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FEM simulation of extrusion of 3003 alloy tubes①

LIU Lang-fei(刘浪飞), PENG Da-shu(彭大暑), JIN Xiang-yun(靳湘云)
(Department of Materials Science and Engineering,
Central South University of Technology, Changsha 410083, P.R.China)

[Abstract] In manufacturing 3003 small tubes, impact extrusion was applied in order to obtain seamless tubes with high accuracy and high surface finish. In impact extrusion of such tubes, die damages are often observed. These damages are related to process variables such as tools structure and temperature, extrusion ratio, initial billet temperature, characteristics of the extrusion speed and lubrication. It is economical and efficient to use FEM (finite element method) to simulate metal flow, stress, strain and temperature under different extrusion conditions. The simulation results are helpful to the investigation of die damages and the optimization of extrusion process parameters.

[Key words] FEM; thermal coupling; impact extrusion; 3003 alloy; tubes
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1 INTRODUCTION

Al alloys have been widely used in aerospace industry due to its high strength-to weight ratio, excellent toughness and good resistance to corrosive environment. The 3003 thin wall small tube products are used in heat exchanger of aerospace vehicles.

The diameters of 3003 alloy tubes are from 3.0 ~ 8.0 mm, and thickness about 0.3 ~ 0.7 mm. In order to meet the high accuracy, impact extrusion with the extrusion ratio of over 40 is applied. But the flow stress of 3003 alloy is highly sensitive to strain rate and temperature, so in high-speed extrusion, die is under high stresses and easy to be damaged.

FEM can be used to simulate the process of extrusion, and get such results as stress, strain, strain rate, temperature, and node velocity distribution. Using these results, impact extrusion parameters can be optimized to reduce the amount of trial necessary to get acceptable product[1~3].

The main objective of this paper is to investigate the influence of process variables on product quality and die life, and propose an optimum scheme for trial. The final goal is to optimize the process parameters based on the experimental and FEM analyses, to improve product quality and die life.

2 PREPARATION OF INITIAL SIMULATION CONDITIONS

The general process of tube extrusion is shown in Fig.1. The hollow billet in the container is inserted into the bore by a mandrel, and extruded through the annular gap between the die opening and the mandrel. Lubricant is placed near the die ope
vide lubrication between the billet and the die. In the process of impact extrusion, many factors need to be taken into consideration to establish the initial simulation condition[4]. To improve the accuracy of simulation, the flow stress and coefficient of friction of 3003 alloy were tested[5~6].

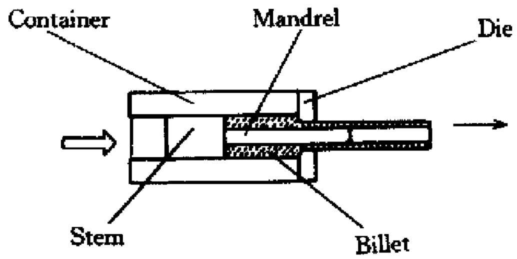

Fig.1 General process of tube extrusion

2.1 Flow stress data of 3003 alloy

The flow stress data of 3003 alloy was tested on Gleeble-1500 with the strain rate from 1 s^{-1} to 50 s^{-1}. The test results and discussion can be seen in Ref.[5].

2.2 Coefficient of friction

The friction condition between the billet and tools (container, die and mandrel) is complicated. We applied ring upset testing on Gleeble-1500 to get the effective shear constant. The test results can be seen in Ref.[6].

2.3 Geometry

The geometry of the billet was selected based on the actual extrusion except the length of the billet. The length of the billet was shortened in order to decrease the number of mesh needed to undergo the simulation process, which will save computer resource and make the simulation faster[7]. The geometry of

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the billet was d20 mm/ d6.9 mm × h10 mm. The diameter of container was d20 mm, extrusion die was d7.5 mm and mandrel was d6.9 mm.

3 SIMULATION ON IMPACT EXTRUSION OF 3003 ALLOY TUBE

3.1 Simulation cases

In order to optimize the parameters of the extrusion process, four cases with varied billet temperature and ram speed were prepared shown as Table 1.

Table 1 Four cases of tube extrusion process

No.	Initial billet temperature/ ℃	Ram speed/ ($mm \cdot s^{-1}$)
1	20	10
2	20	165
3	240	10
4	240	165

3.2 Meshing and remeshing

For FEM simulation of tube extrusion, the metal flow pattern can be divided into three parts[8]:

1) Initial state of extrusion;
2) Steady state;
3) Final state of extrusion.

