Isothermal Forming of Aluminum Alloy Control Arm

Feng Xu1,2, Dongmei Gong 2 Ke Chen 1,*, Kemin Xue3 and Ping Li3
1School of Mechanical Engineering, Hefei University of Technology, Hefei, China.
2School of Mechanical and Vehicle Engineering, West Anhui University, Lu’an, China.
3School of Material Science and Engineering, Hefei University of Technology, Hefei, China.

*Corresponding author e-mail: abberleyman@gmail.com

Abstract. The aluminum alloy control arm is difficult to be obtained without cracks and the using ratio of material is usually under 50% by conventionally open-die forging. The isothermal forming was carried out to form aluminum alloy control arm. The forming process of isothermal forming is studied by FEM simulation and experiment. The influence of pre-forging on final forging is analyzed and then the filling, local velocity field, equivalent strain and any possible defects etc. of optimized pre-forging in the final forging are studied. A suitable pre-forging can be produced through numerical analysis and experiment, and problems like insufficient filling, metal folding have been perfectly avoided. The forging streamline and its internals are evenly distributed with no crack on the surface, the trend of crack can be predicted and the using ratio can be promoted to 90%.

Key words: Aluminum alloy; control arm; Isothermal forming; pre-forming.

1. Introduction
Precise isothermal forging is an advanced technology, developed in recent years as proposed by Yoshimura et al. (2000). Because of the narrow scope of forging temperature of aluminum alloy, high coefficient of its heat conductivity and strong deformation degree on the product in processing, the phenomena of cracking, insufficient filling and folding turn up easily, presented by Shen et al. (2000) and Gong et al. (2009). At present, the precise isothermal forging technology is more widely used in aluminum alloy forgings. The precise isothermal forging technology has been used by Shan et al. (1997) and (2005) to form the cylindrical aluminium-alloy housing and the aluminium-alloy rotor. As a guide and transmission element of car suspension system, control arm transmits kinds of strength to car body, and guarantees the wheels move in a certain trace for enough rigidity, strength and long service life as well. In real open-type production, there are two main problems: cracks are easily formed on components, resulting in faulty part; the using ratio of materials, fewer than 50%, is too low. Therefore, there is great necessity to study on forging technology to make large-scale production, cut down production cost, and improve forging quality, producing ratio and the using ratio of material at the same time.

Through the establishment of 3-D geometrical model of aluminum alloy control arm, this paper analyzes the numerical simulation of its precise isothermal forging and the problems of insufficient
filling, metal folding and crazing in the precise isothermal shaping by finite-element analysis software. The experiments, on the basis of the numerical simulate result, obtains good-shaped forgings, which provides the theoretical experimental basics for the practical production of aluminum alloy control arm.

2. Forming Process Analysis
The 3-D geometrical model of control arm is set up as shown in Fig 1. This part has the largest length, 500mm, and the height to width aspect ratio is 3.75:1 in Part I. A cylindrical branch, whose diameter is 58mm, is in Corner II in the middle. The slender neck connected with the cylindrical branch is 30mm in the thinnest part. The ladder-shaped part in Part III makes the parting surfaces in two different planes. In the component, both sides of the middle part have two ribs.

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3. FEM model
In the isothermal finish forging, since the elastic deformation part is far smaller than the plastic deformation part, the former can be ignored to build rigid-plastic material model. The die material is defined as rigid body. ALUMINUM-6061 is chose as workpiece material. The friction form of blank and die is shearing friction with the friction coefficient defined as 0.1. The result can be calculated through conjugate-gradient solver and direct iteration method. The temperature of blank, lower die and upper die is set at 460°C. The temperature is kept invariable, the moving speed of upper die is set at 1mm/s, and the tetrahedron remeshing technology designed by Martins et al. (2003) and Hang et al. (2004) is used in analog simulation. Because of the large size, complex shape and long simulation cycle of aluminum alloy control arm, only the isothermal final forging technology is simulated numerically in order to save simulate time and 4000 tetrahedron meshes are used to divide blank.

