Kovove Mater. 50 2012 125–130
DOI: 10.4149/km_2012_2_125

Research on isothermal forging of a complex-shaped aluminum alloy component

F. Li[1*], J. F. Lin[2], G. N. Chu[3], H. Y. Sun[2], X. L. Zhang[1]

[1] *College of Materials Science and Engineering, Harbin University of Science and Technology, Harbin 150040, P. R. China*
[2] *School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, P. R. China*
[3] *School of Naval Architecture, Harbin Institute of Technology at Weihai, Weihai, 264209, P. R. China*

Received 18 February 2011, received in revised form 14 March 2011, accepted 7 May 2011

Abstract

In order to reveal the flow rules of metal during the precision forming of the high rib-thin web forging, the simulation and experiment were conducted to investigate the deformation regularity based on a typical aluminum alloy T-joint forging during different forming process stages. The simulation results indicate that: the most difficult to fill is the corner on big-end of the T-joint because of larger resistance. But the corner can be filled by pressure-keeping and the peak value of temperature appears at the lateral web of T-joint, which is 453 ℃. With the forming process, the load was gradually increasing, and the increasing rate obviously accelerated. The simulation coincides with the results of the experiment, it also indicates that by placing reasonably the billet, keeping pressure, and being in strict accordance with those established process specifications, the dimensional accuracy can once meet the design requirements of the high rib-thin web aluminum alloy forging.

Key words: isothermal forging, high rib-thin web, metal flow, numerical simulation

1. Introduction

Energy saving and high efficiency forming technology have recently become the primary direction in plastic processing field. Near-net shape forming technology has been developed rapidly and plays an important role in developed countries [1]. But, due to the character of die forging, such as forming complexity and pear controllability, forging process is mostly dependent on experience and trial and error method, which are limited to the qualitative analysis of the forging process and can not meet the needs of modern design [2].

With the progress of science and technology, the distribution law of stress and velocity fields during forging forming deformation can be disclosed successfully from the mechanical point of view through combining FEM and plastic theory [3], which is helpful to optimize metal flow behavior [4], to avoid defects and then to optimize the process parameters [5, 6]. These methods offer an effective way to improve product quality and mechanical properties [7].

For the forging of high rib-thin web aluminum alloy component, defects such as underfilling or folding are prevailing due to the complex shape and long flow path of some local metal [8] up to now; the research of forming mechanism and quality control is still deepened against such shape component. In this paper, the deformation rules of a typical component were studied based on numerical simulation, and at the same time, an experiment was conducted to analyze defects formation mechanism. The results can provide a theoretical basis for process design and deformation flow control of rib-web shape component.

2. Research program

2.1. Component structure characters and process analysis

The specimen used in this study is one of the important connecting components of a rocket, which is under complex loading during its application process.

---

*Corresponding author: tel.: +86-451-86392501; e-mail address: hitlif@126.com

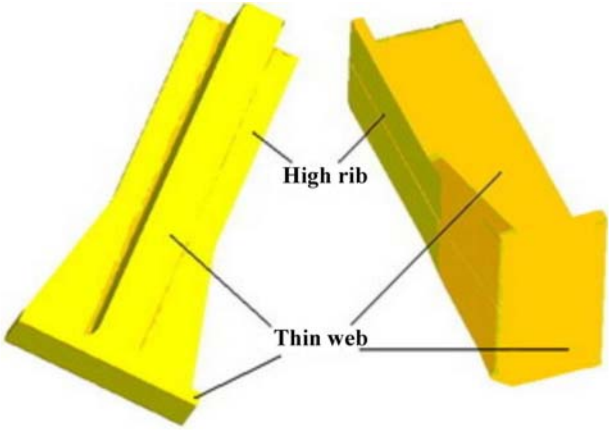

Fig. 1. Schematic of rocket joint.

In the view of the structure character, it is a typical thin-wall part with high strengthening reinforcing as shown in Fig. 1.