In tube extrusion, most of the deformation occurs near the die outlet and none occurs far away from it. So when meshing, the portion far away from the die outlet is no longer taken into account. Therefore, at least two kinds of mesh density should be considered while creating a new mesh[9].

The FEM simulation of tube extrusion with high extrusion ratio (over 40) is often interrupted by the occurrence of a negative Jacobean due to the collapse of one of the mesh elements located near the extrusion outlet, which is a direct result of severe deformation in the reduction region. Therefore, automatic remeshings are necessary to keep the simulation process going. Remeshing will not always succeed. So, more elements and shorter time per simulation step may be applied to deal with these problems. In the examples of these four cases, 5 000 to 6 000 elements of four kinds of mesh density were applied as shown in Fig.2.

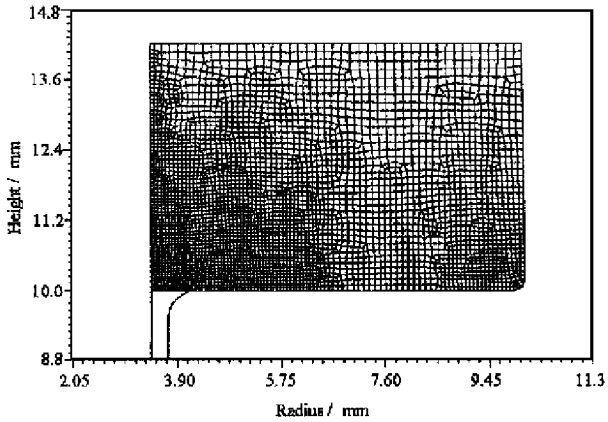

Fig.2 Intitial mesh with different mesh density

4 DISCUSSION AND ANALYSIS

4.1 Simulation results

The general view of the extrusion characteristic stress, strain, strain rate, temperature and distribution from case 3 are presented in Figs.3(a) to (d). The effective stress, strain and strain rate distribution in Fig.3(a), (b) and (c) show that, the deformation is concentrated in the small region near the die outlet, where the maximum stress is present. This is the main reason of die damage. The temperature distribution in Fig.3(d) shows the heating due to deformation and friction and the heat exchange between the billet and tools.

The distribution of the parameters in all cases are similar, except that the actual values are quite different, as shown in Table 2, in which some values are compared at the same stroke.

Table 2 Comparison of simulation results with cases 1, 2, 3 and 4

Case	Max. effective stress/ MPa	Max. temperature/ ℃
1	207.63	279.6
2	231.28	322.2
3	102.67	310.3
4	126.06	342.3

4.2 Effect of ram speed and initial billet temperature on stress distribution

The distribution patterns of the stresses are all similar to Fig.3(a). The effect of initial billet temperature on max effective stress is greater than that of ram speed. For example, maximum stress value with the initial billet temperature of 240 ℃ is about half of that with room temperature. This will prolong the die life[10].

4.3 Effect of ram speed and initial billet temperature on temperature distribution

The distribution patterns of all cases are similar, while the values are quite different. The maximum temperatures are seen in the small region adjacent to the mandrel before the extruded material exit from the die. In comparing the maximum temperature, under the condition of the same ram speed between Cases 1 and 3 or Cases 2 and 4, the maximum temperatures keep higher with higher initial billet temperature than those with lower initial billet temperature.

In Cases 1 and 3, less deformation heating occurs due to the lower strain rate, compared respectively with Cases 2 and 4. Because all cases are com-

