitable for simulating the multi-way loading process of other multi-ported valves and components with cavity or flange in multi-direction. Based on the forming condition in Ref.[6], simulation for multi-way loading process of valve with three cavities was carried out to validate the model developed. The shape and dimensions of valve with three cavities (material is lead) are shown in Fig.3.

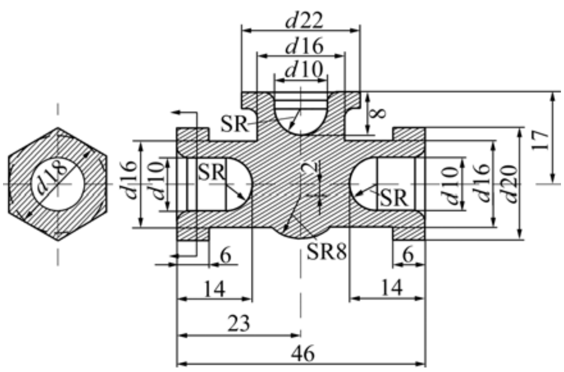

Fig.3 Dimensions of valve with three cavities (Unit: mm)

The loading conditions in Ref.[6] were as follows: at the first loading stage, two horizontal (x axial) male dies were loaded until two horizontal cavities were formed, and then the male dies were held on that position; at the second loading stage, vertical (y axial) male die was loaded until vertical cavity was formed.

The comparison of numerical simulation results with the experimental results obtained in Ref.[6] is shown in Fig.4. It can be seen from Fig.4 that shapes of forging in numerical simulation show a good agreement with that obtained by experiment in Ref.[6], which indicates that the 3D-FE model established is reliable.

3 Loading path and finite element analysis

3.1 Loading path

HU et al[9] studied the multi-way loading forming process of triple valve based on loading condition which was adopted by GONTARZ[6] (as shown in Section 2.4), and found that, the extra cavum occurred at the first stage and reached the maximum at the end of the first stage; and the extra cavum was prone to resulting in folding defect when vertical (y axial) male die was loaded at the second stage. Based on the forming condition in Ref.[9], simulation of triple valve multi-way loading process was carried by using the established 3D-FE model. The extra cavum is also found in the 3D-FE result, so it also indicates that the established model is reliable. In order to avoid folding defect, the vertical male die should be loaded before the former loading male dies (x axial male dies) reached the maximum displacement. Based on a physical experiment used lead, XU[8] also found that the metal flow and quality of component could be improved by loading three male dies at the same time while that was difficult to carry out in industrial processing.

The phenomenon of occurrence of extra cavum is also found in the forming process of cross valve under multi-way loading. Thus, in order to avoid folding, the following loading way should be adopted: let the x and y axial male dies reach their maximum displacements at the same time. Based on this loading way, the forming process of cross valve can be realized in two loading paths according to shapes of forging and dies, which are different in the following putting way of billet. 1) Loading

