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3-D RIGID PLASTIC FEM SIMULATION OF EXTRUDING-BULGING PROCESS OF TEE TUBES[①]

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ABSTRACT 3-D rigid plastic FEM (Finite Element Method) is adopted to simulate the extruding-bulging process of tee tubes. Deformed mesh and velocity field in different stages are obtained, and strain-rate and stress distributions are obtained at the same time. The deformation and flowing laws of tubular blank in extruding-bulging process of tee tubes are revealed, which provide scientific and reliable basis for correctly designing technological scheme and rationally selecting parameters.

Key words FEM extruding-bulging process tee tubes

1 INTRODUCTION

Tee tubes are widely applied as important pipe junctions in pipage in all kinds of industry departments. With the development of industry, the need for tee tubes is increasing and the demand to their quality is becoming more and more strict, thus the conventional manufacturing methods could not agree with this demand. Tee tubes in our country at present depend on import largely for the backward technology. Extruding-bulging of tee tubes is a forming method which fills plastic media in the tube as a force-transmitting media. The advantages of this technology are high utilization ratio of material, high ratio of finished products, short period of manufacture and low comprehensive cost, compared with formerly technologies such as casting, forging, welding, hot-drawing, soft die forming, hydraulic pressure bulging. The deformation and flowing laws of tubular blank in extruding-bulging are not understood well for its appearance before long. FEM (finite element method) is the most effective numerical method to solve the problems of continuous areas approximately, which can provide the approximately continuous mathematical description about the process of plastic deformation. In this paper, 3-D rigid-plastic finite element method is adopted to simulate the process of extruding-bulging of tee tubes, and the laws of metal deformation and flowing are revealed. They provide scientific basis for designing technological scheme correctly and selecting process parameters reasonably.

2 FUNCTIONS OF FEM SOLUTION

The basis of rigid-plastic finite element method is the principle of Markov's variation equation. To element e in the discretion construction, its corresponding functional equation is

$$\pi^e = \int_V \bar{\sigma}\dot{\bar{\varepsilon}}\,\mathrm{d}V - \int_{S_F} F_i u_i \,\mathrm{d}S + \int_V \frac{\alpha}{2}\dot{\varepsilon}_V^2\,\mathrm{d}V \quad (1)$$

where $\bar{\sigma}$ is equivalent stress, $\bar{\sigma} = \sqrt{(3/2)\sigma'_{ij}\sigma'_{ij}}$; $\dot{\bar{\varepsilon}}$ is equivalent strain ratio, $\dot{\bar{\varepsilon}} = \sqrt{(2/3)\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}$; F_i is force of given surface on force surface S_F; u_i is velocity vector; α is penalty constant to neglect the incompressibility condition (it is 10^5 in this paper); $\dot{\varepsilon}_V$ is volume strain velocity, $\dot{\varepsilon}_V = \dot{\varepsilon}_{ii}$.

A functional equation can be obtained after aggregating all elements as follows:

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$$\pi = \sum_j \pi(j) \tag{2}$$

According to the principle of Markov's variation equation, the solution of the problem is obtained when the first-order variation of functional equation is zero. Variating the functional equation(2) with first-order variation and then calculating its standing value, an algebraic function group can be obtained, which is a rigidity equation:

$$\frac{\partial \pi}{\partial V_I} = \sum_j \left(\frac{\partial \pi}{\partial V_I}\right)_{(j)} \tag{3}$$

where j stands for element j, I stands for node I.

The rigidity equation (3) is a nonlinear group of equations taking velocity component of nodes as the unknown variation, and Newton-Raphson iteration method is usually adopted to solve it. But at first, it must be linearized. The procedure of linearization is as follows: carrying out equation (3) with Taylor series near the supposed initial velocity field where $V = V_0$ and neglecting the high-order differential variations of ΔV beyond the second-order. Then we can obtain

$$\left[\frac{\partial \pi}{\partial V_I}\right]_{V=V_0} + \left[\frac{\partial^2 \pi}{\partial V_I \partial V_J}\right]_{V=V_0} \Delta V_J = 0 \tag{4}$$

The equation above can also be written as a matrix equation:

$$K\Delta v = f \tag{5}$$

where K is rigidity matrix, f is residual error of node-force vector.

Equation (5) is rigidity equation, the displacement increment of every node can be carried out to solve it. After each step of iteration, the node velocity field should be corrected with the following equation, and the corrected velocity field can be used as the initial velocity field in the next step:

$$v_{n+1} = v_n + \beta\Delta v_{n+1} \tag{6}$$

where β is the deceleration factor, $0 < \beta \leq 1$.

