INTERFACE DEFORMATION CHARACTERISTICS OF BIMETAL FORMING①

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ABSTRACT According to the bimetal (Cu & Al) extrusion process, the interface deformation characteristics of Cu & Al have been analyzed by using rigid plastic finite element method (FEM) with the frictional elements inserted between two contacting metals. The finite element equations considering the frictional element have been obtained. The bimetal flow patterns under different interface friction coefficients and yield stress ratios are given. Also, the influences of the interface friction coefficients and the yield stress ratio between two contacting metals on the interface variation and forming process have been discussed.

Key words bimetal forming interface deformation characteristics frictional element

1 INTRODUCTION

The bimetal wire and tube made by bimetal forming technology have high strength, corrosion resistance and good electrical conductivity. Therefore, they are widely used in aeronautics, machinery, chemistry, communication, electronic and electrical power industries. During bimetal forming process, two kinds of metals are deformed together in a die so that they can be combined together. The combination mechanism of bimetal parts is a research focus of this technology and the combination strength of the interface is very important for bimetal parts. To bring to light this mechanism is beneficial to improve the technical level of bimetal forming and its product quality. Nowadays, there are some experimental researches, and some assumptions, for example, the recrystallization mechanism, metallic bond mechanism, energy theory and diffusion mechanism[1, 2] have been proposed. Furthermore, Atinks & Weistein[3] analyzed the compression, drawing and extrusion process by using revised flow stress method and balance condition, Avitzur[4] also analyzed the extrusion and drawing process of wire and tube by using revised balance equation method. These experimental and theoretical researches are very useful for improving bimetal or multi-metals forming process, selecting process parameters and carrying out equipment design. However, there are many simplifications in these methods, especially on assuming there is no sliding on interface between contact metals during forming process and neglecting unstable friction characteristics on the interface. There is a heavy limitation in bimetal interface deformation characteristics analysis based on these simplifications and assumptions. Therefore, in order to overcome this deficiency, we study the interface deformation characteristics of bimetal forming process[5, 7, 8] by using the rigid plastic FEM with frictional elements inserted between contacting metals in this paper.

2 MODEL OF FRICTIONAL ELEMENT AND ITS FEM EQUATION

2.1 Model of frictional element

As shown in Fig. 1, the frictional element *ijkm* is a slip-permitted 4-points iso-parametric element inserted in the interface between two mother materials, and its plastic energy dissipation is equivalent to friction power generated by sliding. At the same time, the frictional element

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satisfies the following assumptions:

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

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

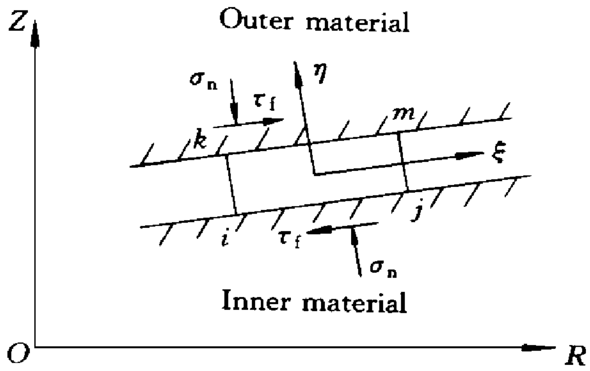


Fig. 1 Frictional element model

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[5]:

$$W_b = \rho\left(\int_V \bar{\sigma} \cdot \dot{\bar{\varepsilon}}_b \cdot \mathrm{d}V + \int_{S_f} \tau_f \cdot \Delta v \,\mathrm{d}S\right) \tag{1}$$

where ρ is the relative density($\rho = 0.99$); $\bar{\sigma}$ is the effective flow stress(equal to the smaller one of the flow stress of two mother materials); $\dot{\bar{\varepsilon}}_b$ is the effective strain rate; Δv is the relative sliding speed on the interface; τ_f is the friction stress of interface and it can be expressed as

$$\tau_f = \frac{\bar{\sigma}}{\sqrt{3}}\left[1 - \exp\left(-\frac{\sqrt{3}\,\sigma_n \mu}{\bar{\sigma}}\right)\right] \tag{2}$$

where μ is friction coefficient on the interface; σ_n is normal stress.

