FEM SIMULATION OF BIMETAL FORMING PROCESS BASED ON FRICTIONAL ELEMENT TECHNOLOGY①

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ABSTRACT According to the bimetal forming process, the FEM simulation technology of the plastic deformation process of the bimetal has been deeply studied. The frictional element technology was used to deal with the boundary problem of bimetal forming. And this technology was used successfully to simulate the bimetal extrusion process.

Key words bimetal forming frictional element FEM simulation

1 INTRODUCTION

Bimetal forming process is an important maching method to produce functional materials. This method has its particular merits to save precious metals, to raise material utilization ratio, to enhance mechanical properties and anti-corrosion capabilities of products, and to satisfy properties in multiple environments. Therefore, bimetal forming process has been widely used in producing electric wire, cable, high heat conduction, electric conduction wire and liner. It is also one of the methods to produce composite materials.

The theory of bimetal forming process is in the primary phase. The major difficulty is how to deal with the interlayer between two different metals during forming process. It is assumed that interlayer slip is not permitted between two materials in traditional analytic methods. So interlayer motion can not be accurately described, and steady solution is difficult to obtain in repeated sticking and sliding nonlinear process[1, 2]. So numerical method is considered to solve the problem. It is currently thought rigid viscoplastic FEM to be one of the best methods to process large deformation plastic flow problem[3]. According to this interlayer problem, the frictional element is introduced in FEM analysis by Yoshino *et al*[4, 5] to coordinate plastic deformation of different materials, and satisfying results have been achieved in steady forming process problem. However, the variation of interlayer can not be analyzed during forming process. In bimetal forming process, the interlayer combination strength between two different materials is a problem of great interest, therefore, it is very important to analyze the interlayer variation during forming process. For this reason, the frictional element and non-steady FEM theory are combined. The frictional element participates in plastic deformation together with bimetal materials, and dynamic boundary distinguishment technology between the deforming body and the dies is developed. A FEM simulation system suited to bimetal forming of non-steady plastic forming process analysis is established, and plastic forming behavior of bimetal materials and their interlayer in any time can be completely described. The numerical simulation of forming process can provide useful theoretical guidance in controlling and improving bimetal forming process, enhance die design level and reliability, and shorten the cycle of die manufacturing and innovation. Therefore, it has become a leading research in the field of plastic maching.

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2 PROPERTIES OF FRICTIONAL ELEMENT AND ITS FEM EQUATIONS

The key problem of bimetal forming process is how to deal with interlayer deformation between two different metals. For convenience of rigid plastic FEM analysis, the frictional element to coordinate bimetal deformation is introduced.

2.1 *Properties of Frictional Element*

As shown in Fig. 1, the frictional element is a slip-permitted 4-point isoparametric element inserted in the interface between two mother materials, and its plastic energy dissipation is equivalent to frictional power generated by sliding. At the same time, the frictional element satisfies the following assumptions:

Fig. 1 Model of frictional element

(1) The thickness rigidity of the frictional element is the same as that of the mother material, and the rigidity in length and circumference direction is zero.

(2) It is regarded as adhesion when slip is very small, the frictional element has a tiny slip velocity, and the frictional power can be calculated. So it does not need to distinguish sliding or adhesion.

2.2 FEM *Equations of Frictional Element*

Based on the assumptions in 2.1 and referred to power equation of rigid plastic FEM, the energy equation of the frictional element can be expressed as follows:

$$W_b = \rho\int_V \sigma_y \dot{\varepsilon}_b \, dV + \int_s \tau_f \Delta u \, dS \qquad (1)$$

In eq. (1), the first item is the element plastic deformation power, and the second one is the element frictional power, where

ρ: relative density; ($\rho = 0.99$)

σ_y: effective flow stress; (equal to the smaller one of the flow stress of two mother materials)

$\dot{\varepsilon}_b$: effective strain rate. It is supposed as:

$$\dot{\varepsilon}_b = \rho^{k-1}\left(\frac{4}{9}\dot{\varepsilon}_\eta^2 + f^2 \cdot \dot{\varepsilon}_v^2\right)^{1/2} \qquad (2)$$

where

f: the function of rigid plastic volume variation ρ;

$$f = \frac{1}{2.49(1-\rho)^{0.514}}$$

k: constant; ($k = 2.5$)

$\dot{\varepsilon}_v$: volume strain rate.

