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Materials

Forging process modeling of cone-shaped posts

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Abstract: Using the rigid visco-plastic Finite Element Method (FEM), the process of forging for long cone-shaped posts made of aluminum alloys was modeled and the corresponding distributions of the field variables were obtained based on considering aberrance of grids, dynamic boundary conditions, non-stable process, coupled thermo-mechanical behavior and other special problems. The difficulties in equipment selection and die analysis caused by the long cone shape of post, as well as by pressure calculation were solved.

Key words: coupled thermo-mechanical analysis; constitutive relationship; rigid visco-plastic FEM; cone-shaped post

1 Introduction

The forging of cone-shaped posts is done at high temperatures and high pressures, and this is a complex thermodynamic process. The uneven distributing of physical parameters such as stress, strain, strain rate and temperature brings great influence on the quality of posts during the forging. Up to now, reports about these aspects have not been found yet. The choice of equipment, the design of die frames and the establishment of technology prior to the forging usually still follow the traditional way. The influence of multiplicate factors cannot be synthetically considered in those formulae and trial-manufacture is needed for every different materials, so it cannot meet the demand for exploitation of new products. In this paper, the coupled thermo-mechanical analysis of the forging process for long cone-shaped posts made of aluminum alloys was done by the using rigid visco-plastic FEM in order to obtain accurate and logical results to instruct practical production.

2 Fundamental

2.1 Constitutive relationship

Arrhenius equation [1,2] is used as the constitutive relationship of aluminum alloys during high temperature deforming.

$$\bar{\sigma} = \frac{1}{\alpha}\ln\left\{(Z/A)^{1/n} + \left[(Z/A)^{2/n} + 1\right]^{1/2}\right\} \qquad (1)$$

where $\bar{\sigma}$ is the equivalent flow stress; Z is Zener-Hollomon parameter which is $\dot{\bar{\varepsilon}}\exp(\Delta H/RT)$, where $\dot{\bar{\varepsilon}}$ is the equivalent strain rate, ΔH is the deformation activation energy, R is the gas constant, and T is the deformation temperature; A, n and α are material constants. ΔH=156.8 kJ/mol, A=2.52×10^{10} s^{-1}, n=2.72, α= 0.035 mm^2/N in this paper.

2.2 Basic equations of rigid visco-plastic FEM

In this paper, the deforming aluminum alloy is considered as a rigid visco-plastic body that satisfies the balance equation, geometry equation, volume incompressible conditions, yield criterion, Levy-Mises equation and boundary conditions under constant temperature. A new function is obtained by using the penalty function method to solve the volume incompressible problem, and its variation is:

$$\delta \pi = \int_V \bar{\sigma}\delta \dot{\bar{\varepsilon}} \mathrm{d}V + \alpha\int_V \dot{\varepsilon}_V \delta \dot{\varepsilon}_V \mathrm{d}V - \int_{S_F} F_i \delta \upsilon_i \mathrm{d}S = 0 \qquad (2)$$

where V and S are volume and surface area respectively, $\dot{\varepsilon}_V$ is the bulk strain rate, F_i is the surface force loaded on the force boundary, υ_i is the velocity field of the plasmodium, and α is the penalty factor whose value is usually very large (commonly α=10^5-10^6).

By mesh generation of FEM, equation (2) is translated into a set of non-linear equations whose unknown variables are the weights of node velocity. Using Newton-Raphson iteration method [3] its final

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matrix equations is:

$$[S]\{\Delta u\}=\{R\} \tag{3}$$

where $[S]$ is the stiffness matrix, $\{R\}$ is the load vector and $\{\Delta u\}$ is the increment vector of node velocity.

2.3 Basic equations of heat transfer FEM during forging

A coupled analysis of deformation and heat transfer is used to calculate the temperature distribution of the post. The control equation of non-stable heat transfer [4] is:

$$k\{T_{,ii}\}+\{\dot{q}\}=\rho c\{\dot{T}\}\ (i=1, \ldots, n) \tag{4}$$

where $\{T\}$ is the temperature vector, $\{\dot{T}\}$ is the temperature velocity vector, $\dot{q}$ is the intensity of inner heat source, ρ and c are the density and specific heat of the material respectively, and k is the thermal conductivity of the material.

Suppose the environment temperature is constant, considering the contact heat conduction and heat exchange of convection and radiation between the post, die and air, the pending equation of FEM is:

$$[C]\{\dot{T}\}+[K]\{T\}=\{Q\} \tag{5}$$

where $[C]$ and $[K]$ are the total matrix of heat content and that of heat transmission respectively, $\{Q\}$ is the heat flow vector related to the heat source in the conductor and the conditions of boundary exchange.

