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# Investigation of semi-solid aluminum alloy filling-plastic flowing in thixoforging

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**Abstract**：The semi-solid filling-plastic flowing integrated forging process of semi-solid 6061 Al alloy was simulated by commercial finite element software DEFORM-3D. Temperature, fluid and stress-strain fields were considered in numerical simulation. The simulation results show that the plastic deformation of billet of the ends is higher than that of billet in the straight cylinder. The value of plastic deformation varies with loading mode and plastic deformation fields at the stage of increasing pressure to constant value. When the thixoforging experiments were performed at 590 ℃, 15 mm/s of punch velocity and 46 MPa of pressure side urn, it gets the filling wholly and dense internal organization of semi-solid thixoforging parts is gotten. Finite element analysis results are compatible with experimental ones.
**Key words:** semi-solid thixoforging; filling-plastic flowing; plastic deformation; DEFORM-3D software

## 1 Introduction

The mechanical properties of workpiece made by semi-solid forging based on solidification with less plastic deformation cannot meet requirements of the important force components and structural parts in automobiles and aircrafts[1−3]. Technology of semi-solid aluminum alloy filling-plastic flowing integrated forging was introduced to solve this problem. The semi-solid billet in mold cavity is filled and concreted at a lower pressure and then takes the shape similar to the workpiece. Then, solidification metal is forced to move into the space made by activity module in die by increasing pressure to a constant value. The true plastic deformation is achieved under the pressure, resulting in high mechanical properties of workpiece[4].

FEM technology can be used to simulate the process of semi-solid filling-plastic flowing integrated forging[5]. At the forming stage, the viscosity characteristic is presented, so the model of material can be treated as rigid visco-plastic ones[6]. Elastic deformation can be ignored using this model of material[7]. Rigid visco-plastic constitutive model of semi-solid 6061 Al alloy was established at different temperatures and different strain rates. Based on the theory of rigid visco-plastic finite element, the commercial software DEFORM-3D can be used to simulate the semi-solid filling-plastic flowing integrated forging[8−10].

## 2 Establishment of FEM model

### 2.1 Establishment of geometrical model

The experimental principle of the semi-solid filling-plastic flowing integrated forging is presented in Fig.1. When the billet is reheated to semi-solid state, it has the ability of viscid fluid immediately. The semi-solid material was solidified under the low pressure for 20 s, then it got the initial shape. The semi-solid material pushes the sliding sleeve to move forward under the high pressure until the sliding sleeve arrives at the limiting stopper. Fig.2 shows the suit of the whole mould.

Entity models of the billet, left and right half dies, left and right sliding sleeves and punch were established using the commercial software UG. Then they resulted in ‘stl’ model format. This format files were imported in DEFORM-3D by its pre-processor. Here, billet sizes were $\Phi$50 mm×100 mm. The relationship between position and movement of geometrical models could be defined after the models had been established. The left and right dies were regarded as static objects, punch was active, and the billet, the left and right sliding sleeve were slaved.

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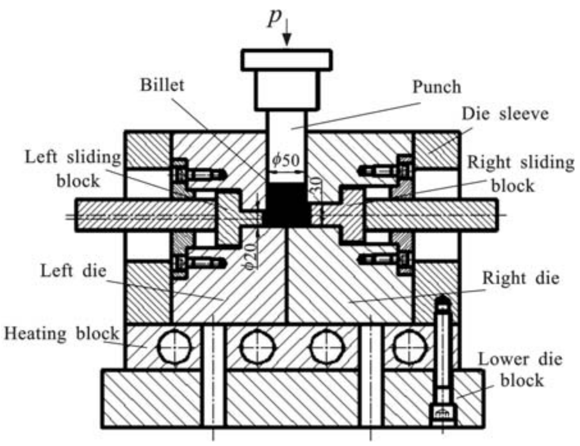