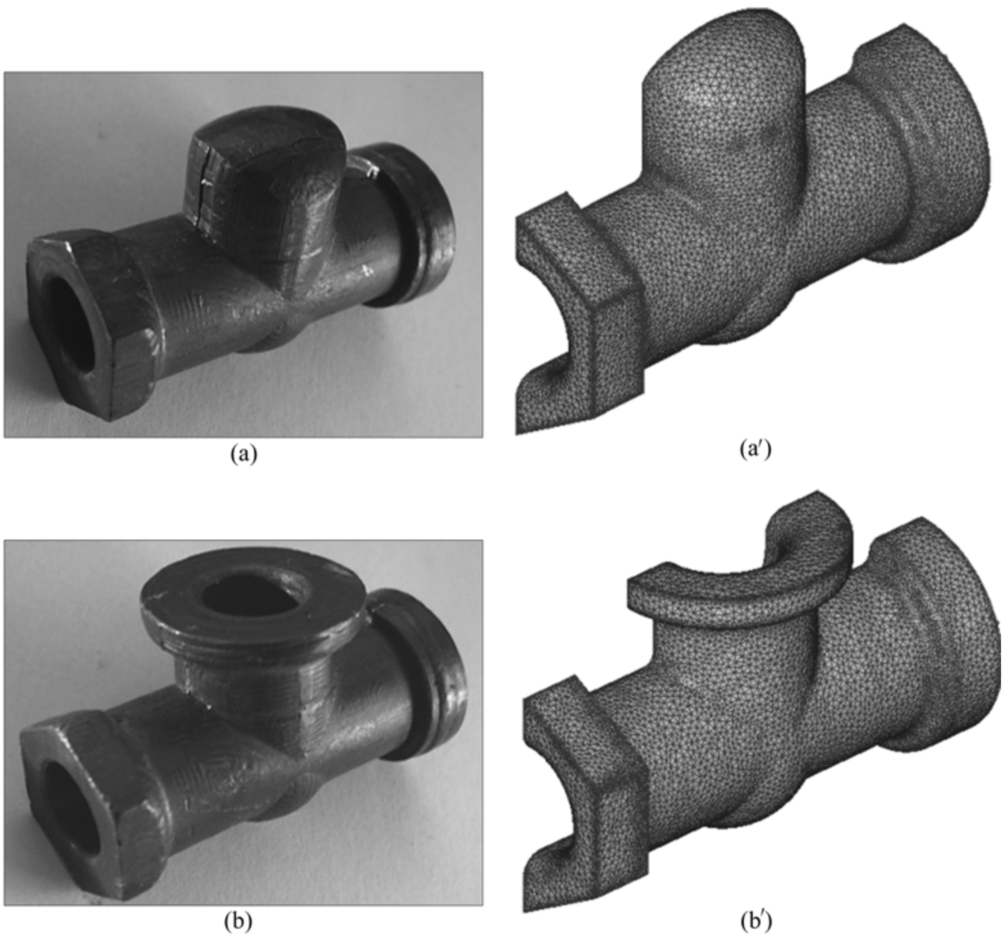

Fig.4 Shape of forging: (a) Experimental result[6], after first stage; (a′) FEM result, after first stage; (b) Experimental result, after second stage; (b′) FEM result, after second stage

path Ⅰ. Put the billet along x axis; the y axial protrusion is formed via lateral extrusion at the initial forming stage; and the y axial cavity is formed via lateral and backward extrusion. 2) Loading path Ⅱ. Put the billet along y axis, the x axial cavity is formed via lateral and backward extrusion. The differences between the two loading paths are the putting way of billet and the ratio of x axial displacement to y axial displacement. The loading paths shown in Fig.5 were used in the finite element analysis (FEA).

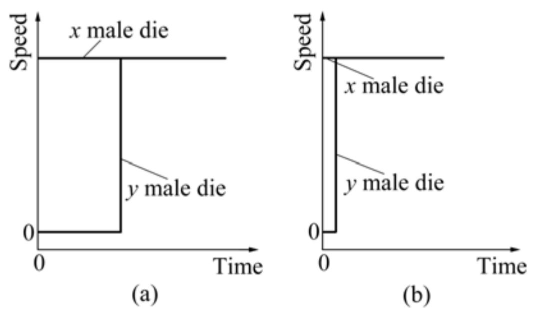

Fig.5 Loading path of male dies: (a) Loading path Ⅰ; (b) Loading path Ⅱ

3.2 Comparison between non-isothermal process simulation and isothermal process simulation

In forging process, change of temperature field can reflect the changes of metal flow and formability of workpiece which have a direct influence on the forging load and quality of component formed. The temperature evolution during the forging depends on the heat generated from the plastic deformation, contact state between billet and dies, heat transfer, etc. Workpiece not only exchanges heat with the environment by means of radiation and heat convection, but also transfers heat to dies via contact areas between workpiece and dies. These heat transfer processes lead to heat loss resulting in the drop of the temperature. The majority (90% in coupled thermo-mechanical analysis) of plastic deformation work converts to heat to make temperature rise. However, in the previous research, the isothermal process assumption is adopted[6, 8−9]. In this work, the coupled thermal-mechanical effect is considered well.