4. FEM simulation results of isothermal forming process
According to the simplification principle of pre-forging shape and die structure used by Quan et al. (2008), the shape is designed depending on the external outline of part, and the blank is set at equal thickness (Fig2). After final shaping, the left-side forging is insufficient filled and the cylinder branch in the middle is folded, while the rest are all fully filled. From the local velocity field diagram of Fig3, we can see that in the filling process of the branch, the metal consistently flows to the branch cylinder cavity. But after the branch is fully filled, the metal flows to the middle part. At these two times, the metal flows in converse directions. Therefore, its shape of pre-forging goes against the forming of final forging.
Fig. 2 Forging drawing of finish-forging

Fig. 3 Local velocity field diagram

In order to have the metal material distribute evenly to assure the final forging with no folding, cracks and other defects, technology supplement is made to the vertical corner of branch and arm (Fig. 4(a)), which depends the character that a cylinder branch is in the middle curve part. The fash is cut after shaping. With the pre-forging put into die cavity, the final forging obtained is shown in Fig 4. Obviously, the left-side of forging is insufficiently filled. Since technology supplement is set around the branch, the existing area of assembled material avoids the insufficient filling of branch. The forging finally obtained has no metal fold. With a relatively smaller size in the left-side thick part, when the metal flows into the lower die to some extent, the material in the head is not enough to fully fill the left-side part. It needs the entire move of the majority of metal in the middle to fill the left-side part, which is relatively more difficult to fill and will easily lead to insufficient filling. A further improvement of pre-forging is needed.

Fig. 4 Forging drawing of finish-forging

Contraposing the defects mentioned above, the shape of pre-forging should be further optimized to improve filling performance—to increase the thickness of the left-side blank which is difficult to forge after having set some technology supplements to the vertical corner. After the optimized blank put into the die cavity (Fig. 5 (a)), the final forging obtained is fully filled in all parts with no metal folds on it (Fig. 5 (b)), which proves that this pre-forging could improve filling performance.
5. Simulation Analysis of Finish-forging

5.1. Defect Analysis

With low plasticity and mobility, aluminum alloy is sensitive to notch. What’s more, the die is not of good shape, so the strong tensile stress on the forging surface may cause surface cracks in the final forging. As for the dies with peripheral rib, usually, it is because the fillet radius of the rib root is too small that the shearing force between the flowing metal and the static metal is strengthened to cause cracks presented by Cavaliere (2000).

Fig. 6 is the distribution map of surface expansion ratio of closed-die isothermal forging of aluminum alloy. From Fig. 6, we can see that the ratio in the rib is relatively big with the biggest surface expansion ratio in the supplement part. Because of no inclination in the rib and the comparatively small fillet radius, when the die constantly moves downward, the metal is pushed back to the rib incessantly. It creates a big shearing stress, so the surface expansion ratio is relatively high. The supplement part has such a severe deformation that the metal flows strongly with the biggest surface expansion ratio.

Fig. 6 Surface expansion ratio

The tensile stress on the surface of forging easily causes cracks on it, but the compression stresses from three directions could remove the inner defects and damages of metal. Fig. 7 is the distribution map of maximum principal stress. With a 92% displacement, the tensile stresses in Part I, II, III and the rib part is comparatively strong. In this phase, because of the free surface and insufficient filling of metal in the corresponding area, the metal is under the combining effect of a tensile stress and compression stresses from two directions. The tensile stress is relatively strong, however, still weaker than the tensile strength of 6061 aluminum alloy. As the die moves downwards incessantly, with a 99% displacement, the tensile stress reduces, and the compression stress increases causing the free surface reduce as well. Due to the reduce of free surface, according to the ideal resistance of deformation, as explained by Wang et al. (2011):

\[ P = \frac{y \ln R}{(1 - R)} \]  

In which \( y \) is the nominal flow stress of forging, and \( R \) is the relative area reduction, with the other factors invariable and the deformation resistance gradually increased, Part I and III are still insufficiently filled and there still exists the free surface. However, the tensile stress reduces relatively,
Part II is fully filled and the metal is under the effect of compression stress from three directions. In conclusion, in the whole forging process, the biggest tensile stress of material is 67.4Mpa, far smaller than the tensile strength of 6061 aluminum alloy. Therefore, crakes will not form on the surface.

![Diagram of stresses](image)

(a) 92% displacement  (b) 99% displacement

**Fig.7 Maximum principal stress**

5.2. Local Velocity Field Analysis

The large size of aluminum alloy control arm makes Part I, II, III the most difficult parts to fill and the easiest parts to cause defects. Now, let’s have further analysis on the filling process and metal movement in Part I.

When the upper die flows to the position of Fig.8 (b), the middle-lower trace points in the vertical direction wind right, which illustrates that the metal on the horizontal direction moves in different speeds. Fig.9 (a) is the sketch map of metal movements. In the map, the left-side metal moves faster than the right-side part; the metal around the vertical line almost does not flow horizontally but downwards, while the metal far from the vertical line flows left in a high speed.

