Research Article

Wei Zhang* and Yandong Yu

Closed-die Forging Technology and Numerical Simulation of Aluminum Alloy Connecting Rod

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Abstract: In order to improve quality and reveal the law of precision forging, closed-die forging technology is used in this paper to conduct a numerical analysis of the forming process of aluminum alloy connecting rod by the DEFORM software. Forming effects under different loading modes were acquired, and forming process, blank flow characteristics, stress-strain distribution and load-stroke curve characteristics were analyzed. Study results indicate that the forming effect under the loading mode featuring first movement of lateral punch and then movement of upper and lower punches is good with high quality forge piece and no defect, the closed-die forging technology of aluminum alloy connecting rod is reasonable and feasible. Under a certain deformation velocity and deformation mode, aluminum alloy connecting rod forming load firstly reduces and then increases, the forming load is in direct proportion to deformation velocity. When the forming process is finished, forming load reaches 130T, it accords with the production practice. The study results provide a certain reference for guiding the formulation of closed-die forging production technology of aluminum alloy connecting rods.

Keywords: Aluminum Alloy Connecting Rod, Closed-die Forging, Numerical Simulation, DEFORM software

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1 Introduction

The connecting rod, as an important component of the engine, constitutes crank-link mechanism with air cylinder, piston, bent axle and main bearing [1]. Most connect-

ing rods of small-scale gasoline engines are made of high-strength aluminum alloy. As the important components of small-scale gasoline engines, connecting rod is not only complicated shape, high requirement for dimensional accuracy and favorable wear resistance but also shall not have defects both inside and on the surface such as crack, mingling, pore, etc.; conventional metal machining technology can reach design requirements of parts, but its production efficiency is extremely low and material utilization efficiency is low, and moreover, industrial production in large batches can't be realized. Nowadays pressure casting or ordinary hot die forging and follow-up machining are generally adopted for batch machining in China, through which qualified aluminum alloy parts can be obtained. However, due to poor surface smoothness of aluminum alloy under pressure casting and casting defects always existing inside parts like pore and mingling, their mechanical properties are greatly degraded, thus being difficult to satisfy usability requirement. Meanwhile, product percent of pass in the follow-up machining is low (about seventy percent) because of existence of casting defects like pore, mingling, etc. Ordinary hot-die forging forming of aluminum alloy connecting rods features tedious production procedures, complicated technological process, low material utilization efficiency (about sixty percent) and high production cost as well as defects like surface crack, folding, disorderly metal flow line, etc. Therefore, it will be of great practical significance to research and develop precision forging forming technologies of aluminum alloy connecting rod-type forge pieces in order to improve their machining quality and mechanical properties [2–4].

Closed-die forging is a forming technology which places workblank inside a closed die cavity under three-way stress state and extrudes it using punches so that the die cavity is filled with metal to obtain complicated trimming-free flash. However, closed-die forging forming process is complicated with many control parameters so that optimal parameter selection, complicated die design and machining in the closed forging technology of complicated parts become more difficult [5–7]. It's hard for traditional forming technology and die design method depending on experience and trial and error to satisfy compli-

*Corresponding Author: Wei Zhang: Rongcheng College, Harbin University of Science and Technology, Weihai, 264300, China; Email: zhangw_hrbust@163.com

Yandong Yu: School of Materials Science and Engineering, Harbin University of Science and Technology, Harbin, 150040, China; Email: yandong_yu@163.com

cated forming conditions and high requirements for precision and quality. Therefore, it is necessary to conduct simulation, technological analysis and optimization design of closed-die forging process using the numerical simulation technology. Cross-sectional change of the aluminum alloy connecting rod is major along the length direction with great forming technical difficulties, which poses enormous challenges to the study of closed-die forging forming of aluminum alloy connecting rods [8, 9].

On this basis, researchers have carried out a large quantity of research on numerical simulation of closed-die forging forming of aluminum alloy connecting rods [10–15], but deviation from actual technology still exists in aspects of multi-field coupling problem in the thermal deformation process of aluminum alloy connecting rods and the influence of changes of different thermal deformation parameters on stress-strain fields. Therefore, how to accurately predict relationships between different forming modes and forming quality, reveal precision forging forming laws of aluminum alloy forge pieces and prevent defects is an urgent problem to be solved [16–18].

Therefore, theoretical analysis and numerical simulation were combined in this paper to establish a finite element computing model for closed-die forging forming of aluminum alloy connecting rod, and then aluminum alloy connecting rod forming process, blank flow characteristics, stress-strain distribution and load-stroke curve characteristics were analyzed, aiming at predicting relationships between different forming modes and forming quality more accurately so as to provide a reference for development and optimization of precision forging forming technology of aluminum alloy connecting rods.