Although the forming time of cross valve is short (which is not more than 4 s) and the initial temperature of dies is only 50 ℃ lower than that of billet, there are differences between non-isothermal process simulation and isothermal process simulation. This is because the loading speed is high (10 mm/s) and aluminum alloy is sensitive to deformation temperature. The distributions of strain in two analyses are similar, as shown in Fig.6, but the values of strain in coupled thermo-mechanical FEA are larger than those in FEA only considering deformation. In loading path Ⅰ, the difference of the maximum ($\varepsilon_{\max}$) and minimum ($\varepsilon_{\min}$) effective strain in the finish-forging cross valve between two FEA is about 5%.

Fig.7 shows the forging load in forming process of cross valve under multi-way loading. There are significant differences of forging loads at the latter forming stage between two analyses. In loading path Ⅰ, the maximum load of dies in FEA only considering deformation is larger than that in coupled thermo-mechanical FEA: 27% for x axial male die, 36% for y axial male die, and 42% for z axial female die. This indicates that the heat converted from plastic deformation work has an important influence on deformation and flow stress in the plastic zone. Thus, the coupled thermo-mechanical FEA should be employed to investigate the process of aluminum alloy cross valve forming by multi-way loading.

3.3 Influence of loading path on forming process

The displacement of male dies is different under two loading paths due to the difference of cavity depth on x and y axis. The displacements of x and y axial male die are expressed as s_x and s_y, respectively, then $s_x/s_y \approx 2.2$ for loading path Ⅰ and $s_x/s_y \approx 1.1$ for loading path Ⅱ. The loading paths are significantly different, but it can be seen from Fig.6(a) and Fig.8 that the deformation and strain have a little difference in both loading paths.

In loading path Ⅱ, metal in center zone (shown in Fig.2) in front of punches has the equal flow tendency whether along x or y axial direction due to the little difference of displacements between x and y axial male dies. But in loading path Ⅰ, metal in the center zone is more difficult to flow along x axial direction than along y axial direction at the stage when y axial male dies are loaded, because the x axial cavity is almost formed before the y axial cavity begins to form.

The comparison of forging load between two loading paths is shown in Fig.7. The maximum loads of x axial male and female dies in loading path Ⅰ are more than those in loading path Ⅱ. The maximum load of y axial male dies in loading path Ⅰ is less than that in loading path Ⅱ.

In loading path Ⅰ, the maximum load of x axial male die is 40% more than that of y axial male die. However, the maximum load of x axial male die is 8% less than that of y axial male die in loading path Ⅱ, and thus unbalanced force of dies could be decreased to improve service of dies. Furthermore, the displacement of male die in loading path Ⅱ is less and the contact time between dies and billet is shorter, so the energy consumption is lower than that in loading path Ⅰ.

4 Distribution of strain

The distributions and changes of strain in two loading paths are similar when one forging rotates around z axis for 90° due to the putting way of billet. Taking loading path Ⅱ as example, the distributions and changes of strain in forming process are analyzed, as shown in Fig.9.

At the initial stage, the deformation occurs in the zones around the rounded edge (see Fig.2) of punches (Fig.9(a)), and then the deformation zones extend (Fig.9(b)). The extending speed along loading direction of male die is quicker. Finally, the deformation almost occurs in direction perpendicular to axial line of billet (y axial direction for loading path Ⅰ, and x axial direction