**Fig.1** Schematic of semi-solid filling-plastic flowing integrated forging

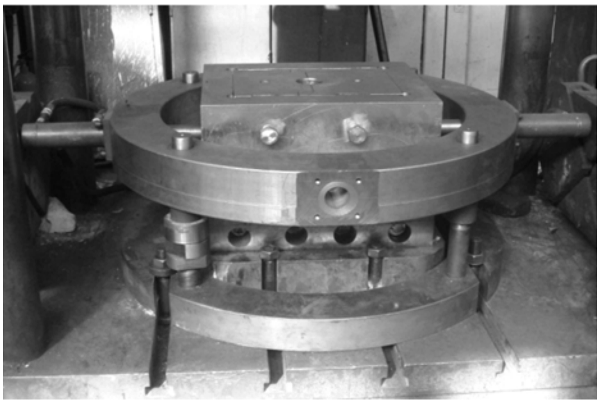

**Fig.2** Mold drawing

### 2.2 Establishment of material model

Material constitutive equation is a model of properties of material. Semi-solid filling-plastic flowing integrated forging is a very complicated rigid-viscid-plastic process. Elastic deformation can be ignored in semi-solid thixoforging process because the toll of elastic deformation is far smaller than plastic one in this process. Considering the influence of the flow stress and temperature on the strain rate, rigid-visco-plastic finite element formula is adopted as follows[11]:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp[-Q/(RT)] \qquad (1)$$

where $\dot{\varepsilon}$ is the strain rate; $\sigma$ is the flow stress; $Q$ is the activation energy; $R$ is the molar gas constant; $T$ is the absolute temperature; $A$, $\alpha$ and $n$ are the parameters independent of temperature.

For lack of the semi-solid material model in the DEFORM-3D material database, measuring the semi-solid true stress−strain relationship is required by compression experiment at different strain rates for establishing semi-solid material model of 6061 Al alloy.

## 3 Analysis of simulation results

### 3.1 Temperature fields in semi-solid filling process

When the semi-solid billet goes into the cavity, it has the ability of fluidity. It can take the cavity shape. The solidification is a major process. Fig.3 shows the temperature fields in the semi-solid filling process at temperature of 590 ˚C and punch speed of 15 mm/s. It is known that temperature decreases fast at the location contacting with the mould from the picture. When the liquid metal flows into the interval between sliding block and die, the temperature of the corner rises because of severe deformation. The stage of metal filling is ended at the 30th step and solidification is completed.

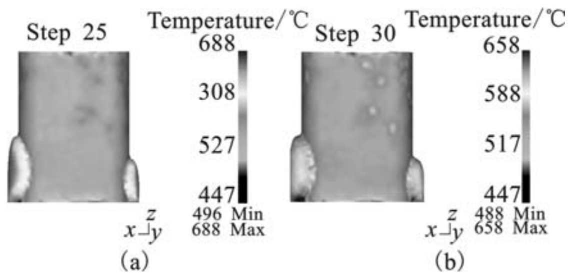


**Fig.3** Temperature fields at different steps: (a) 25th step; (b) 30th step

### 3.2 Temperature fields in thixoforging process

At the end of simulation of thixoforging process, five points are found in the part,as shown in Fig.4.

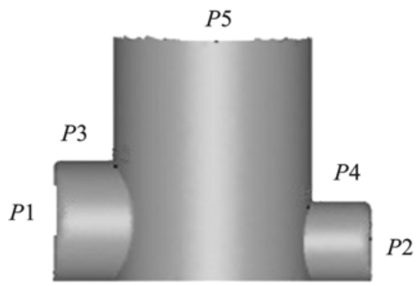


**Fig.4** Schematic of intercept points

Fig.5 shows the curves of temperatures at different points. It is included that the temperature of the part decreases with the stage of thixoforging. The velocity of temperature decreases the fastest at Point $P3$. Points $P1$ and $P2$ were little higher than Point $P3$ because of plastic deformation. Points $P3$ and $P4$ were in the location of severe plastic deformation so the temperature at the beginning of thixoforging not only does not decline but also raises slowly, as shown in Fig.6 But when temperature reached a constant value, it begins to decrease. Because strain is high at the beginning of thixoforging, a large amount of heat is produced. When this point is out of the location of large deformation, the heat produced by deformation declines and the heat transfer by contacting begins to play a leading role.