2.4 Technical treatment of coupled thermo-mechanical FEM modeling

Considering the difficulties with strictly coupled thermo-mechanical analysis [5], This paper uses a quasi-coupled solution, which separately solves the problem by taking velocity field and temperature field as two subsystems. Specific steps are: (1) to solve for the velocity field increment $\{\Delta u\}$ under the original temperature field; (2) to calculate parameters of the deforming field, such as deforming power, friction power, and so on, which influence the calculation of the temperature field; (3) to forecast the next temperature field and by modifying the mechanical characters and high temperature physical parameters of materials, and to calculate the velocity field. The iteration calculation goes on until the velocity field becomes convergent and increment loading is completed.

3 Treatment of some special problems

3.1 Determination of frictional force

Using the inverse tangent friction model, the friction stress on the contact surface is:

$$\vec{\tau}=-(2/\pi)m\tau_s \arctan(\vec{v}_s/A) \tag{6}$$

where m is friction parameter satisfying $0 \le m \le 1$, and taken as $m=0.3$ in this paper; τ_s is the shear yielding strength of the material; A is a positive constant that is several orders of magnitude smaller than the velocity of die and usually is 10^{-4} to 10^{-5}; $\vec{v}_s$ is the relative slip velocity of the contact surface between the facility and the material, that is:

$$\vec{v}_s=\sum_l N_i \vec{v}_{si} \tag{7}$$

where N_i is the shape function of contact nodes at the element boundary, $\vec{v}_{si}$ is the relative slip velocity at node i, and l is the number of nodes at the element contact boundary.

3.2 Treatment of dynamic boundary conditions

The die boundary description should satisfy the following conditions: (1) it can thoroughly reflect the restriction characteristic of the die on the deforming material; (2) it will avoid complicated mathematical description in order to meet the demand for programming. For the 2D and axisymmetric problem, the subsection of the die boundary is described by combination of beelines, circle arcs and spline curves. By using the roundlet arc to transit turning parts, not only can the processing characteristic of the die be expressed, but also the oddity of velocity at inflexion can be expediently dealt with. During plastic deforming, primary free boundary nodes are likely to contact nodes by contacting with the boundary of the die, so by computing the intersection between displacement vector of boundary nodes and the boundary of the die, the problem of contacting is solved. Judgements of contact nodes deviating from the die and restrictions relieving are done using to the method in reference [6].

3.3 Remesh technology of grids

Usually, large deformation will lead to a very large strain that can result in a serious aberrance of finite element grids. Thus, the calculation cannot be proceeded, and the aberrant grids need to be remeshed. The difficult and key point of the remesh technology of grids is the building of a new grid system. An automesh generation method of four-nodes quadratic elements based on boundary shape is adopted. In this method, grid modes are generated layer by layer from the boundary to the inner. And, technologies about the intersecting, sewing and lubricating of grids need to be solved. Boundary elements have good deforming characteristic and quite fit remesh process.

4 Numerical modeling for forging process

4.1 Models

Because of the symmetry of the billet, a half of it is taken for analysis. Using four-nodes quadratic iso-parametric elements, 640 elements and 672 nodes are plotted at the middle surface of the original billet (**figure 1**). The geometrical shape of the aluminum alloy forging is an axisymmetric cone (**figure 2**).

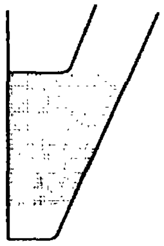

Figure 1 Element plotting form.

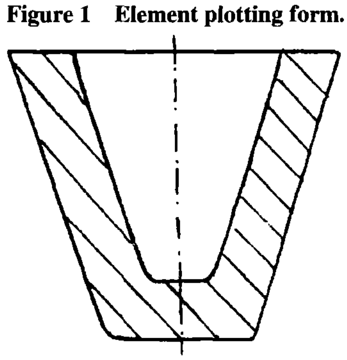

Figure 2 Hot forging shape of the aluminum alloy.

4.2 Correlative known parameters

The velocity of the bulgy die is 45 mm/s. The original temperature for forging is 420°C. The environmental temperature is 20°C. The dimensions of posts are ϕ234mm/ϕ450 mm×780 mm. The thermal conductivity of the material is k=30.34 W/(m^2·K) with ρ=2490 kg/m^3 and the specific heat c=420 J/(kg·K). The heat density of the thermal conductivity of the die material is k=34.6 W/(m^2·K) with the density ρ=7860 kg/m^3 and the specific heat c=448 J/(kg·K).

There is a heat exchange by convection and radiation between the free surface of the forging and the ambience during the processing. There is also a contact heat exchange when the forging contacts with the dies, and a temperature rise occur to the forging because of the plastic deformation and the friction of the contact surface. The ratio of heat radiation is 0.6, and the thermal conductivity is 18.34 W/(m^2·K) with a heat power conversion coefficient of 0.9 in the calculation.