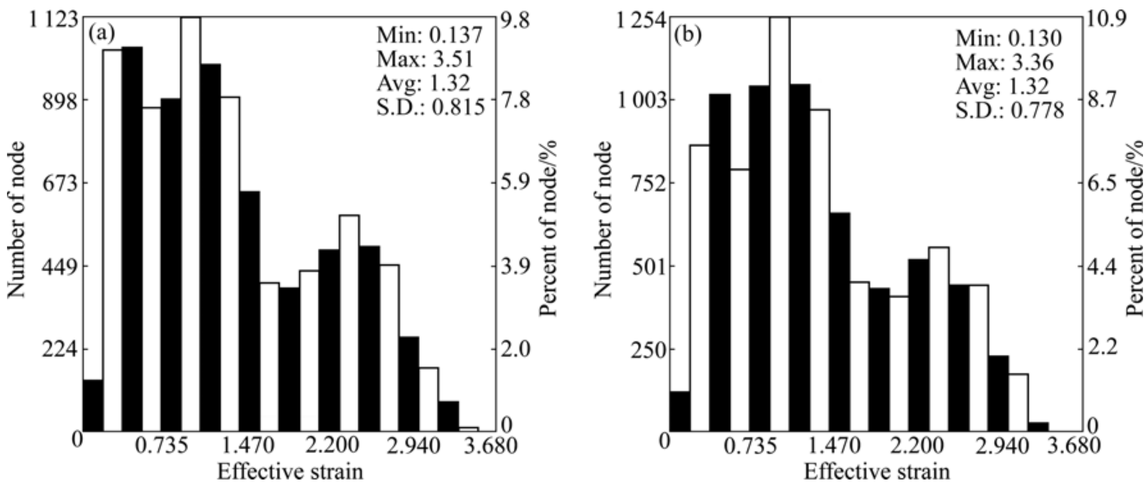

Fig.6 Distribution of effective strain in forging (loading path Ⅰ): (a) FEA of non-isothermal process model, (b) FEA of isothermal process model