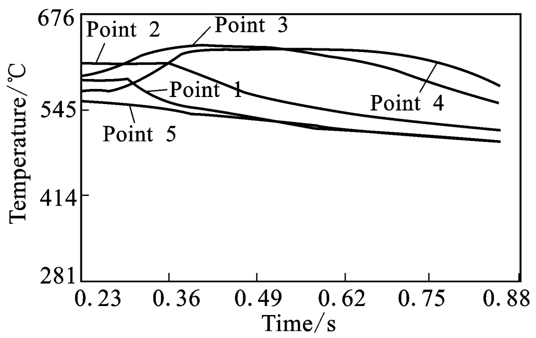


**Fig.5** Curves of temperature at different points

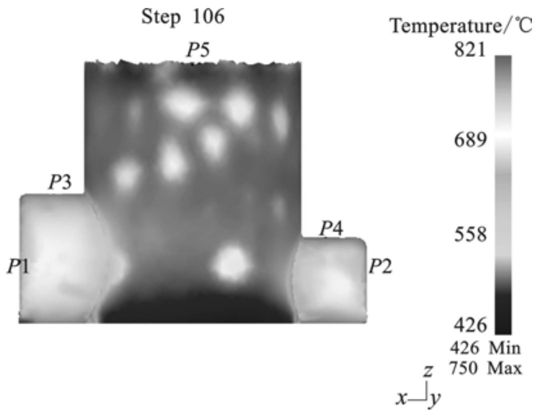


**Fig.6** Drawing of temperature distribution

### 3.3 Effective strain fields in thixoforging process

Fig.7 shows the effective strain distribution fields. At the beginning of thixoforging process, severe deformation mostly appears around the corner of billet. A few of deformation occurs in the body of workpiece. At the second stage, the semi-solid billet pushes the sliding block forward with increasing the punch pressure. The deformation of $\Phi$20 mm cylinder was bigger than that of $\Phi$30 mm one. The both ends of the cylinder were severely deformed, and the whole billet had yielded to deformation. When the sliding block reached the maximum position, the effective strain was smaller than that at the last stage because of the hydraulic system.

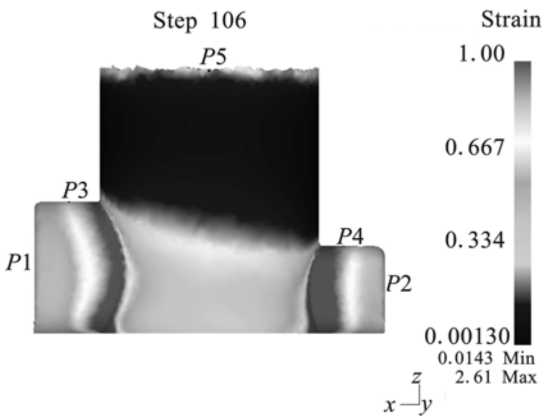


**Fig.7** Effective strain at different positions

Fig.8 shows the curves of effective strain at different points. It was concluded that the effective strain at the position which was contacted by punch was the smallest because of no plastic deformation, and it was regarded as rigid movement. The effective strains of points $P1$ and $P2$ rise slowly because of little plastic deformation. The effective strain of corner increased slowly at the beginning, and then increased rapidly, but at last decreased rapidly. It is because the two points of billet were in transfer area and plastic deformation was smaller at the beginning when they arrived at the corner, and high deformation was made. When deformation was in stable area, the plastic deformation declined, so the effective strain began to decrease.

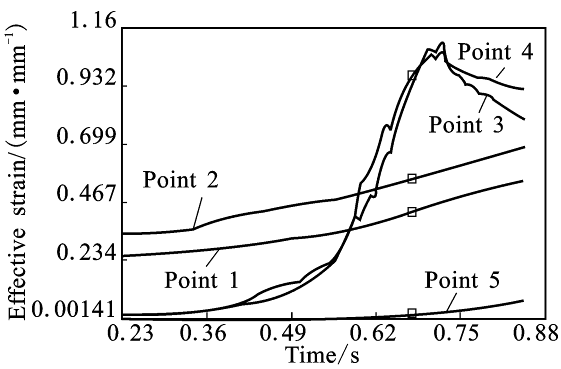


**Fig.8** Curves of effective strain at different points

### 3.4 Effective stress fields in thixoforging process

Fig.9 and Fig.10 show the effective stress distribution and the curves of effective stress at different points, respectively. It was known that the effective stress increased shortly at the beginning because it was in elastic deformation and the time was short. Elastic deformation was neglected and it was in accordance with the hypothesis. There was the large friction at Point $P1$ because of contact between Point $P1$ and punch, so the stress was the largest. Because the velocity of deformation was fast, the bigger friction was produced by workpiece and die. The stress of outside surface of workpiece was higher, and decreased gradually from outside to inside of workpiece. The stresses of Points $P3$ and $P4$ were much higher, which was caused by change of metal plastic deformation direction.