3 MODELING OF FEM SOLUTION

3.1 Geometrical description of die surface

The surface of the die cavity near the junction of the main and branch tube is complex and difficult to describe with regular curve surface. Considering the flexibility and universal suitability of B-spline, in this paper, double cubic even B-spline is adopted to describe the surface of the die cavity of extruding-bulging of tee tubes. In this kind of description, the subdivision of surface patches can be performed by changing the subdivision density coefficients of the surface patches along the two parameter directions, the surface patches can be divided into triangles or rectangles according to demand, and normal vector of each surface patch is provided at the same time. This description provides convenient and flexible numerical geometrical information to process dynamic boundary conditions in finite element method. Considering the symmetry of the object, only one-forth of die surface is described in this paper. Fig.1 shows the description result and Fig.2 shows the description result after subdivision.

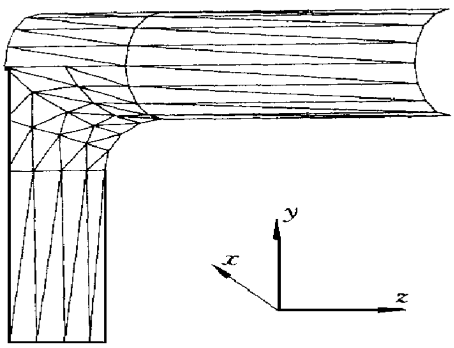

Fig.1 Geometrical description of cavity surface with double cubic even B-spline

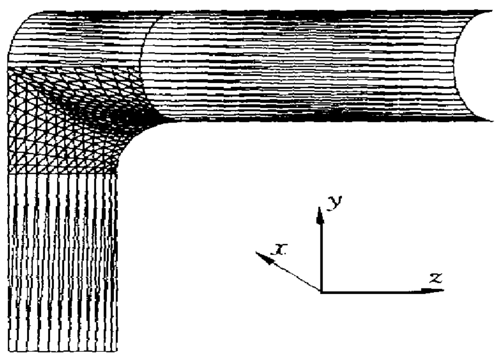

Fig.2 Die cavity surface after division

3.2 Modeling of solution

The procedures of extruding-bulging of tee tubes are as follows: put the tubular blank filled with plastic transmitting media into lower die of a set of split die, then close the set of die and fix it with a correct die-locking force, extrude the two sides of tubular blank with equivalent force by the two opposing punches at the same time, under extrusion action of the punches and inner media, the tubular blank is extruded and bulged to form a tee tube. Considering the practical conditions during deformation, in order to calculate with FEM conveniently and guarantee the calculating precision, the following suppositions are made during the process of modeling mechanical model:

(1) The extruding speed of punches is constant;

(2) The pressure of inner media produces an even effect on the inner surface of tube;

(3) Neglecting the temperature effect.

The eight-nodes hexahedron element is adopted to discretize the mechanical model. The tubular blank is discretized into 1 024 elements and 1 701 nodes; the surface of the die is divided into five patches and described with B-spline respectively, eventually, is subdivided into 480 trianglar patches altogether. During practical applications, the numbers of discretized elements of tubular blank and little patches subdivided of the die surface can be readjusted respectively according to realistic condition. Fig.3 shows the mathematical model adopted in this paper.

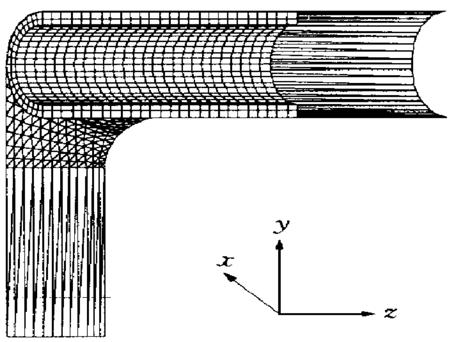

Fig.3 Mathematical model adopted in numerical simulation

4 SIMULATION RESULTS

There are too many factors which affect extruding-bulging of tee tubes, the effect produced by each factor on the forming is not constant during the whole forming process. It is impossible and unnecessary to consider all factors in the numerical simulation. The parameters adopted in this paper are as follows:

(1) The radius of the die is 10.65 mm.

(2) The pressure of inner media is obtained by Ref.[13]. The initial pressure of inner media is 45 MPa, and the pressure changes with the deformation, and acts on inner surface of tube evenly.