$(\dot{\varepsilon}_v = \dot{\varepsilon}_r + \dot{\varepsilon}_\theta + \dot{\varepsilon}_z)$

Because $\rho = 0.99$, the volume of the frictional element keeps nearly fixed. In the perpendicular direction, the stress has the rigidity of σ_y, so it can prevent the nodes of two materials from invading each other.

Matrix expression of $\dot{\varepsilon}_b$ is:

$$\dot{\varepsilon}_b = (\dot{\varepsilon}_n^T \cdot C_s \cdot \dot{\varepsilon}_n)^{1/2} \qquad (3)$$

where

$$C_s = \begin{bmatrix} 4/9 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & f^2 \end{bmatrix} \qquad (4)$$

$$\dot{\varepsilon}_n = \begin{bmatrix} \dot{\varepsilon}_\eta \\ \dot{\gamma}_{\xi\eta} \\ \dot{\varepsilon}_v \end{bmatrix} = R \cdot \dot{\varepsilon}_m \qquad (5)$$

$\dot{\varepsilon}_n$ is strain rate vector in ξ-η coordinate system, R is the rotation matrix with dip angle θ from the frictional element to R axis, $\dot{\varepsilon}_m$ is strain rate in original coordinate system.

$$R = \begin{bmatrix} \cos^2\theta & \sin^2\theta & -\cos\theta\cdot\sin\theta & 0 \\ 2\cos\theta\cdot\sin\theta & -\cos\theta\cdot\sin\theta & \cos^2\theta - \sin^2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (6)$$

$$\dot{\varepsilon}_m = \begin{bmatrix} \dot{\varepsilon}_r \\ \dot{\varepsilon}_z \\ \dot{\gamma}_{rz} \\ \dot{\varepsilon}_v \end{bmatrix} = B_m \cdot u_m \qquad (7)$$

B_m is shape matrix.

$$B_m = \frac{2}{|J|}\begin{vmatrix} B_i & 0 & B_k & 0 & B_m & 0 & B_j & 0 \\ 0 & C_i & 0 & C_k & 0 & C_m & 0 & C_j \\ C_i & B_i & C_k & B_k & C_m & B_m & C_j & B_j \\ G_1 & G_2 & G_3 & G_4 & G_5 & G_6 & G_7 & G_8 \end{vmatrix} \quad (8)$$

where J is Jacobi determinant, B, C, G can be obtained by shape function.

So eq. (2) can be expressed as:

$$\dot{\varepsilon}_b = (u_m^T \cdot B_m^T \cdot R^T \cdot C_S \cdot R \cdot B_m \cdot u_m)^{1/2} = (u_m^T \cdot K_b \cdot u_m)^{1/2} \quad (9)$$

where $K_b = B_m^T \cdot R^T \cdot C_S \cdot R \cdot B_m$.

For the frictional item, we assume the thickness is t, then:

$$\Delta u \approx t \cdot \dot{\gamma} \quad (10)$$

so we have:

$$\int_s \tau_f \cdot \Delta u \, ds \approx \int_s \tau_f \cdot \dot{\gamma} \cdot t \, ds \approx \rho \int_V \tau_f \cdot \dot{\gamma} \cdot dV \quad (11)$$

$$\dot{\gamma} = \rho^{k-1}\{0 \quad 1 \quad 0\} \begin{Bmatrix} \dot{\varepsilon}_\eta \\ \dot{\gamma}_{\xi\eta} \\ \dot{\varepsilon}_V \end{Bmatrix}_p = \rho^{k-1}\{0 \quad 1 \quad 0\} \cdot R \cdot B_m \cdot u_m = D \cdot u_m \quad (12)$$