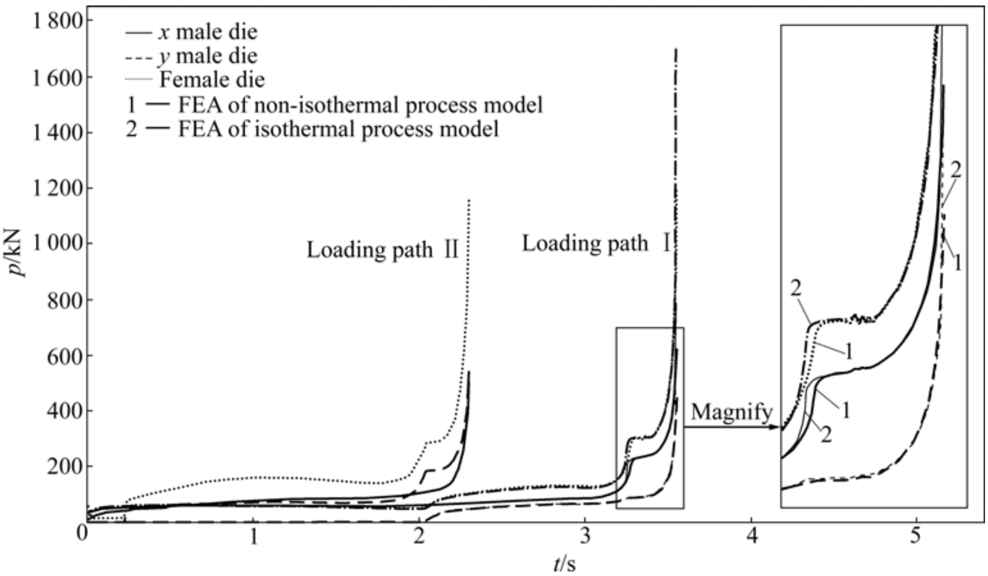

Fig.7 Forging load in forming process

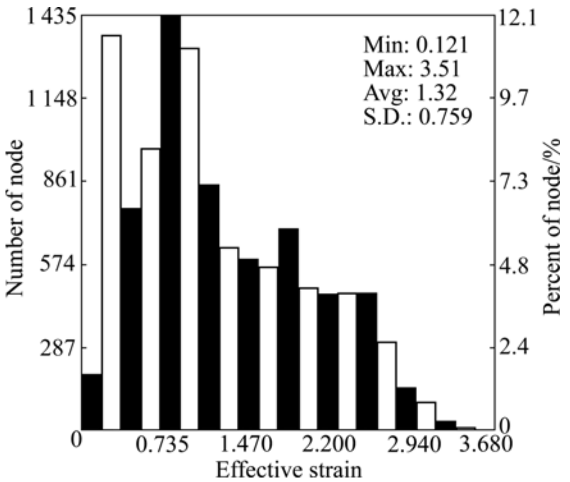

Fig.8 Distribution of effective strain in forging (loading path Ⅱ)

for loading path Ⅱ). But the metal in the ends of cylindrical billet moves rigidly because the metal almost does not yield (Fig.9).

There is a rigid zone in front of punch (Fig.9(a)), in which the metal does not yield. With the punch advancing, the size of rigid zone minifies gradually (Fig.9(b)). Finally, the rigid zone disappears (Fig.9(c)), that is, the whole metal in the center zone yields. The metal in the region near the female die yields later than the metal in the region near the male die, and the deformation is little, as shown in Figs.9(d)−(f).

At the finish-forging stage, the deformation zones of two loading paths are the same, but deformation occurred in loading path Ⅰ is posterior to deformation occurred in loading path Ⅱ. In loading path Ⅰ, most of deformation occurs at the latter forming stage and the rigid zone in front of punch only disappears in finishing.

5 Distribution of temperature

Fig.10 shows the temperature evolution under two loading paths. The distributions of temperature at the finish-forging stage under two loading paths are similar when one forging rotates around z axis for 90° due to the putting way of billet (Figs.10(c) and (f)). The maximum and minimum of temperatures in two loading paths are almost same, the values of the average temperature and

At the initial forming stage, the temperature in and around the contact areas between billet and dies is lower than the initial temperature due to heat loss to the dies that have an initial temperature 50 ℃ lower than the initial billet temperature, as shown in Figs.10(a) and (d). With the increase in displacement of male die, the main plastic deformation zone is in the center zone, as shown in Fig.9. Because the heat generated from the plastic deformation increases and the heat loss is less than other zones, the temperature rises in this zone. When the forging is finished, the temperature could be 20 ℃ higher than the initial temperature. The little deformation zone is the low temperature zone because the heat loss is greater than heat generated. Especially in the rigid zone, the temperature drops during forging, and the minimum temperature of finishing forging is 20 ℃ lower than the initial temperature. In the whole process, the temperature is in the range of 430−470 ℃, which is within the forging temperature range of the forming material[15].

In loading path Ⅱ, the temperature drops at first and then rises quickly in the zone in front of punch, and the temperature will be higher than initial temperature after a short time (Fig.10(e)). However, in loading path