(3) The friction coefficient between the outer surface of tube and the cavity of die is $m = 0.05$.

(4) The outer diameter of tube is $d_0 = 21.3$ mm, wall thickness is $t_0 = 2.6$, length is $l_0 = 40.0$ mm.

(5) The extruding speed of punch is 1.0 mm/s.

Fig.4 shows the deformed mesh with different extrusions. Fig.5 shows the velocity field with different extrusions. Figs.6 and 7 show the strain-rate and stress distributions on the inner surface with extrusion amount of 23.5%.

5 ANALYSIS OF SIMULATION RESULTS

According to the distributions of deformed mesh and velocity field in different stages, the plastic deformation of tee tube is divided into five different zones during the process of extruding-bulging, as Fig.8 shows.

(1) Zone I and zone II are compression zones.

The direction of each node's velocity vector consists with the axial one of tubular blank, and no shear deformation exists in this zone, as shown in Fig.5 of the distribution of velocity field of nodes. Thickness of tubular wall increases a little, as shown from Fig.4 of deformed mesh in different stages. All the above calculating results show that zone I and zone II are compression zones.

(2) Zone III is uneven plastic deformation

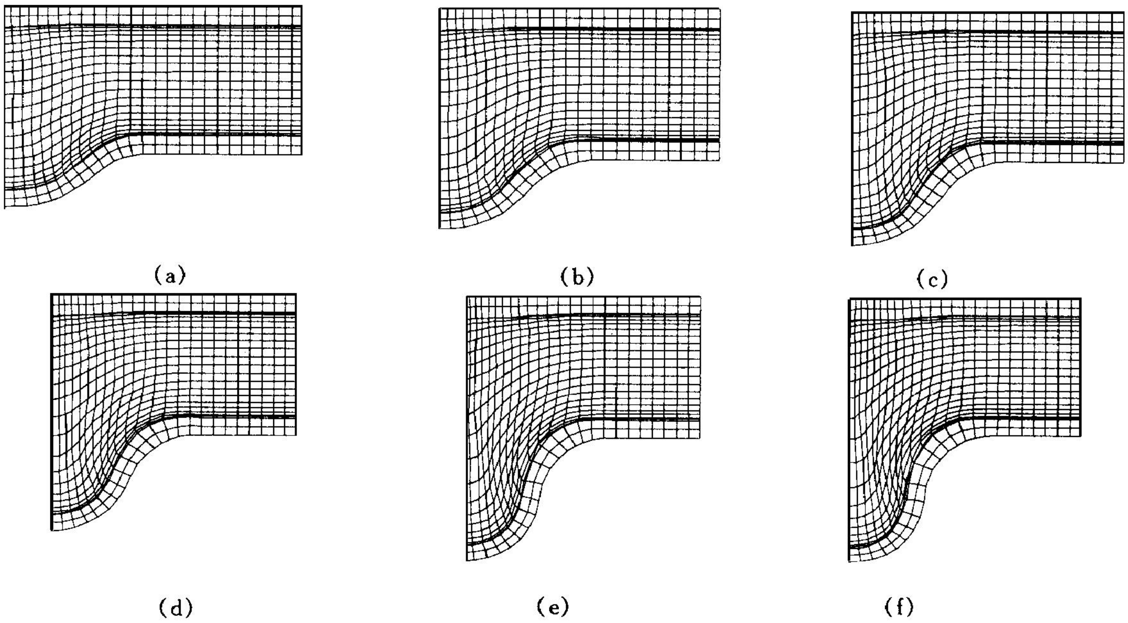

Fig.4 Deformed meshes with different extrusions

(a) —Extrusion 16.0 %; (b) —Extrusion 18.5 %; (c) —Extrusion 21.0 %;
(d) —Extrusion 23.5 %; (e) —Extrusion 26.0 %; (f) —Extrusion 28.5 %