### 3.5 Velocity fields in thixoforging process

Fig.11 shows the velocity fields in the last stage. It was found that the velocity at the bottom of $\Phi$50 mm cylinder was smaller than that at the two ends of part. The flowing of metal was not uniform, and the velocity of $\Phi$30 mm cylinder was faster than that of $\Phi$20 mm cylinder. It was in accordance with streamlines of workpiece, as shown in Fig.12.

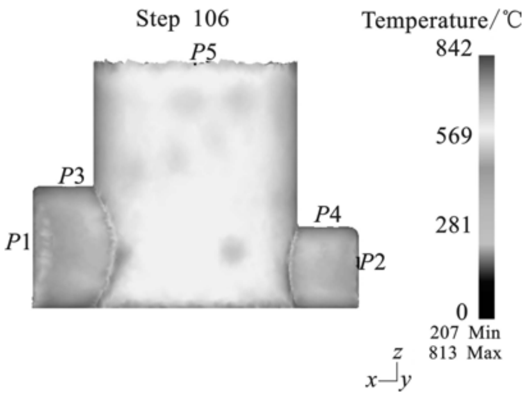


**Fig.9** Effective stresses at different positions

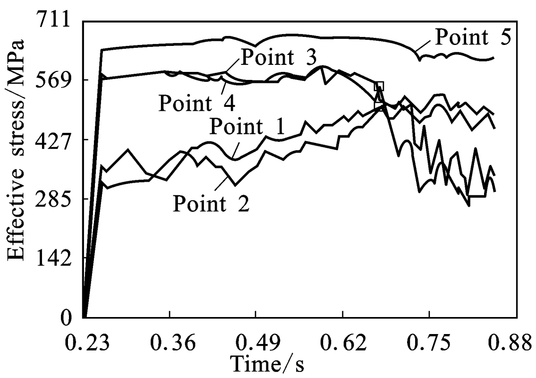


**Fig.10** Curves of effective stress at different points

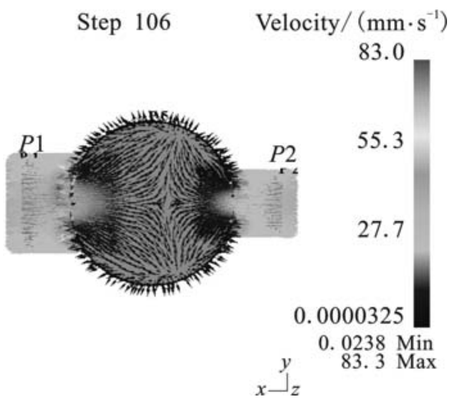


**Fig.11** Velocity fields at last step

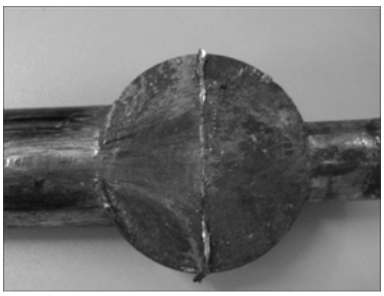

**Fig.12 Streamline of workpiece**

## 4 Experiments

### 4.1 Experimental procedure

In order to verify the regularity of plastic flowing, temperature and strain rate of thixoforging process of 6061 Al alloy, isothermal experiments were performed at 590 ˚C for different holding times on 200 t hydraulic pressure machine. The hydraulic system shown in Fig.13 was introduced in this experiment as the assistance accomplishing the plastic deformation. The maximum limit pressure of overflow valve is designed to be 46 MPa and it was adjustable. Increasing the punch pressure to a certain value higher than overflow valve one, the sliding block was forced to move forward. Fig.14 shows the hydraulic stereogram.