When the upper die flows to the position of Fig.8(c), the moving speed of the right-side metal towards the upper-and-lower side was obviously higher than that of the left-side part, and the moving speed towards up was higher than that towards down. Since the moving speed of the left-side metal was relatively low, the upper-and-lower trace points of the vertical line deviate to the left. In this phase, the left-side metal was subjected to the pressure from three directions. Because the three-side die is of rigid body, under the pressure from three directions, the metal flows to the side of the smallest pressure. From Fig.9 (b), we can see that in the ladder-shaped part of die, the metal moves in a high speed. Due to the existence of free surface, with a 92% displacement on the upper die, the free surface in the bottom was big, so the metal tends to fill the down part in a high speed; with a 99% displacement, due to the reduce of free surface, according to Formula 1, with the other factors invariable, smaller the free surface in the bottom is, bigger the deformation resistance of metal will be in the moving downward, making the moving speed relatively low.

When Part I is fully filled, the majority of metal doesn’t flow. The upper metal keeps the moving speed of die and then stops moving. However, the trace points in the vertical line keep winding, no phenomenon like cross-flow occurs, and the metal streamline rationally distributed along the outline.

![Diagram of deformation](image)

(a)Before finish-forging  (b)92% displacement  (c)99% displacement  (d)100% displacement

**Fig.8 The deformation of the tracking**
6. Experimental Research
Physical experiment with the 1600t hydraulic press is conducted after the forging die is designed. In the final forging, the die is preheated to 460℃, and the whole deformation is kept in homoeothermic condition. In accordance with its heating norm in forging, the aluminum alloy is put into the resistance furnace of RX2 series with macromolecule lubricant used. After trial-producing, a good quality forging is obtained. In Part III of Fig.10, an overflow cavity is set for balancing blanking, so it is needed to have slight machinery processing to cut off redundant materials.

7. Conclusion
(1) By optimizing pre-forging and setting certain technology supplements to the vertical corner of branch and arm, the assembled material before shaping thus improves its filling character, and removes the defect of metal folding in the cylinder branch. All parts of the final forging have been sufficiently filled.

(2) In the analysis of forging, the small fillet radius of rib root strengthens the shearing force between flowing metal and static metal and it is easy to form crakes near the technology supplement part; due to the free surface in filling in Part I, II, III, there is strong tensile stress on the forging surface, which is also easy to cause crakes.

(3) According to the designed technology and numerical simulate result, trial-production has been made and a good quality forging has been obtained, which proves the feasibility of this technology well.

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References

[1] Cavaliere, P., 2004. Isothermal forging of AA2618 reinforced with 20% of alumina particles. Composites Part A: Applied Science and Manufacturing 35,619-629.

[2] Gong, X. T., Zhou, J., Xu, W. J., Yang, F., Shi, X., 2009. The Development of IsothermalForging Technology for Aluminum Alloy. China Metalforming Equipment Manufacturing and Technology 2, 23-25

[3] Huang, Z. C., Bao, Z. X., Zhou, T. R., 2004. Study on remeshing technique for 3D finite element in metal forming processes. Forging & Stamping Technology 5,35-39.

[4] Martins, P. A. F., Marmelo, J. C. P., Rodrigues, J. M. C., Barata Marques, M. J. M., 1994. Plarhmsh3-A three-dimensional program for remeshing in metal forming. Computers & Structures 53:5,1153-1166.

[5] Quan, G. Z., Tong, Y., Ai, B. S., Liao X., 2008. Simulation and Experimental Study on Forming Process of Large Aluminum Alloy Shell Forging. China Mechanical Engineering 13,1582-1585.

[6] Shan, D. B., Liu, F., Xu, W. C., Lu, Y., 2005. Experimental study on process of precision forging of an aluminium-alloy rotor. Journal of Materials Processing Technology 170,412-415.

[7] Shan, D. B., Wang, Z., Lu, Y., Xue, K. M., 1997. Study on isothermal precision forging technology for a cylindrical aluminium-alloy housing. Journal of Materials Processing Technology 72,403-406.

[8] Shen, G. S., Furrer, D., 2000. Manufacturing of aerospace forgings. Journal of Materials Processing Technology 98,189-195.

[9] Wang, G.C., Shi, W.C., Xue, K.M., Li, P., Xu, F., 2011. Cold precision forging technology of spur gear based on divided flow method. Die and Mould Technology 1,10-13.

[10] Yoshimura, H., Tanaka, K., 2000. Precision forging of aluminum and steel. Journal of Materials Processing Technology 98,196-204.