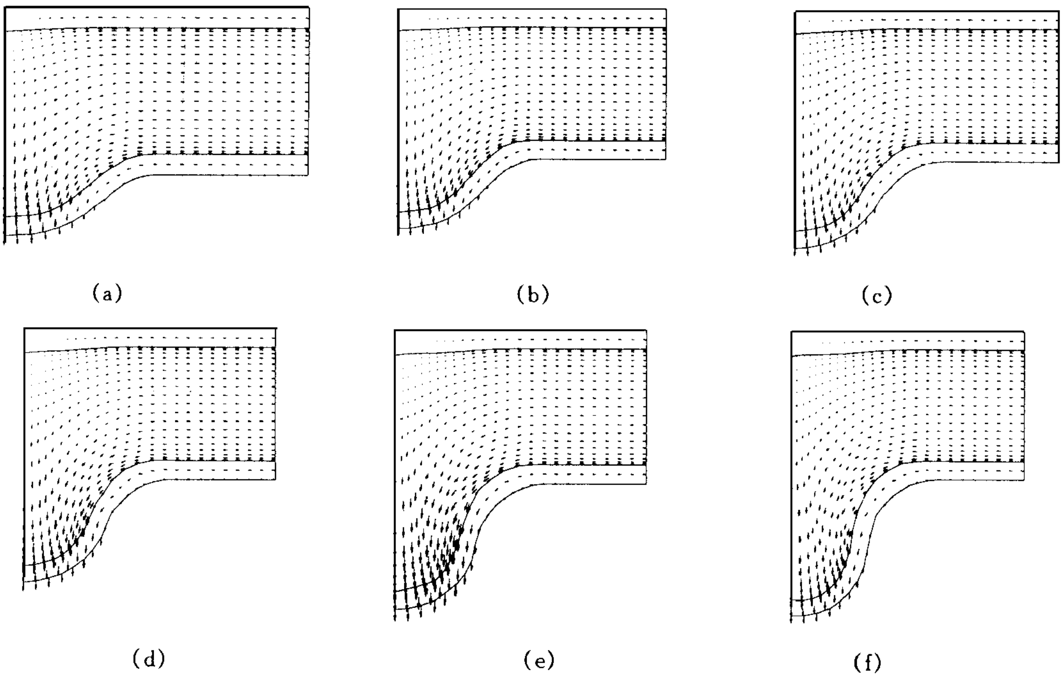

Fig.5 Velocity fields with different extrusions

(a) —Extrusion 16.0 %; (b) —Extrusion 18.5 %; (c) —Extrusion 21.0 %;
(d) —Extrusion 23.5 %; (e) —Extrusion 26.0 %; (f) —Extrusion 28.5 %

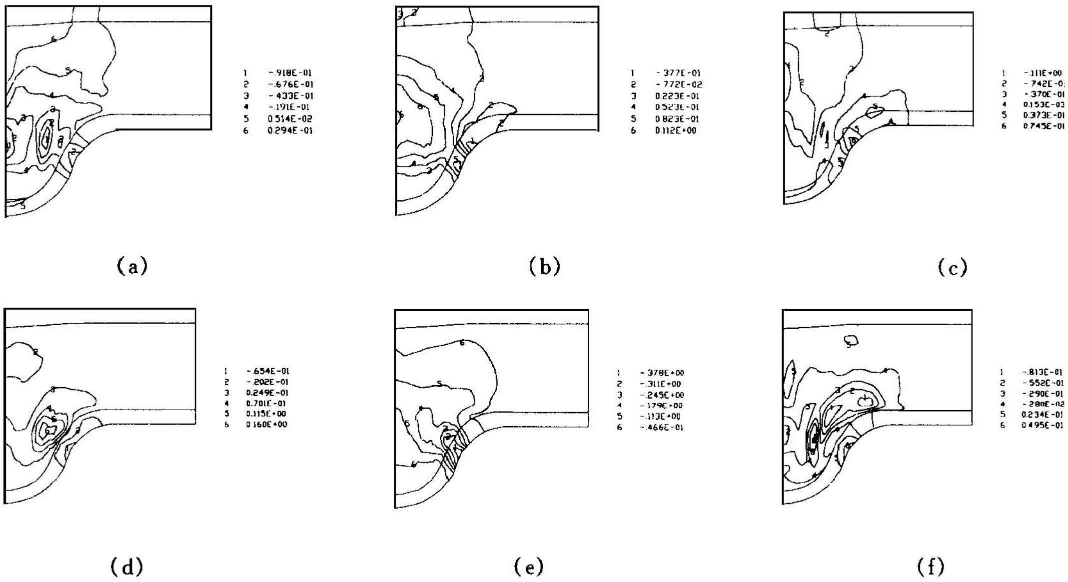

Fig.6 Strain-rate distributions on inner surface with extrusion amount of 23.5 %
(a) — $\dot{\varepsilon}_x$; (b) — $\dot{\varepsilon}_y$; (c) — $\dot{\varepsilon}_z$; (d) — $\dot{\gamma}_{xy}$; (e) — $\dot{\gamma}_{yz}$; (f) — $\dot{\gamma}_{xz}$

