Numerical Simulation and Technical Study of Radiator Aluminum Extrusion

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Abstract: Radiator profile structure is complex and difficult to produce, how to correct design aluminum extrusion die is critical. In this paper, a radiator extrusion die is designed by experience. After tryout, the level degree is bad and profiles are not correctly assembled. In order to find the specific reasons, a numerical simulation is carried out to the initial design. A finite element analysis model is established, the extrusion processes in steady state and transient flow state are simulated. Profile exit displacement, metal flow velocity, temperature distribution, metal flow stress, transient pressure change and die temperature, die stress are analyzed, the affection of process parameters on the extrusion process is studied too. Based on analysis result and tryout, we propose to add flow-promotion angle in up die, to add baffles on the low die and to modify bearing length. The modified die effectively solves the initial die design problem which velocity distribution in exit section is not uniform. Simulation results are good agreement with practice, finally produced profiles are qualified and can be correctly assembled. Instead of the tryout, we can guide the die design by FEM (finite element method).

Key words: Radiator extrusion die, numerical simulation, assembly, FEM

INTRODUCTION

Aluminum profiles have the advantages of beautiful appearance, high strength, corrosion resistance and easy recycle, they are widely used in the field of construction, rail transport, aerospace and communications (Shi et al., 2010; Liu et al., 2012a). In the actual production, hollow profiles are usually produced by porthole die, the principle are as follows: Under the extrusion machine’s pressure, the solid aluminum ingot with high temperature passes through the shunt hole and separates into several metal streams. Then it is re-welded in the welding chamber with a high temperature, high pressure and high vacuum. Lastly it outflows through the die gap formed by the up die and low die and pipes or hollow profiles that meet certain size requirements are formed.

The traditional extrusion die design mainly relies on the engineering experience and analogy, which results in a lot of manpower and material waste and seriously affects the production efficiency and product quality (Bastani et al., 2009; Liu et al., 2009; Man et al., 2011; Ishimura and Kanauchi, 2010; Wisselink and Huestink, 2004). In this paper, FEM is introduced into the extrusion die design. By virtual simulation, we are able to obtain the difficult physical characters of the aluminum alloy in the mold cavity, such as velocity, temperature, stress and strain etc. Some production defects can be forecasted, for example, the profile is whether twist, bend or wave. Instead of the tryout and rework procedure, the extrusion process and die design can be evaluated by FEM, proper technological and design parameters can be obtained before the practical production (Liu et al., 2012a, b).

PROBLEM IN TRYOUT

A radiator profile is studied in this study, it has the characters of large overall dimension, large wall thickness difference, flat wide shape and asymmetry. It is assembled by 6063 aluminum extrusion profile shown in Fig. 1a.

The common quality problems of aluminum radiator include shape and dimension deviation, uneven mechanical property, surface quality and assembly. Design and manufacture of the extrusion die is the key to the profile quality. Because the radiator is assembled by the teeth bite in both sides, it requires higher forming accuracy and production is more difficult.

Figure 1b shows the stub bar in initial tryout. The metal flow velocity is not uniform, in the middle screw holes and both sides is faster, in the middle tendons is slower. Figure 1c shows the assembly result of two profiles which come from steady production and are after tensile straightening. Contrasted with Fig. 1a, the profile levelness is not 90°, the product don’t meet the assembly requirement.

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**FINITE ELEMENT SIMULATION**

**Geometry model:** In order to deeply analyze the manufacturing process, we use FEM to study the material flow, temperature distribution, die stress and ram load. Recently commercial software HyperXtrude, DEFORM-3D and FLUENT are used for hot extrusion die design extensively. HyperXtrude (Huang et al., 2010) is a hp-adaptive finite element program to analyze fluid flow and heat transfer problems, it is widely used in metal processing industry where materials undergo plastic deformation and flow is described by incompressible Navier-Stokes equations.

A 3D extrusion model is constructed by Pro/E software, the model is imported into HyperMesh software for mesh. The regions of billet, pocket and welding chamber use tetrahedral mesh, bearing and profile exit use triangular prism mesh, die uses tetrahedral mesh. The mesh size of analysis model is determined by the material deformation degree (Zheng et al., 2012). Because the material deformation near the bearing is more violent, mesh size is relatively fine. While billet only occurs upsetting deformation, mesh size is relatively coarse. In order to ensure the analysis accuracy, effectively control the mesh number and save calculation time, the mesh size in porthole and welding chamber is properly fine (Lof and Blokhus, 2002; Zhao, 2006; Shi et al., 2010). There are 1536943 elements and 391056 nodes, the finite element mesh model is shown in Fig. 2.