The relative sliding speed Δv can be expressed as

$$\Delta v = t \cdot \dot{\gamma} \tag{3}$$

Changing eq. (1) into the following format:

$$W_b = \rho\left(\int_V \bar{\sigma}(u_m^T \cdot K_b \cdot u_m)^{1/2} \mathrm{d}V + \int_V \tau_f \cdot D \cdot u_m \,\mathrm{d}V\right) \tag{4}$$

we can obtain the solution when the following equation is satisfied,

$$\partial W_b / \partial u_{mI} = 0 \tag{5}$$

where u_m is a component of node speed vector u_m^T. After linearizing eq. (5), we expand it with Taylor series at the point $u_m = u_0$, then

$$\left[\frac{\partial W_b}{\partial u_{mI}}\right]_{u_m = u_0} + \left[\frac{\partial^2 W_b}{\partial u_{mI} \partial u_{mI}}\right]_{u_m = u_0} \cdot \Delta u_{mI} = 0 \tag{6}$$

This is the rigidity matrix equation of the frictional element.

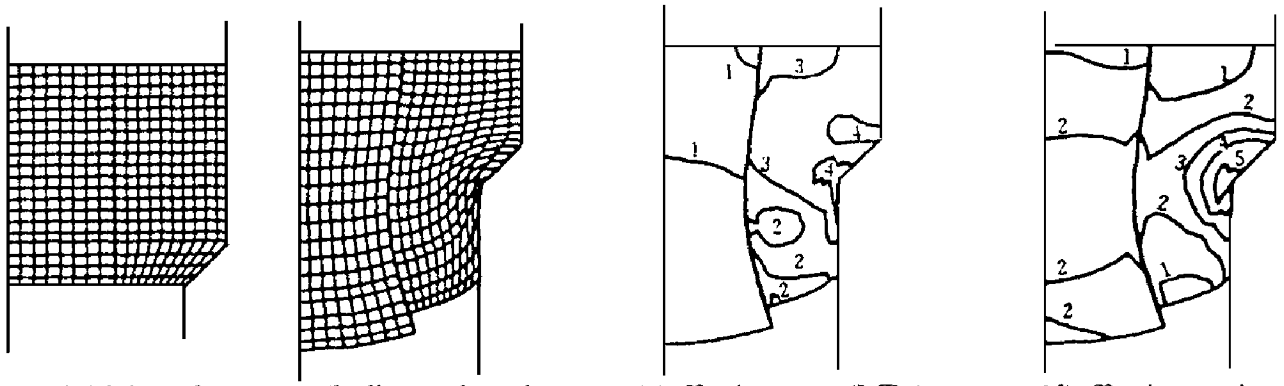
According to eq. (6), we can find that the rigidity matrix [K] of the frictional element is a symmetric matrix and it has the same order as other rigidity matrixes. So, it can be added with other rigidity matrixes directly.

3 INTERFACE DEFORMATION CHARACTERISTICS OF BIMETAL EXTRUSION PROCESS

3.1 Numerical simulation of extrusion process

The bimetal symmetric extrusion process has been studied in this paper. The outer material is Cu, and its flow stress equation is $\bar{\sigma} = 95.9\,\dot{\varepsilon}^{0.15}$. The inner material is Al, and its flow stress equation is $\bar{\sigma} = 23.1\,\dot{\varepsilon}^{0.169}$. Fig. 2(a) shows the initial mesh. The half tape angle of the die is 45°, the entry radius of the die is 20 mm and the exit radius of the die is 15mm. The thick line expresses frictional elements. The thickness of frictional element is 0.15 mm, and the friction coefficient of contacting interface between inner and outer metals is $\mu_{bm} = 0.3$. The friction factor between outer metal and the die is 0.15 because there is lubricants between them. Fig. 2(b) shows the distorted mesh when punch displacement is equal to 8 mm. Fig. 2(c) and Fig. 2(d) show the distributions of effective stress and effective strain, respectively.