Eq. (1) can be expressed as:

$$W_b = \rho\left[\int_V \sigma_y (u_m^T \cdot K_b \cdot u_m)^{1/2} dV + \int_V \tau_f \cdot D \cdot u_m dV\right] \quad (13)$$

In eq. (13), we evaluate the first and the second derivative, then:

$$\frac{\partial W_b}{\partial u_{mI}} = \rho\left[\int_V \frac{\sigma_y}{\dot{\varepsilon}_b} \cdot K_{bIJ} u_{mJ} dV + \int_V \tau_f D \, dV\right] \quad (14)$$

$$\frac{\partial^2 W_b}{\partial u_{mI} \partial u_{mJ}} = \rho\left[\int_V \frac{\sigma_y}{\dot{\varepsilon}_b} K_{bIJ} dV + \int_V \left(\frac{1}{\dot{\varepsilon}_b}\frac{\partial \sigma_y}{\partial \dot{\varepsilon}_b} - \frac{\sigma_y}{\dot{\varepsilon}_b^2}\right)\frac{1}{\dot{\varepsilon}_b} \cdot K_{bIk} u_{mk} u_{mM} K_{bmJ} dV\right] \quad (15)$$

We expand it with Taylor series at the point $\boldsymbol{u}_m = \boldsymbol{v}_0$, then:

$$\left|\frac{\partial \pi}{\partial u_{mI}}\right|_{u_m = v_0} + \left|\frac{\partial^2 \pi}{\partial u_{mI} \partial u_{mJ}}\right|_{u_m = v_0} \cdot \Delta u_{mJ} = 0 \quad (16)$$

ΔU_{mJ} can be obtained by solving eqs. (14), (15), (16).

3 SIMULATION OF BIMETAL FORMING

Based on the previous analysis of the frictional element, frictional element is introduced in rigid viscoplastic FEM equations in this paper. The FEM simulation system developed by ourselves is used to simulate bimetal forming process. The numerical simulation results of bimetal forward extrusion are given in the following. The outer material is Cu, and its flow stress equation is $\bar{\sigma} = 3.08\dot{\bar{\varepsilon}}^{0.132}$; the inner material is Al, and its flow stress equation is: $\bar{\sigma} = 9.03\dot{\bar{\varepsilon}}^{0.136}$.

Fig. 2 shows the mesh deformation of bimetal extrusion. Fig. 2(a) is the initial mesh, and Fig. 2(b) is the distorted mesh during deformation process. Because the deformation resistance force of the inner and outer materials is different, (the one of the inner material is smaller), the plastic flow of the inner material is faster than that of the outer material. With the development of deformation, the frictional force of the die surface prevents the outer material from flowing, as shown in Fig. 2(c), and the difference of metal flow in the front becomes larger. Fig. 3 is effective stress, and Fig. 4 is effective strain in the state of Fig. 2(c). From Fig. 3 and Fig. 4, stress and strain distribution nearly keeps the characteristic of common extrusion. However, because of the frictional boundary, the shearing deformation of the frictional element influences the whole deformation process, and the distribution of stress and strain is more inharmonious. This is also one of the characteristics of bimetal plastic forming process.

4 CONCLUSIONS

The FEM simulation of bimetal plastic forming process is an effective method to reveal bimetal deformation behavior. The key to the method lies in dealing with the interlayer of the

Fig. 2 Mesh deformation of bimetal extrusion

Fig. 3 Effective stress

1 —20. 39 MPa; 2 —43. 76 MPa; 3 —55. 44 MPa; 4 —67. 13 MPa; 5 —72. 97 MPa

Fig. 4 Effective strain

1 —0. 15; 2 —0. 36; 3 —0. 56; 4 —0. 78; 5 —0. 97

different materials. The introduction of the frictional element effectively solves the problem of bimetal forming FEM simulation technology. And the frictional element can also be used to solve other interlayer analysis problem. From the extrusion simulation, it is indicated that the FEM simulation of bimetal forming process based on the frictional element technology can really reveal the characteristics of bimetal forming process and make quantitative analysis of field quantity.

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