5 Results and analysis

When the aluminum alloy is forged under given conditions, its curve of total load P *vs.* displacement is shown in **figure 3**. It can be seen that the total load rises with displacement Δh increasing. At the beginning of deforming, the density of dislocation in the forging accumulates gradually with the displacement increasing, leading to a linear increase in deforming resistance. So the load rapidly increases linearly. The load is 2000 kN when the displacement is 50 mm, and the displacement continues increasing with the proceeding of deformation. The dynamic softening during hot deformation weakens the speed of work hardening a little. So the curve presents a non-linear change and the load rises gradually. The load is 5200 kN when the displacement is 600 mm.

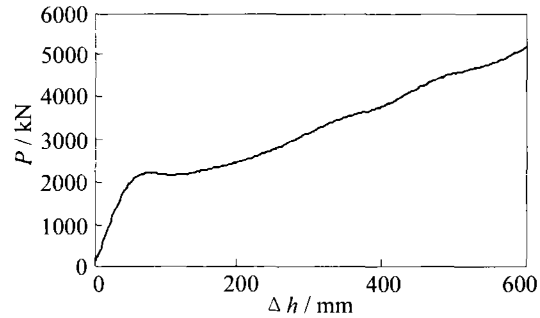

Figure 3 Load-displacement curve.

When the aluminum alloy is forged under the given conditions, the lowest temperature is 382.3°C at the parts contacting with the die because of heat exchange, which makes a temperature fall a little; and the temperature increases at the other area because of deformation which results in a temperature rise, and the highest temperature 432.7°C is at the center of the forging (**figure 4**). The reason is that there is a large plastic deformation at the center of the forging, and the result is that the temperature rises quickly and the loss of heat exchange is small. At the area of forging near the die, the temperature distribution is mainly controlled by the heat exchange of the contacting interface, where deformation is small.

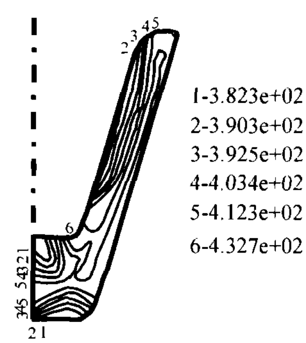

Figure 4 Temperature distribution.

From the distribution of equivalent plastic strain rate (**figure 5**), it can be seen that at the corner of the die, the deforming rate of the aluminum alloy forging is quite high, but at other parts it is relatively low and even.

Figure 6 shows that the distribution of the total equivalent plastic strain is uneven in the aluminum alloy forging. At the contacting area between the material and the bulgy die and between the material and the bottom of the concave die, the deformation is so large and the maximal equivalent plastic strain is 4.838. Deformation is relatively small at the other areas.

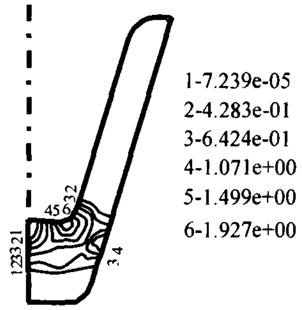

Figure 5 Equivalent plastic strain rate.

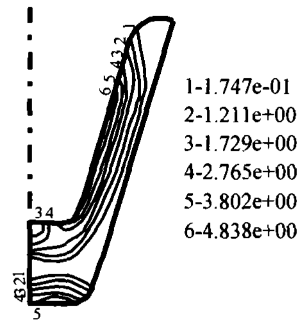

Figure 6 Total equivalent plastic strain.

The distribution of equivalent stress shown in **figure 7** is similar to that of equivalent plastic strain rate. The area of the maximum equivalent stress is up to 206.5 MPa at the corner of the bulgy die. Near it the equivalent stress value is also relatively large. There is apparent deforming concentration. However, the distribution of equivalent stress is comparatively low and even at the other parts of the aluminum alloy forging.

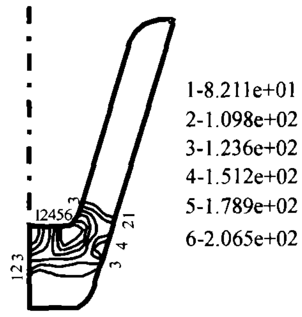

Figure 7 Equivalent stress.

6 Conclusion

Considering thermo-mechanical relations in temperature and deforming, the numerical simulation of long cone-shaped posts for aluminum alloys in forging was done by the rigid visco-plastic finite element method. The relations between the total load and the displacement, stress, strain, temperature and strain rate in the forging were obtained. Thereby, the difficulties in equipment selection and die analysis caused by the long cone shape of posts as well as by pressure calculation were solved. According to the numerical simulation, the die was designed and the corresponding forging technology was developed, which are used to produce qualified products in practice.

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