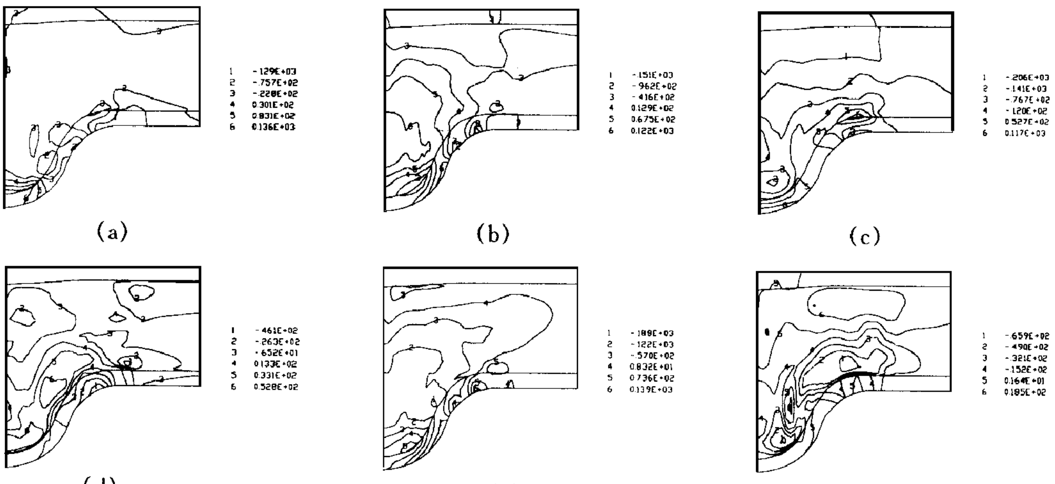

Fig.7 Stress distributions on inner surface with extrusion amount of 23.5 %
(a) — σ_x; (b) — σ_y; (c) — σ_z; (d) — τ_{xy}; (e) — τ_{yz}; (f) — τ_{xz}

zone.

The figure of distribution of field variations shows that, the metal in this zone is located at the junction of the main and branch tubes, and acted by tangential tensile stress and axial compressive stress, at the same time, suffered strong bending deformation. So deformation in this zone is complex and serious.

(3) Zone Ⅳ is deformed zone.

In this zone, the stress of blank is radial compressive stress and axial tensile stress. This metal can be regarded as a transmitting zone, whose duty is to transmit the load acting on the end of the branch tube to the uneven plastic deformation zone (Zone Ⅲ), and make the metal of uneven plastic deformation zone flow into the branch tube and fill the deformed zone.

(4) Zone Ⅴ is bulging zone.

In this zone, the load acting on the metal along thickness (radius) direction can be neglected. Due to the compressive effect of inner media, the metal bears tensile stress tangentially and produces bulging deformation. During bulging, the shape change of the blank depends on the increase of its area. So it is inevitable to decrease the thickness of the end of the branch tube. It is well revealed by Fig.6 and Fig.7.

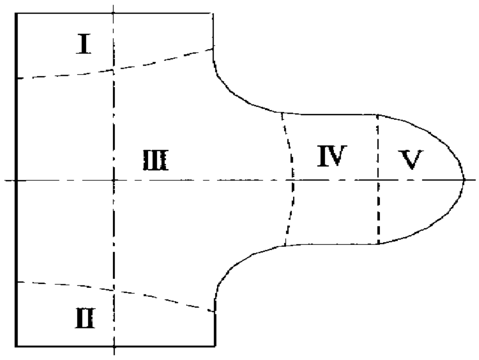

Fig.8 Schematic diagram of deformed zone division

The calculating results of FEM and the division of deformation zones reveal the deformation and flow laws of tubular blank. Internal plastic media produce bulging force due to the extruding effect of punches, metal of tubular blank is forced to flow into the branch cavity of die under bulging of inner media and extruding of punches, the extruding of punches, which forces metal to replenish branch tube continuously, prevents the decrease of branch thickness effectively. The deformation degree of tubular blank depends on transmitting zone and maximal reduction of the metal of end of branch tube.

6 CONCLUSIONS

(1) A perfect model for FEM calculation is presented on the basis of the practical situation of extruding-bulging of tee tubes. The procedures of extruding-bulging are simulated successfully with the model, and the simulation results are in good agreement with the practical forming process.

(2) On the basis of FEM simulation results, the plastic deformation of tee tubes is divided into five different zones, thus revealing the laws of metal deformation and flowing.

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