As shown in Fig. 2(b), (c) and (d), the plastic flow of Al is faster than that of Cu because the deformation resistance force of Al is smaller than that of Cu. It is indicated that there is relative sliding on the interface of Al and Cu



(a)initial mesh (b)distorted mesh (c)effective stress(MPa) 1-20.39, 2-43.76, 3-55.44, 4-67.13 (d)effective strain 1-0.514, 2-0.359, 3-0.564, 4-0.768, 5-0.974

Fig. 2 Simulation of bimetal forming process

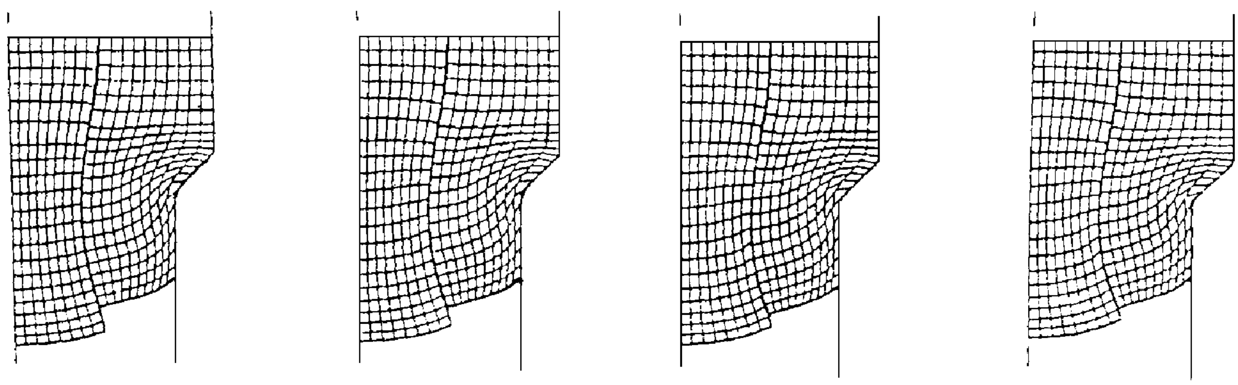
metals and there is bending on the interface. This situation coincides with experiments[6]. The effective stress of Al is smaller than that of Cu because Al is not in large deformation zone and its deformation resistance force is smaller. The effective strain is bigger than that of Cu because of the same reason.

3.2 Influences of μ_{bm} and $\sigma_{s2}:\sigma_{s1}$

In this paper, two parameters which obviously influence on the bimetal forming process have been analyzed by using FEM simulation system. They are interface friction coefficient μ_{bm} and the yield stress ratio between two contacting metals $\sigma_{s2}:\sigma_{s1}$.

Fig. 3 shows the distorted meshes with different interface friction coefficients (μ_{bm} = 0.05 ~ 0.3). We can find that the bigger the μ_{bm} is the smaller the slid is on the interface because there is bigger shear force and pressure applied to the mother materials. The shear force becomes stable when μ_{bm} is increased to a critical value. On the other hand, the inhomogeneous deformation between two metals will be alleviated by increasing μ_{bm}. Fig. 4 shows a relationship between μ_{bm} and the interface slip. Fig. 5 shows the relationship between μ_{bm} and the exit radius ratio(R_{ext1}/R_{ext2}). The R_{ext1}/R_{ext2} will increase when μ_{bm} increases and it will be limited to 0.625. Therefore, it can be concluded that the increase of μ_{bm} will result in enhancing the interface restriction.