Machining is traditional method to manufacture such components. This method is not only time consuming but also expensive. Moreover, it reduces the fatigue performance significantly due to the fact that the metal fibrous tissue was cut off during the manufacturing process.

Applied closed-die forging can once directly access to near-net shape forging. What is more, the flow line of the part is along the geometry distribution. Consequently, this can avoid the above-mentioned problem.

For such component, underfill prevails when using conventional forging. The main reason for the defect is due to low pre-heat temperature of the die, which would induce the billet temperature to decrease rapidly. As a result, material deformation resistance increases rapidly, which makes easy to produce defects underfill, etc. Because of the change in temperature during deformation process, the actual temperature during billet deformation is lower than the recrystallization temperature. As a result, the metal after forming is not completely recrystallized. Considering the problems mentioned above, isothermal forming is adopted in this study.

According to the formability characteristics of space aluminum alloy, the isothermal closed-die-forging can reduce the forming difficulties, and also can make the grain refinement.

2.2. Finite element model

According to the actual symmetry of the die and billet, 1/2 was taken as a study object in simulation, as shown in Fig. 2, which could reduce the number of elements and improve the calculation speed.

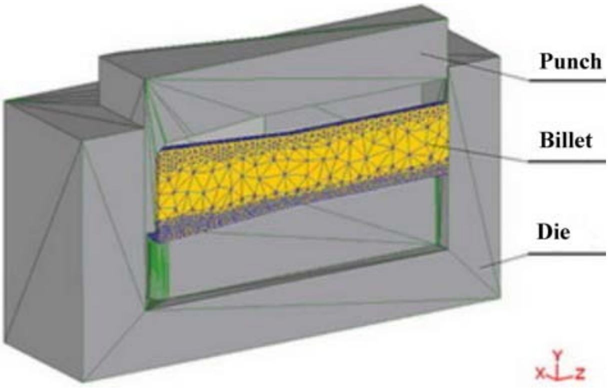

Fig. 2. Finite element model.

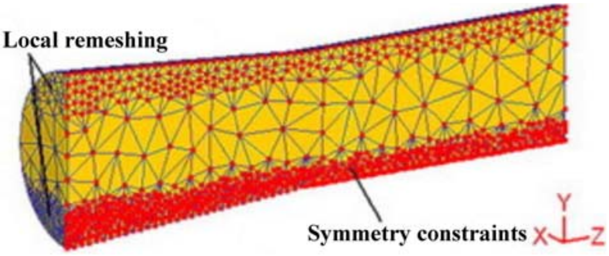

Fig. 3. Boundary conditions and local refinement.

2.3. Boundary conditions and local mesh refinement

In this study, four-node tetrahedron solid element was selected, and local mesh refinement was used according to the shape of the formed part in the transition area and the larger deformation area as shown in Fig. 3, which includes 5188 nodes and 21839 elements of the billet.

Symmetry constraints are implied on billet symmetry plane before the simulation to restrain deformation, in order to accurately reproduce the shape case.

2.4. Research program

The experimental material is the spray deposition aluminum alloy 7075. The die material is H13 steel. The punch speed is $1\,\mathrm{mm\,s^{-1}}$. In finite element simulation, the shear friction factor is 0.3, which is obtained through ring hot compression test. The initial temperature of billet and die was 430 ℃.