**Material model:** In order to define the viscid-plastic material behavior, an accurate stress and strain state depending on strain rate and temperature is important. In this study, the material uses Sellars-Tegart model (Fang et al., 2007):

$$\sigma = \frac{1}{a} \sinh^{-1}\left(\frac{Z}{A}\right)^{n} \tag{1}$$

where, $\sigma$ is the flow stress, $a$, $n$ and $A$ are temperature-independent constants and $Z$ is the Zener-Hollomon parameter, which is defined by:

$$Z = \dot{\varepsilon} e^{\sigma/RT} \tag{2}$$
where, \( \dot{\varepsilon} \) is the effective strain rate, Q is the activation energy, R is the universal gas constant and T is the absolute temperature. Figure 3 shows the relationship between flow stress and temperature for AA6063 (Fang et al., 2007). The die composed of H13 is modeled as rigid body (Zhou et al., 2003). The material properties are shown in the Table 1.

**Boundary and initial condition:** Friction of aluminum on steel at extrusion temperature is usually considered as sticking, except in bearing zones where some sliding can occur. Coulomb friction is used in the paper in order to consider the sticking and sliding, friction coefficient is set as 0.3.

Heat transfer models may differ a lot in different FEM codes. Based on the HyperXtrude database, a heat transfer coefficient of 18000 (W m\(^{-2}\) k) between aluminum and steel is used. Air cooling is applied around the tools by using a convection coefficient of 15 (W m\(^{-2}\) k) (Fang et al., 2007).

![Flow stress vs Strain rate](image)

Fig. 3: Material model for AA6063

<table>
<thead>
<tr>
<th>Material name</th>
<th>Density (kg m(^{-3}))</th>
<th>Specific heat (J kg(^{-1}) K(^{-1}))</th>
<th>Thermal conductivity (W m(^{-1}) K(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA6063</td>
<td>2700</td>
<td>900</td>
<td>198.0</td>
</tr>
<tr>
<td>H13</td>
<td>7870</td>
<td>460</td>
<td>24.3</td>
</tr>
</tbody>
</table>

Finally, the boundary conditions and processes parameters are loaded on the model by HyperXtrude. The simulation parameters are shown in the Table 2.

**RESULT DISCUSSION**

**Displacement:** Figure 4 shows the profile exit displacement in X direction. Blue parts go in X negative direction and the maximal displacement is up to -2.5 mm. The red parts go in X positive direction and the maximal displacement is up to 3.028 mm. Deflection in X direction results that the profiles are not correctly assembled. In the first tryout, the bearing length of the up die and the low die is not reasonable, which leads that the profiles in the inner and outer wall do not flow out from the die hole at the same time. The displacement deviation in other different zones is not obvious and does not affect the assembly.

**Velocity:** Figure 5 shows the velocity vector when metal flows through the porthole and welding chamber.

In the porthole section, because two intermediate porthole areas are less than the others, when metal bypasses the diversion bridge into the portholes, flow rate in there are lower. In the welding chamber section, metal from six portholes gathers together, the metal continues the flow trend in the porthole, the surrounding flow is relatively slow and the middle flow is relatively fast.

Figure 6 shows the exit velocity distribution. The flow velocity in the middle ribs is slow, in two screw holes is fast and in both sides is fastest. Because slow flow velocity causes compressive stress, fast flow causes tensile stress, the exit profile bends like Fig. 1b.

![Displacement in X direction](image)

Fig. 4: Displacement in X direction
Fig. 5: Velocity vector in different sections

Fig. 6: Exit velocity distribution

Fig. 7: Temperature distribution

**Temperature**: Figure 7 shows the temperature distribution in the porthole, welding chamber and bearing. In both sides of the profile, the metal flows fast, the heat gathered from the metal flow is more, so higher temperature occurs.
in there. In the middle, the metal flow velocity is slower and the heat can transfer to the die timely, so the temperature in these regions is relatively low. At the die bearing, the hot metal flows through the die orifice to form, severe friction generates a lot of heat. Most of the heat retains in the metal, only little heat transfers to the die surface, so the temperature in the die bearing is highest.

Large temperature gradient has a great impact on the profile quality, for example, color temperature and uneven organization are easy to form after subsequent cooling. In order to achieve a uniform metal temperature distribution in the exit, we can modify the bearing length to adjust the frictional state and improve the metal temperature distribution.