Fig. 6 shows the distorted meshes with different yield stress ratios between two contacting metals ($\sigma_{s2}:\sigma_{s1}$ = 2:1 ~ 6:1). From Fig. 6, we can find that the bigger the ratio of $\sigma_{s2}:\sigma_{s1}$ is



(a) $\mu_{bm}=0.05$ (b) $\mu_{bm}=0.10$ (c) $\mu_{bm}=0.20$ (d) $\mu_{bm}=0.30$

Fig. 3 Distorted meshes with different μ_{bm}

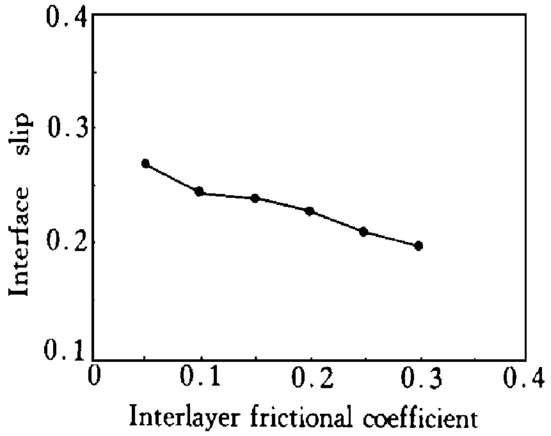


Fig. 4 Relation between μ_{bm} and interface slip

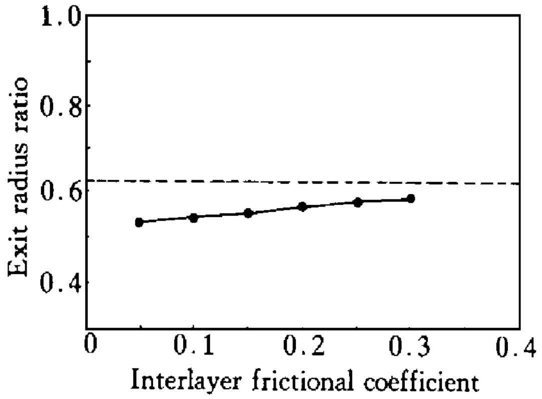


Fig. 5 Relation between μ_{bm} and R_{ext1}/R_{ext2}

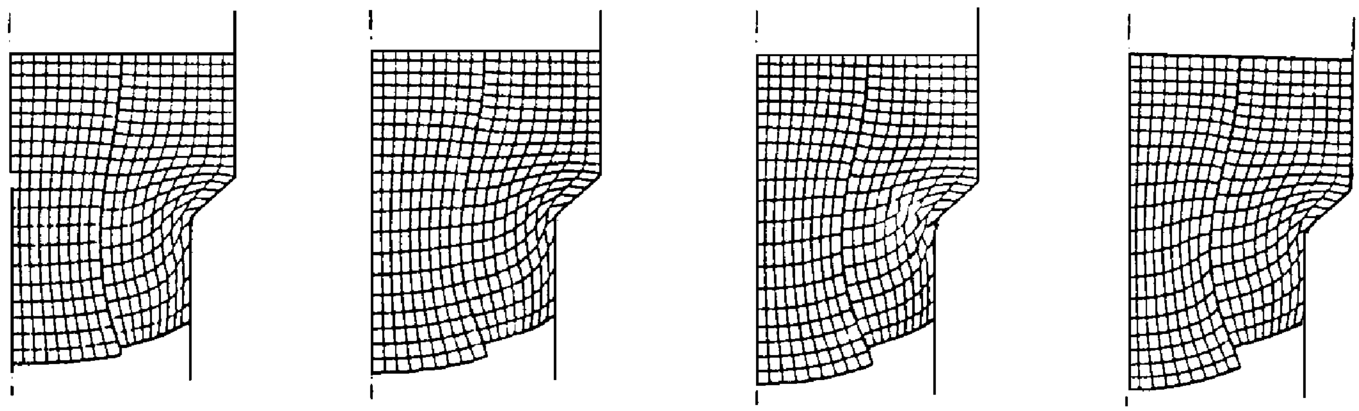
the bigger the interface slip and the interface bending are. When the ratio of σ_{s2}: σ_{s1} reduces, the inhomogeneous deformation and interface bending will be alleviated. That means it is better for bimetal forming at this time. Therefore, it is good for improving the quality of bimetal products to reduce the ratio of σ_{s2}: σ_{s1}. Fig. 7 shows the relationship between the ratio of σ_{s2}: $\sigma_{s1}$and interface slip. Fig. 8 shows the relationship between the ratio of σ_{s2}: σ_{s1} and exit radius ratio (R_{ext1}/R_{ext2}). When the ratio of σ_{s2}: σ_{s1} is greater than 1, the entry radius ratio is smaller than the exit radius ratio. In this situation, the hardness of inner material is bigger than that of outer material. The inner material can flow faster than the outer material. So, a part of inner metals without pressure applied at exit area can expand freely. This is a reason why R_{ext1}/R_{ext2} is bigger than R_{ent1}/R_{ent2}. The dotted line in Fig. 8 indicates the entry radius ratio.