2 Finite element analysis model

2.1 Closed-die forging technology

Closed-die forging is also called closed extrusion. Its principle is: large enough die clamping force is used to combine two or several detachable dies into one closed die cavity, and metal workblank fills the die cavity through extrusion under one-way or opposite movement of one or multiple punches so as to obtain a flash-free forge piece approximate to net dimensions with the same shape and dimensions as the die cavity as shown in Figure 1.

Figure 1: Closed-die forging technology.

Figure 2: forged connecting rod.

2.2 forged connecting rod and prefabricated blank

The aluminum alloy forged connecting rod piece formed through three-way closed-die forging is shown in Figure 2.

According to the principle that metal volume remains unchanged before and after plastic deformation, shape of fabricated blank can be determined according to Figure 3.

2.3 Geometric model used in numerical simulation

During the closed-die forging forming process of aluminum alloy connecting rod, as plastic deformation of blank is far greater than its elastic deformation, it is proper to numerical simulation using rigid-plastic finite element method [19, 20].

Based on UG and Deform-3D software platform, the geometric model used for numerical simulation of closed-die

Figure 3: prefabricated blank of connecting rod.

Figure 4: Geometric model of closed-die forging of connecting rod.

forging of aluminum alloy connecting rod, which is established using rigid-plastic finite element theory, consists of upper die, upper round punch, upper square punch, lower die, lower round punch, lower square punch and lateral punch as shown in Figure 4.

Figure 5: Grids of connecting rod workblank.

2.4 Model grid partitioning

The connecting rod workblank belongs to a regular geometry, tetrahedron elements are used for grid partitioning, minimum unit edge length of grids is 1mm, grid aspect ratio is 3, and total number of grids is 39,572, all of which satisfy the requirement for computational accuracy. Grid structure of the connecting rod workblank is shown in Figure 5.

2.5 Material properties and computational boundary

AL6061 material is used, the used workblank is regarded as a plastic body, constant shear friction model is used as the model between workblank and die, the die is regarded as a rigid body, and friction factor is taken as 0.3 [21, 22]. In consideration of temperature change, initial workblank temperature is set as 400°C, temperature between punch and die is set as 200°C, and heat exchange coefficient between die/punch and workblank is 5KW/(m°C), where velocity of movement of punch is set as 10mm/s.

2.6 Closed-die forging forming technology scheme

6061 aluminum alloy connecting rod has complicated structure and its forming process is as follows: the prefabricated blank is placed in the lower die, and after upper and lower dies are clamped, upper round punch, upper

Figure 6: Simulation results of mode of movement in scheme 1.

Figure 7: Simulation results of mode of movement in scheme 2.

square punch, lower round punch, lower square punch and lateral punch conduct forging forming according to a certain direction and velocity of movement. Dies and punches have two modes of movement:

- (1) Three parts of the connecting rod are formed simultaneously namely punches in three directions simultaneously move;
- (2) The large head part is firstly formed, followed by middle part and small head part, namely lateral punch firstly moves, followed by upper and lower punches.

3 Analytic result

For scheme (1) described in section 2.6, 5 punches are made under synchronous movement, and numerical simulation of the whole forming process is shown in Figure 6. As shown in Figure 6, upper, lower and lateral punches are under simultaneous movement. When the deformation starts, metal flow direction is quite even with stable forming process, where rod part metal mainly flows towards the side which needs more materials, and metal mainly flows towards the small head side. Large head-end metal mainly forms the large head side. As it's far away from the small head end, it's difficult for metal to flow towards small head end. When the stroke ends, small head end has not been completely formed yet while folding phenomenon exists at large head end. For scheme (2) specified in section 2.6, lateral punch is firstly loaded so that large head of the connecting rod is formed, 4 upper and lower punches are then loaded, and finally the workblank is formed as shown in Figure 7.

It can be seen from Figure 7 that lateral punch takes the lead in moving, and large head side of the connecting rod is firstly formed. When upper and lower punches move again, surplus metal flows evenly towards the unfilled region. When the stroke ends, forming and filly are completed without defects like wrinkle.

4 Discussion

4.1 Pressure-stroke curve analysis of closed-die forging process

Through the pressure-stroke curve, flow features of aluminum alloy blank in different phases of the compressional deformation process can be qualitatively judged, and its deformation state is gradually transited from unstable state to steady compressional deformation process. Figure 8 shows X-directional load borne by the lateral punch and Figure 9 shows Z-directional loads borne by upper and lower punches. According to the curves, the workblank can be divided into the following phases in the extrusion process:

Phase I: after upper and lower dies are clamped, upper and lower punches are still, only lateral punch conducts loading, the workblank starts generating plastic deformation at the large head end and gradually fills the cavity, extrusion force is gradually enlarged, and when lateral punch reaches the stipulated stroke, lateral extrusion

Figure 8: X-directional load.