**Flow stress:** Figure 8 shows the distribution of metal flow stress. When the metal turns into steady flow state, the material flow stress distribution can be divided into three regions. The first flow area locates inside the wall of container and die, stress distribution is uniform. The second locates at the junction of container and die and at the bottom of welding chamber, metal is almost at a stationary flow state, the flow stress in these dead zones is minimal. The third locates at the bearing, a lot of compressed metals flow from the bearing orifice, the flow stress sharply increases in there.

**Pressure:** Figure 9 shows the pressure distribution in the container, porthole and welding chamber section.

When the metal flows through above sections, the metal pressure gradually decreases. The average pressure in welding chamber is up to 300 MPa and reaches ten times yield strength of the AA6063 alloy at this temperature. The pressure distribution in the welding chamber is uniform and meets the re-welding requirement.

Metal is congregated and re-welded in welding chamber. If the welding cavity volume is greater, the ratio
Fig. 10: Extrusion pressure-time curve

Fig. 11: Die temperature

of the welding chamber cross-section and the products cross-section is bigger, hydrostatic pressure built up in the welding cavity is greater, the metal in the welding chamber will stay longer and the welding quality will be higher.

During the extrusion process, mechanical condition is changed with metal volume, contact surface between the metal and container, contact friction stress, extrusion speed and temperature. The pressure on the extrusion pad changes with the metal mechanical condition.

Figure 10 shows the extrusion pressure change with time. When the extrusion pad moves forward, metal is upset, the extrusion pressure increases within a short period of time. After the extrusion pressure reaches the breakthrough point, the metal begins to flow out from the die orifice, the extrusion pressure decreases a little and tends to a stable state.

Die temperature: Figure 11 shows the overall temperature distribution of the die. The temperature in the low die is lower, in the up die is higher. The temperature in the middle of the die is higher, in the around area is lower.

When the metal flows through the up die, the metal is stick to the die wall, so more heat is transferred to the up die and the overall temperature distribution of the up die is higher. While the low die contacts with the flow metal only at the welding chamber and bearing surface, heat timely transfers to the die edge and environment, so the temperature in the low die is lower.

Die stress: Figure 12 shows the stress distribution of the die. The overall stress distribution of the die is small and uniform, the stress of up die is smaller than that of low die, stress concentration occurs in the bearing. Along the extrusion direction, the die suffers from the pressure of extrusion cylinder and the tension of profile outflow. The die bridge undergoes the shearing force caused by metal flow, die head is under unequal metal pressure, so deflection may generate in the die. The bearing is weak and it is more vulnerable to damage by the intense friction of flow metal. During the extrusion process, the tension of the profile has great impact on the die bearing, we can see that the maximal stress locates at the bearing of the up die and at the small cantilever of the low die.
MODIFICATIONS

Amendment method: By numerical simulation, we conclude that lack of feeding in the middle ribs leads to slow flow velocity in there. Combined with the stub bar in the tryout, we do little modifications to the die. For the up die, we propose to appropriately increase the area of the two middle portholes, to increase the inclination of the die head in order that metal flows easier, to adjust the bearing length in order that metal flows more evenly. For the low die, we set the baffles near the four corners of the die hole in order to properly slow the metal flow velocity there. In addition, we adjust the bearing of the low die in order that metal flows more evenly.

Because increasing the porthole area may cause the flow velocity fluctuations, so the proposal is not used at last. We enlarge the low die insert by spark in order that the metal flows easier. The bearing length in the middle ribs decreases from 2.8-2.4 mm, four baffles are set on the four corners of the lower die, the bearing length in the profile sides increases 0.4 mm. Figure 13 shows the modified die.

Modified results: A steady-state simulation is again carried out using the same process parameters to the modified die. If the velocity gradient in the exit section is uniform, the metal flow will be ideal and good profiles with flat section will be produced.

Figure 14 shows speed distribution in the profile exit. Contrasted with Fig. 6, exit velocity is well adjusted. Though flow velocity in the both sides is slightly faster, in the middle is slower, the profile can be smoothly produced and meet the forming requirements. After spray, two profiles are well assembled together in Fig. 15.
CONCLUSIONS

By numerical simulation, the profile displacement, the metal flow velocity, temperature, pressure, flow stress and die stress are analyzed. Bearing is an important factor affecting the profile exit velocity.

The metal flow is well regulated by adding baffles in the low die and modifying the bearing length, velocity distribution in the orifice is uniform, dimension accuracy has also been improved.

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REFERENCE