3. Discussion of results and analysis

3.1. Analysis of the shape changes

Figure 4 shows the comparison of the deforma-

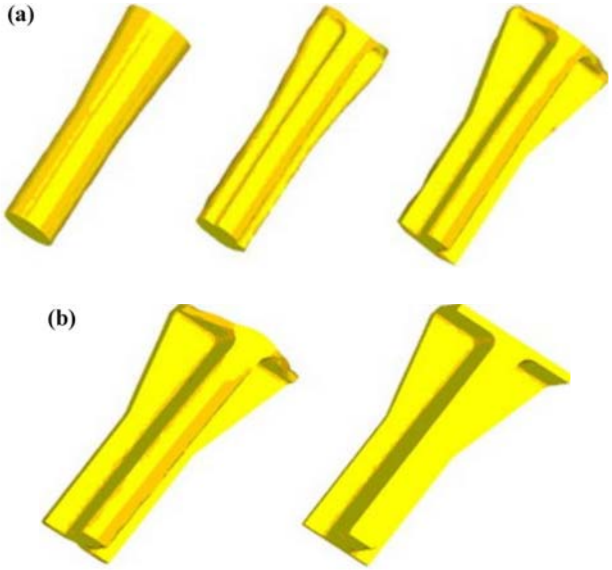

Fig. 4. Comparison of the shape changes: (a) initial stage, (b) final stage.

tion behavior of different forging processes. Figure 4a shows the changes of billet shape during initial stage. It can be seen that with deformation going on, both the ends of billet have a trend to fill the die cavity. As the punch continues downwards, the billet continues to fill the die cavity, and at the same time the web becomes significantly thinner. Figure 4b shows the final stage of the deformation. During this stage the web had basically finished filling. The center portion of the end had formed completely, but the tendon of the bottom and both sides of ends had not filled as shown in Fig. 4b. But due to the fact that the forming is isothermal, followed by the pressure maintaining, the metal can successfully fill the deep cavity, and finally a sound shape was formed.

3.2. Metal flow behavior

Figure 5 shows the comparison of metal flow at different stages. As shown in Fig. 5a, during the initial stage of forming, the metal flow is perpendicular to the die cavity and the flow rate of central metal of forging is bigger because the billet bottom contacts with the die end earlier. Due to the hamper of the punch, the metal close to the side has the trend of vertical flow on both sides, and with the load increased, such flow trend is more significant.

The final stage of the deformation is shown in Fig. 5b. During this stage, the web cavity is filled basically, and therefore, the metal flow rate is lower. But the bars of forging bottom are not filled yet, so the metal flow rate in this position is bigger than in others. During the subsequent holding pressure forming, the parts of forging are filling basically, and then the flow rate of each part of the metal is lower.

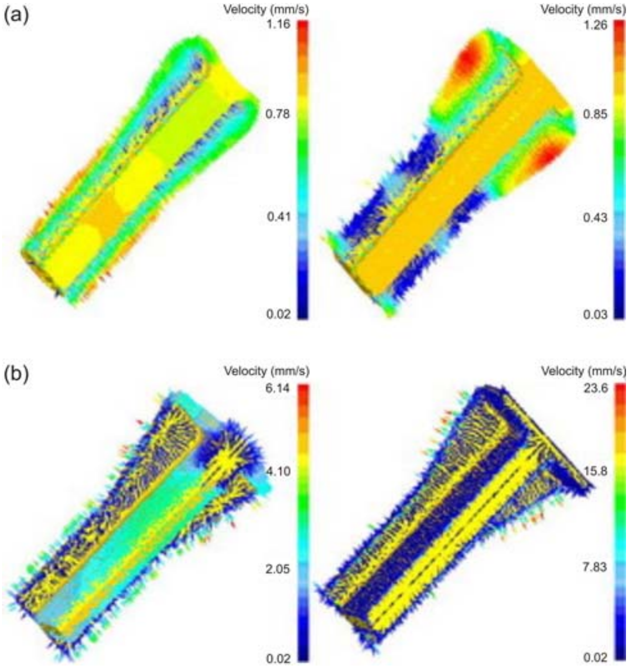

Fig. 5. Comparison of velocity field distribution: (a) initial stage, (b) final stage.