Figure 9: Z-directional loads.

force is $f=200,000\text{N}$ (namely 20 tons). After lateral punch stops moving, extrusion force abruptly declines.

Phase II: lateral punch keeps still, upper and lower punches start extruding, the workblank gradually fills the whole cavity, and pressure borne by lateral punch gradually increases to 20 tons. At the time, pressures borne by upper and lower punches gradually increase.

Figure 10: When movement of lateral punch ends.

Phase III: upper and lower punches continue to extrude. At the final forming time, the workblank is under triaxial compressive stress so that extrusion force of each punch rises at a high velocity. Extrusion force of lateral punch is $f=658,000\text{N}$ (namely 65.8 tons), that of round punch is $f=103,000\text{N}$ (namely 10.3 tons) and that of square punch is $f=544,000\text{N}$ (namely 54.4 tons).

After phase III ends, if extrusion is continued, sharp increase of extrusion force may damage the die and punching machine.

4.2 Analysis of workblank flow characteristics in the closed-die forging process

Aluminum alloy blank flow analysis results in the extrusion process are shown in Figure 10 and Figure 11. Friction between die and blank is adhesive friction. Frictions in different regions have different effects on the blank. The punch makes workblank move forward in the forming process while friction between workblank and die discourages the workblank from moving forward. Therefore, flow velocity field distribution is not very even, especially velocity field nearby the die bearing is larger than those in other regions. According to the least resistance law, metal will flow by selecting a flowable path. The velocity is lower in the place with large flow resistance. As shown in Figure 11, metal flow vectors are basically identical, so forming is favorable without folding and folding defect will not be generated.

Figure 11: When forming ends.

Figure 12: Deformation velocity analysis (1).

4.3 Analysis of workblank deformation velocity in the closed-die forging process

During the aluminum alloy deformation process, if the deformation speed is too fast, cracks can be easily generated. It can be seen from Figure 12 and 13 that deformation velocity of aluminum alloy workblank is high at the large head part—a region where cracks can be easily generated—in the early extrusion phase during the forming process. If cracks are generated, they can be eliminated by controlling punch velocity.

Figure 13: Deformation velocity analysis (2).

4.4 Workblank stress-strain analysis in the closed-die forging process

With the lateral punch into upper and lower dies, stress starts experiencing obvious changes when lateral punch contacts the workblank, the stress at contact part between workblank and lower die is larger than that on its upper surface, and the stress changes the most in the contact between the workblank side and the lateral punch. As the deformation proceeds, stress at the contact part of the lateral punch gradually increases. Stresses in other regions of the workblank somehow increase with relatively uniform distribution, mainly because metal material itself flows and self-homogenizes the stress. When stroke of lateral punch ends, large head of the connecting rod is not completely filled, and maximum stress value of the workblank is 105MPa (see Figure 14). When upper and lower punches start loading, elliptic punch first contacts the workblank, stress value at the round corner experience the greatest change with the maximum strain rate, and metal at this part is under high stress state. When round punch contacts the workblank, round corner where workblank contacts the die is still the stress concentration part, and stress value is 100MPa or so. When strokes of upper and lower punches end, the forged connecting rod piece is completely filled, stress value reaches the maximum value 147MPa (see Figure 15) with uniform distribution, and bosses of large and small heads are well filled.

Strain condition of the workblank in the extrusion process is shown in Figure 16. Equivalent strain distribution is uniform in the whole deformation process, no cracks will

Figure 14: Stress distribution(1).

Figure 16: Strain distribution.

Figure 15: Stress distribution(2).

be generated, and strain values are not large and all within the allowable range.

5 Conclusion

In order to explore closed-die forging forming laws of aluminum alloy connecting rod and reveal the relationship between punch loading mode and forming quality, starting from finite element analysis model, the process of closed-die forging of aluminum alloy connecting rod is simulated and analyzed in this paper. The following conclusions were drawn:

- (1) Results show that the metal flow process can be divided into three stages, the final forming contour is clear and the filling is full with no folding, insufficient filling and uneven flow line
- (2) The loading mode under which lateral punch firstly moves, followed by upper and lower punches is of favorable forming effect and no defects.
- (3) Under a certain deformation velocity and deformation mode, forming load of aluminum alloy connecting rod first increases and then decreases and increases again, and forming load is in direct proportion to deformation velocity, the maximum forming load is 130T.
- (4) Theoretical analysis and numerical simulation were combined in this study. A new method of aluminum alloy connecting rod production using closed-die forging technology was proposed. It can be used as a reference for the development of precision forging process of aluminum alloy connecting rod. However, the influence of process parameters on the microstructure evolution of the forge piece has not been deeply studied, so in the future research, produced forge piece will be combined with simulation results for the sake of correction, which will contribute to a more accurate understanding of closed-die forging forming process laws of aluminum alloy connecting rods.

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