4 CONCLUSIONS

(1) The FEM with the frictional elements inserted between two contacting metals can effectively describe the deformation mechanism of bimetal forming process.

(2) During bimetal forming process, because of the different deformation resistant force between two metals, there are severe shear deformation and relative slip on the interface. There are also inhomogeneous deformation between two metals and interface bending.

(3) The interface friction coefficient plays an important role in bimetal forming process. Increasing the interface friction coefficient is beneficial to alleviate the inhomogeneous deformation and improve the quality of extrusion products.



(a) $\sigma_{S2}:\sigma_{S1}=2:1$ (b) $\sigma_{S2}:\sigma_{S1}=3:1$ (c) $\sigma_{S2}:\sigma_{S1}=4:1$ (d) $\sigma_{S2}:\sigma_{S1}=6:1$

Fig. 6 Distorted meshes with different σ_{s2}: σ_{s1}

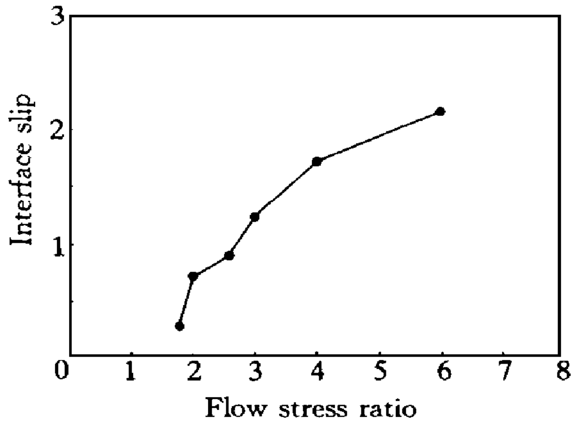


Fig. 7 Relation between σ_{s2}: σ_{s1} and interface slip

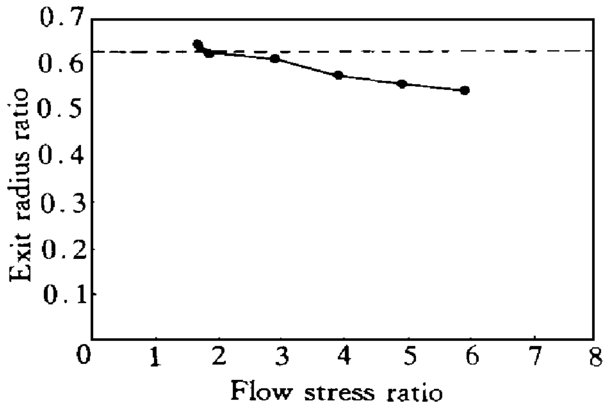


Fig. 8 Relation between σ_{s2}: σ_{s1} and exit radius ratio

(4) The yield stress ratio between two contacting metals will influence the bimetal forming process. Therefore, it is necessary to consider the specifications of deforming mechanics and physics when selecting bimetal.

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