3.3. Mechanics analysis

The velocity fields of the initial stage are shown in Fig. 6a. It can be seen that an equivalent stress near the punch increases more significantly than in the punch downward. Although at this stage the metal of bars has the trend to fill the cavity, an equivalent stress of the position is relatively lower. Even if the load continues to increase, the web metal is still in the main deformation zone. Therefore, the equivalent stress of the web is still large, while the equivalent stress of the bar is relatively small.

The final forming process is shown in Fig. 6b. In this stage, the equivalent stress of the web central region is lower, which can be concluded that the deformation is relatively small, while in other parts still occurs. After pressure maintaining, equivalent stress of the bars and in the corner of the web is greater, predictably, the location is the final shape department.

3.4. Analysis of temperature distribution

Figure 7 shows the temperature distribution of different stages during forging stage.

From Fig. 7a it can be seen, at initial stage, that the billet temperature of bigger end is significantly higher with the punch downward, but the temperature of the other end is relatively small. With the deformation going on, the temperature of the billet bigger

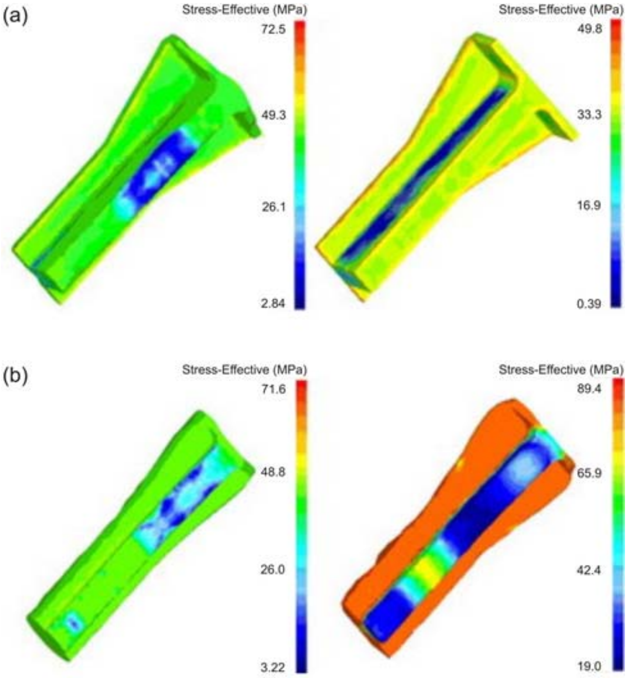

Fig. 6. Equivalent stress distribution of different stages: (a) initial phase, (b) the end of forming process.

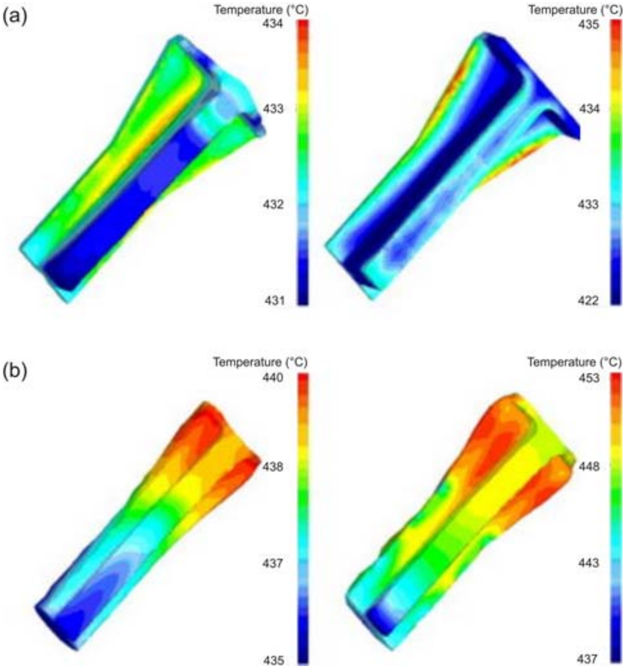

Fig. 7. Temperature distribution law of different stages: (a) initial stage, (b) end stage.

end continues to rise, and it can be concluded that the temperature of this area is still the biggest during this stage.