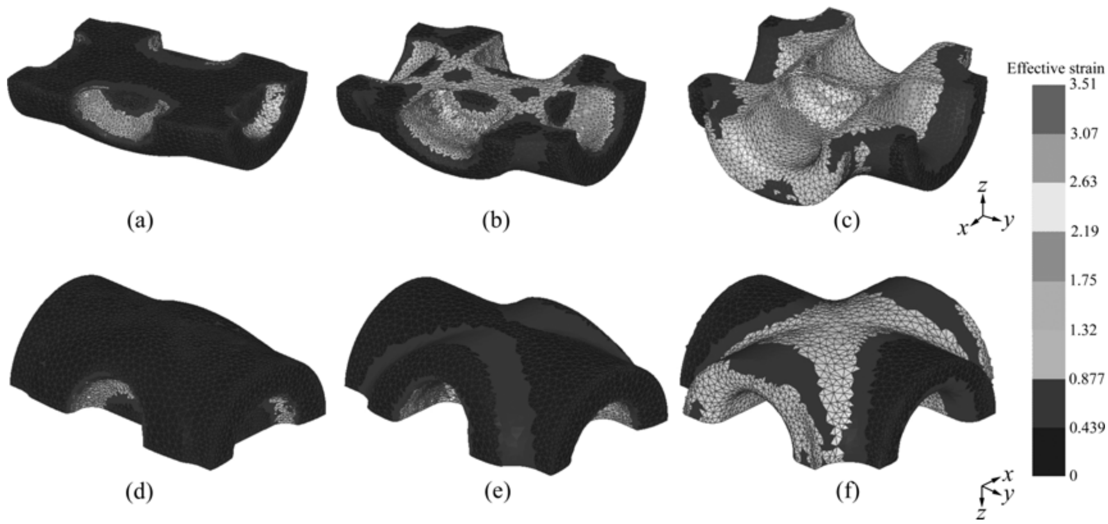

Fig.9 Distributions of effective strain at chosen stages of process (loading path Ⅱ): (a) +*Z*, $s=(1/3)s_x$; (b) +*Z*, $s=(2/3)s_x$; (c) +*Z*, $s=s_x$; (d) −*Z*, $s=(1/3)s_x$; (e) −*Z*, $s=(2/3)s_x$; (f) −*Z*, $s=s_x$

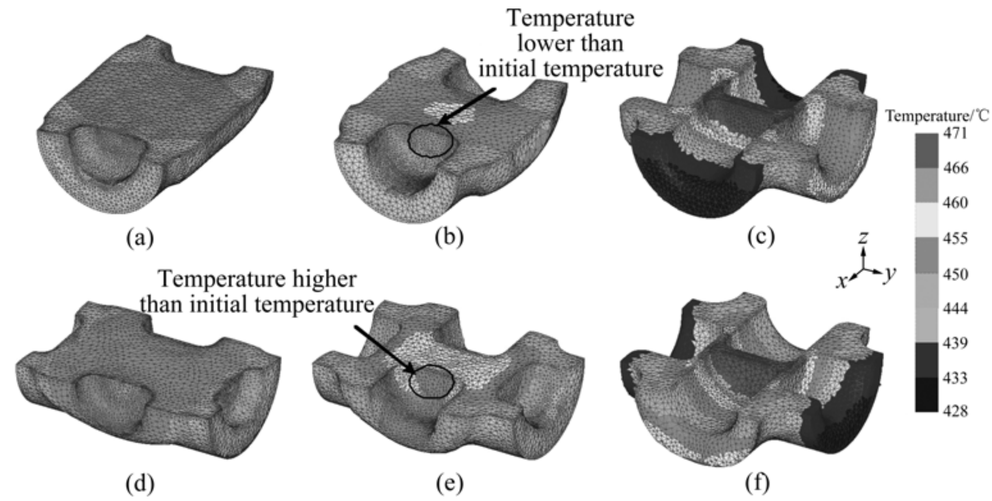

Fig.10 Distributions of temperature at chosen stages of process under loading path Ⅰ(a−c) and path Ⅱ(d−f): (a) $s=(1/3)s_x$; (b) $s=(2/3)s_x$; (c) $s=s_x$; (d) $s=(1/3)s_x$; (e) $s=(2/3)s_x$; (f) $s=s_x$

Ⅰ, the temperature in the zone in front of punch is not higher than initial temperature until forging is close to ending (see Fig.10(c)) for the reason of the low extending speed of plastic deformation zone.

6 Conclusions

1) The simulations show that both loading paths allow for forming the cross valve forging of the correct shape without folding. In loading path Ⅱ, the force of male die is more balanceable than that in loading path Ⅰ. And the distributions of temperature and strain field in loading path Ⅱ are more beneficial to forming cross valve.

2) The distributions of strain and load—time curves between non-isothermal process simulation and isothermal process simulation are similar. But the magnitudes are more different, especially the load at the latter forming stage. It is necessary to pay attention to the influence of heat converted from plastic deformation work on deformation and flow stress in the plastic zone.