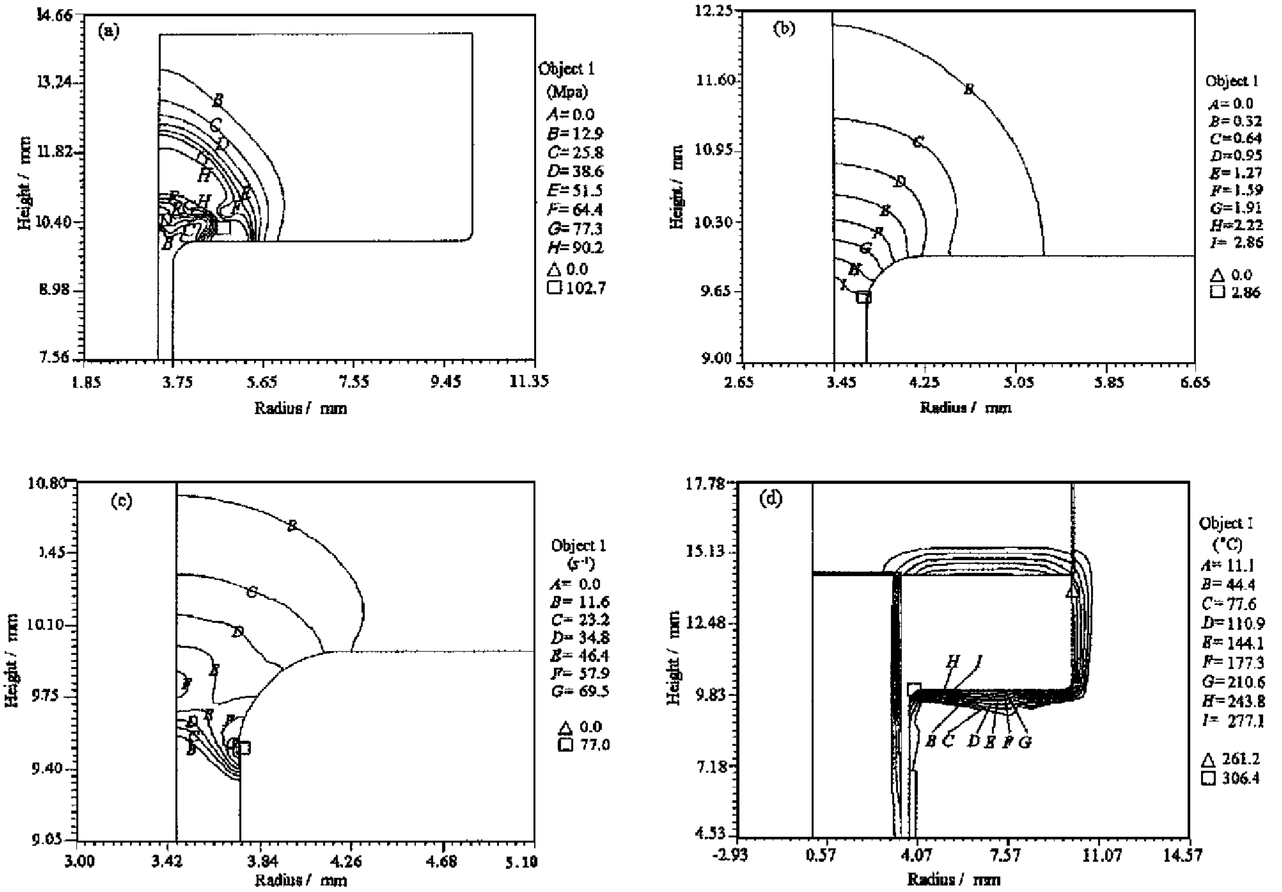

Fig.3 Extrusion simulation results of Case 3
(a) —Stress distribution; (b) —Strain distribution; (c) —Strain rate distribution; (d) —Temperature distribution

pared at the same stroke but different in ram speed, the extrusion process time in Cases 1 and 3 is longer than that in Cases 2 and 4. Therefore, the die chilling effects, which are influenced by the duration of contact time between the billet and tools, are greater in Cases 1 and 3. Temperature rise in all case is remarkably large, especially in Case 2, where it is over 300 ℃. However, the maximum temperature will not rise forever, because the effects of deformation heating and die chilling may go to a dynamic equilibrium state, and the equilibrium point lie on ram speed, initial billet temperature and tools temperature.

4.4 Coefficient of friction

The coefficient of friction in these simulations is treated as shear constant. In fact, with the temperature rising due to deformation and friction heating, the viscosity of the lubricant will decrease[11], especially in some cases where the lubricant may become worse which greatly influences the friction state between the billet and tools. On the one hand, we may develop new lubricant mixed with powder and oil to abate the effects of temperature and ram speed. On the other hand, we had to introduce friction function concerning such factors as ram speed and initial billet temperature, to improve the simulation accuracy.

The above simulation results and analysis contribute to the optimization of the extrusion process and die design.

5 CONCLUSIONS

1) In order to accomplish thermal coupling FEM simulation of tube extrusion with high extrusion ratio, for example over 40, it is very important to select appropriate mesh number, distribution of mesh density and solution control time interval for automatic remeshing. In order to improve simulation accuracy, experimental data, such as flow stress and coefficient of friction need to be introduced.

2) The effect of temperature on maximum effective stress is more obvious than that of ram speed. So, in practical extrusion process, proper evaluation of initial billet temperature is recommended to abate bad stress state of the die.

3) Because high stress is concentrated near the die outlet during the extrusion process, die structure in designing need to be optimized to improve the metal flow, and measures must be taken in die machining to reduce stress concentration.

4) Heating due to deformation and friction is remarkable, especially in cold rapid extrusion, where it

is about 300 ℃. It is necessary to take the effect of it on product property into consideration.

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