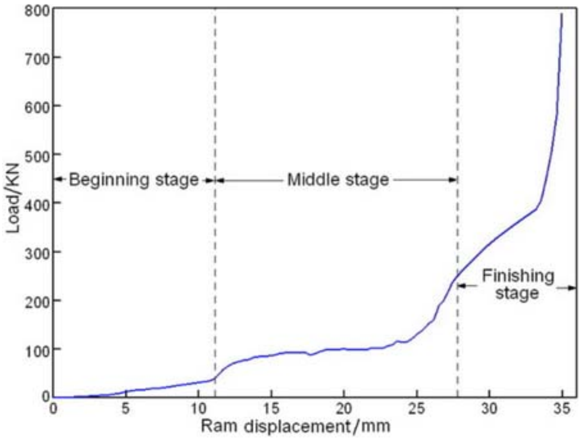

Fig. 8. Curve of displacement and load.

Figure 7b shows the end stage of forging process. During this stage, with billet further filling forming, the temperature distribution of forming changes greatly. The temperature of each part of the billet further increases because of energy release during strenuous forging deformation. In this stage, the temperature of tendons and web junction is maximal. As the pressure is maintaining, the metal continues to fill the difficult filling positions such as the complex cavity and the base bottom corner. Finally, the billet shape is consistent with the mold cavity, and the highest temperature appears on both sides of the T-shaped end, value of which is 453 ℃.

3.5. Analysis of displacement-load dependence

Figure 8 shows the displacement-load curve of forming process. It can be seen the required load gradually increased as deformation went on. According to the character of the displacement-load curve, the forming process can be divided into three stages, such as beginning stage, middle stage and finishing stage as shown in Fig. 8. As is seen on the displacement-load curve, during the starting state the required load value is small. The reason is that during this stage the billet just begins to fill the die cavity and deformation only occurs in the area where the die contacts the billet. During middle stage, with the punch gradually downward, plastic zone expands. As a result, the required load increases. At the end of forming process, when the billets downward filling were basically completed, the end appeared to upset deformation mode, and deformation amount significantly increased, then the required load significantly accelerated and reached its peak.

4. Experimental results

4.1. Preformed billet and experimental programs

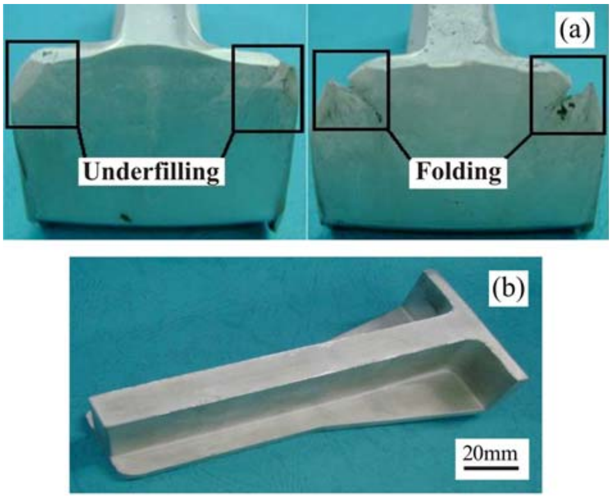

Fig. 9. Forgings and defect photos: (a) typical defects, (b) good forming workpiece.

T-joint forging process can be divided into two steps: pre-forming and forging. The purpose of pre-forming is to remove coarse grain on outer surface and ensure the organizational performance of formed component.

Original billet is obtained by the hot extrusion. Its inner metal is deformed, while the outer one is coarse grain layer due to incomplete grain recrystallization during extrusion process for the low die temperature. So the prior billet need is to carry out upsetting deformation before forging process, and then make a spheroization, which can refine the grain, and help to eliminate segregation created in cast process.