3) The deformation occurs in the zone around the rounded edge of punch firstly, and then extends to the center zone and the direction perpendicular to axial line of billet. There is a rigid zone in front of punch. The size of rigid zone minifies with the increase of displacement, but the minifying speed depends on the loading path.

4) It is well possible to predict the temperature evolution during multi-way loading forming based on the coupled thermo-mechanical finite element model. The analysis of simulation results indicates that the influence of coupling strain on temperature is remarkable.

5) Taking the range of billet temperature and speed of extension of plastic zone as object, it is well possible

to determine an optimum loading path by means of 3D coupled thermo-mechanical FEM simulation.

References

[1] ZHOU Xian-bin. Development of plastical processing technology: More precision, more economy, and more “green” [J]. China Mechanical Engineering, 2003, 14(1): 85−87. (in Chinese)

[2] YANG H, ZHAN M, LIU Y L, XIAN F J, SUN Z C, LIN Y, ZHANG X G. Some advanced plastic processing technologies and their numerical simulation [J]. Journal of Materials Processing Technology, 2004, 151: 63−69.

[3] YANG He, SUN Zhi-chao, ZHAN Mei, GUO Liang-gang, LIU Yu-li, LI Hong-wei, LI Heng, WU Yue-jiang. Advances in control of unequal deformation by locally loading and theories related to precision plastic forming [J]. Journal of Plasticity Engineering, 2008, 15(2): 6−14. (in Chinese)

[4] SHAN De-bin, ZHANG Yan-qiu, WANG Yong, XU Fu-chang, XU Wen-chen, LU Yan. Defect analysis of complex-shape aluminum alloy forging [J]. Transactions of Nonferrous Metals Society of China, 2006, 16(S3): 1574−1579.

[5] LI Cheng-gong, FU Heng-zhi, YU Qiao. Aerospace materials [M]. Beijing: National Defense Industry Press, 2002. (in Chinese)

[6] GONTARZ A. Forming process of valve drop forging with three cavities [J]. Journal of Materials Processing Technology, 2006, 177: 228−232.

[7] ROWE G W, STURGESS C E N, HARTLEY P, PILLINGER I. Finite-element plasticity and metal forming analysis [M]. Cambridge: Cambridge University Press, 1991.

[8] XU Ji-sheng. Study on metal flow in multi-ram forging process of equal diameter tee joint [J]. Forging & Stamping Technology, 2002(4): 11−14. (in Chinese)

[9] HU Zhong, WANG Ben-yi, LIU Zhaung, CHEN Guo-xue, WANG Zhi-cheng. 2-D elastoplastic FEM simulation of the whole forging process of a T-joint part [J]. Journal of Plasticity Engineering, 1996, 3(2): 33−40. (in Chinese)

[10] MAC DONALD B J, HASHMI M S J. Finite element simulation of bulge forming of a cross-joint form a tubular blank [J]. Journal of Materials Processing Technology, 2000, 103: 333−342.

[11] FLUHRER J. DEFORM^{TM} 3D Version5.0 User’s Manual [M]. Columbus: SFT Inc., 2003.

[12] FANG G, ZHOU J, DUSZCZYK J. Extrusion of 7075 aluminium alloy through double-pocket dies to manufacture a complex profile [J]. Journal of Materials Processing Technology, 2008, 209: 3050−3059.

[13] SHAN D B, XU W C, LU Y. Study on precision forging technology for a complex-shaped light alloy forging [J]. Journal of Materials Processing Technology, 2004, 151: 289−293.

[14] ZHANG Shi-lin, REN Song-zan. A concise aluminum alloy handbook [M]. Shanghai: Shanghai Scientific and Technological Literature Publishing House, 2001. (in Chinese)

[15] LI L, ZHOU J, DUSZCZYK J. Prediction of temperature evolution during the extrusion of 7075 aluminium alloy at various ram speeds by means of 3D FEM simulation [J]. Journal of Materials Processing Technology, 2004, 145: 360−370.

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