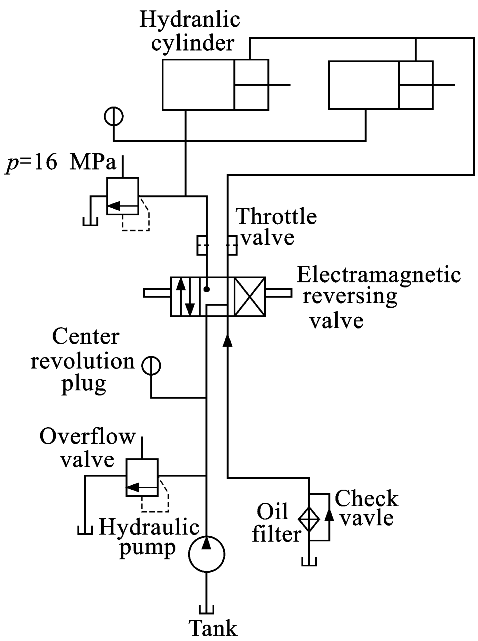


**Fig.13** Hydraulic schematic

### 4.2 Results of experiments and analysis

Fig.14 shows the workpiece from the experiment. The semi-solid billets made by SIMA were heated at 590 ˚C for 50 min, then were put into the die and formed under the different pressures of side urn. The pressures of side urn were 46, 34 and 22 MPa, respectively.

**Fig.14** Workpiece formed by semi-solid thixoforging

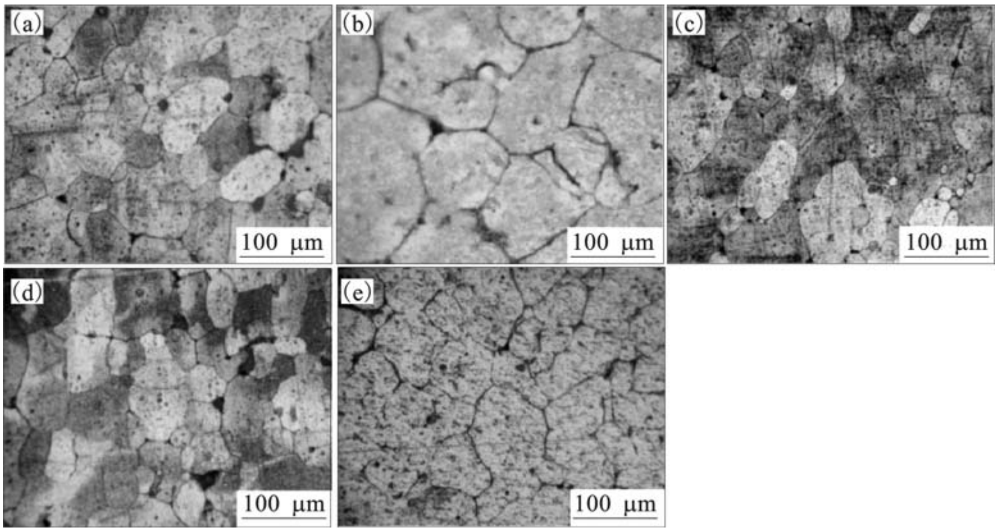


**Fig.15** Microstructures of different points in Fig.4: (1) Point *P*1; (2) Point *P*2; (3) Point *P*3; (4) Point *P*4; (5) Point *P*5

Fig.15 shows the microstructures of different points as the same as those in Fig.4. The sizes of grains of Figs.15(c) and (d) are smaller than those in other images because of plastic deformation. The direction of plastic flowing can be seen from Figs.15(c) and (d), and the globular structure is filled with whole grain and distributed uniformly. These results are compatible with simulation. Table 1 shows the hardness of workpiece at different points formed by thixoforging. It is concluded that the hardness of Point *P*4 is the highest because of the severe plastic deformation, which is in accordance with simulation.

**Table 1** Hardness comparison of workpiece at different points(HV)

| *P*1 | *P*2 | *P*3 | *P*4 | *P*5 |
|---|---|---|---|---|
| 110.53 | 111.03 | 110.76 | 111.57 | 111.18 |

## 5 Conclusions

1) The regularities of temperature, fluid and stress-strain fields are obtained.

2) The increasing pressure makes the sliding block move and the assistant hydraulic system put into effect, which leads to the real plastic deformation. The mechanical properties are improved largely by metallographic structure of workpiece. Both the strength and hardness are improved.

3) The globular structure is filled with whole grain and distributed uniformly. These results are compatible with simulation.

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