Forging process was strictly in accordance with following steps: put module into die sleeve → spray water-based graphite mixture on mold and billet → put mold into furnace → put billet into furnace → preheat upper and lower mold base → take out mold and billet from furnace → die-filling → install plastic shim → apply load → load-off → demold.

In order to avoid heat loss during forging process, the whole heating way was used. Lubricant was water-based graphite, and other experimental conditions were the same with simulation.

Experiment was carried out on 6300KN forging hydraulic machine, which has pressure and stroke control devices. It is convenient to realize operation and control the experiment. At the same time, the temperature control device was applied to insure the precise temperature control.

4.2. Experimental results and analysis

Figure 9 shows the experimental photos of aluminum alloy T-joint after forging.

From Fig. 9a it can be seen that if holding pressure time is shorter, it is difficult for the metal to fill the deep cavity of bars, and underfill defects occur. While billets placing is unreasonable, the filling of big end of T-joint requires additional metal follow-up. Therefore, the corners of the site are easy to produce folding defects as shown in Fig. 9b.

To sum up, when forming process is consistent with the process specifications in this article: to place the billet on the cavity of forgings end as far as possible, and with pressure-keeping sufficiency, the T-shape joint can be successfully manufactured through one-step forging.

5. Conclusion

1. The results of numerical simulation demonstrated during high rib-thin web T-joint forging, that the big end of T-joint is the most difficult position to formation due to the fact that the billet surface suffered greater resistance. In reasonable process, maintaining pressure is necessary, as well as the temperature peak in the outer of both sides of the T-shaped end;
2. With the forming process continuing, the required load is gradually increasing, and the increase rate aggravates gradually until to the forming ends and reaches its peak value, which is at 453 ℃;
3. The experiments verified that if the billet was placed reasonably and the sufficient pressure was maintained, at the same time the craft standard was strictly applied, then high gluten thin web aluminum forgings can be formed at once which meet the design requirements.

Acknowledgements

This paper was financially supported by Research Fund for the Doctoral Program of Higher Education of China (20112303120001) and Natural Science Foundation of Heilongjiang Province of China (E201128). The authors would like to take this opportunity to express their sincere appreciation.

References

[1] ZHOU, Y. G.—ZENG, W. D.—YU, H. Q.: Mat Sci Eng A, *393*, 2005, p. 204. http://dx.doi.org/10.1016/j.msea.2004.10.016
[2] NATEGH, M.—JAFARI, B.: J Mater Eng Perform, *17*, 2008, p. 682. http://dx.doi.org/10.1007/s11665-008-9213-9
[3] JEONG, H. S.—CHOA, J. R.—PARK, H. C.: J Mater Proc Technol, *162*, 2005, p. 504.
[4] PARK, J. J.—HWANG, H. S.: J Mater Proc Technol, *187–188*, 2007, p. 595. http://dx.doi.org/10.1016/j.jmatprotec.2006.11.034

[5] CHOI, S. K.—CHUN, M. S.—VAN, C. J.—MOOM, Y. H.: J Mater Proc Technol, *172*, 2006, p. 88. http://dx.doi.org/10.1016/j.jmatprotec.2005.09.010

[6] CHUNG, S. H.—HWANG, S. M.: Int J Numer Meth Eng, *42*, 1998, p. 1343. http://dx.doi.org/10.1002/(SICI)1097-0207(19980830)42:8<1343::AID-NME408>3.0.CO;2-B

[7] BEWLAY, B. P.—GIGLIOTTI, M. F. X.—HARDWICKE, C. U.—KAIBYSHEV, O. A.—UTYASHEV, F. Z.—SALICHEV, G. A.: J Mater Proc Technol, *135*, 2003, p. 324.

[8] SHAN, D. B.—XU, W. C.—SI, C. H. —LU, Y.: J Mater Proc Technol, *187–188*, 2007, p. 480. http://dx.doi.org/10.1016/j.jmatprotec.2006.11.127