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ARTICLE

# Velocity Field Analysis of Bonding Interface on Cold-Rolled Copper/Aluminum Composite Plate

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**Abstract:** The cold-rolled bonding process of copper/aluminum bimetal plate was investigated by the velocity field of finite element method (FEM). At the same time, deformation characteristics of metal were analyzed in the bonding process. The study method was to combine theory calculation with field data. The circumferential velocity of rollers, rolling reduction rate, synchronous rolling of non-equal sized rollers and asymmetrical rolling of non-equal sized rollers were analyzed. Results show that the velocity field can explain the cold-rolled bonding process of copper/aluminum bimetal plate more effectively; the synchronicity of metal flow on bonding surface decreases with the increase of circumferential velocity about rollers near the exit of deformation area, and the bonding strength is reduced; in the process of synchronous rolling about non-equal sized rollers, diameter ratio of the rolls is 1.4~1.6 with a great synchronicity of metal flow near the exit of deformation area and a high bonding strength; in the process of asymmetrical rolling about non-equal sized rollers, the circumferential velocity rate of rollers is 1.2 with a great synchronicity of metal flow near the exit of deformation area and a high bonding strength.

**Key words:** deformation characteristics; velocity field; bonding strength

Copper/aluminum bimetal plate is a new type of material with different mechanical, physical and chemical properties. It presents the relatively high electric and heat performance as copper, and exhibits the erosion-resistance, economy and light weight as aluminum, which is widely used in vehicles, aerospace, electronic appliances, energy and other fields[1,2].

The influence of annealing-treatment on bonding interface structure and properties of copper/aluminum bimetal plate has been investigated by scholars in China[3], and the roll-cladding technology for copper/aluminum sheet has been analyzed[4,5]. The effect of rolling direction on the creep process of copper/aluminum bimetallic sheet[6] and the process of accumulative roll bonding and folding have been researched by scholars[7, 8]. Studies mentioned above are to be carried out through experiment, but the cold-rolled bonding process of copper/aluminum bimetal plate is difficult to describe clearly with the complex deformation, and the influence of different craft parameters on bonding strength is hard to predict. So, a new method is proposed, where the cold-rolled bonding process of copper/aluminum bimetal plate is investigated by the velocity field of finite element method (FEM). The deformation characteristics of copper/aluminum bimetal plate are analyzed in the cold-rolled bonding process. This paper took the integration of measures including numerical simulation and field tests, and the circumferential velocity of rolling, synchronous rolling of non-equal sized rollers and asymmetrical rolling of non-equal sized rollers were analyzed.

## 1 Velocity Field Principle of Slip-line Field

The ideal plastic flow theory of rigid plastic material is based on the following six assumptions in this paper:

(1) Copper plate and aluminum plate are assumed to be isotropic material, and the influence of oxide film on the surface of the plates is ignored in the cold-rolled bonding process.

(2) The rolls are assumed to be rigid body without deformation in the cold-rolled bonding process.

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(3) Copper plate and aluminum plate are assumed to be without any defects, and the influences of micro cracks or voids of the microstructure are ignored in the cold-rolled bonding process.

(4) In the cold-rolled bonding process, the volume of plates is a constant:

$$\mathrm{d}\varepsilon_x + \mathrm{d}\varepsilon_y + \mathrm{d}\varepsilon_z = \mathrm{d}\varepsilon_1 + \mathrm{d}\varepsilon_2 + \mathrm{d}\varepsilon_3 = 0$$

(5) At each load moment, the principal axes of stress and the principal axes of strain increment coincide.

(6) In plastic mechanics, the material meets the standard Mises yield criterion [9]:

$$J_2 - k^2 = 0 \quad (1)$$

where, $J_2$ is the second invariant of deviator stress tensor, and $k$ is the material yield strength under the pure shear state.

According to the Levy-Mises plastic flow rule of ideal rigid-plastic material[9]:

$$\mathrm{d}\varepsilon_{ij} = \sigma_{ij}'\mathrm{d}\lambda \quad (2)$$

where, $\varepsilon_{ij}$ is the strain tensor, $\sigma_{ij}$ is the stress partial tensor, and $\mathrm{d}\lambda$ is positive instantaneous constant.

Eq.(2) is divided by the $\mathrm{d}t$ of the time increment on both sides, and the stress-strain rate equation [10] is concluded:

$$\dot{\varepsilon}_{ij} = \dot{\lambda}\sigma_{ij}' \quad (3)$$

where, $\dot{\varepsilon}_{ij} = \frac{\mathrm{d}\varepsilon_{ij}}{\mathrm{d}t}$ and $\dot{\lambda} = \frac{\mathrm{d}\lambda}{\mathrm{d}t}$.

According to Eq.(3), the stress-strain rate equations[10] is obtained under the plane strain state:

$$\left.\begin{aligned} \dot{\varepsilon}_x &= \dot{\lambda}\sigma_x' = \dot{\lambda}(\sigma_x - \sigma_m) \\ \dot{\varepsilon}_y &= \dot{\lambda}\sigma_y' = \dot{\lambda}(\sigma_y - \sigma_m) \\ \dot{\gamma}_{xy} &= \dot{\lambda}\tau_{xy} \end{aligned}\right\} \quad (4)$$

The point ($x$, $y$) of Eq.(4) is transferred to the coordinate system of slip line about $\alpha$ and $\beta$, in Eq.(4) where $\sigma_x = \sigma_\alpha$, $\sigma_y = \sigma_\beta$, $\dot{\varepsilon}_x = \dot{\varepsilon}_\alpha$ and $\dot{\varepsilon}_y = \dot{\varepsilon}_\beta$.

$\sigma_\alpha$ and $\sigma_\beta$ are the normal stresses on the plane where the maximum shear stress is to be. So, according to plane strain characters in plasticity, the relation is expressed by the following equation:

$$\sigma_\alpha = \sigma_\beta = \sigma_\mathrm{m} \quad (5)$$

where $\sigma_\mathrm{m}$ is the average stress.

Eq.(5) is plugged into Eq.(4), and the relations can be described by the following equation:

$$\left.\begin{aligned} \dot{\varepsilon}_\alpha &= \frac{\mathrm{d}\varepsilon_\alpha}{\mathrm{d}t} = 0 \\ \dot{\varepsilon}_\beta &= \frac{\mathrm{d}\varepsilon_\beta}{\mathrm{d}t} = 0 \end{aligned}\right\} \quad (6)$$

Eq.(6) can show that slip line is to be without strain increment, in other words, the slip line does not have the scalable characteristic[9].

As shown in Fig.1, we can assume that there are two points $P_1$ and $P_2$, which are infinitely close to each other on the slip line. The speed is $\boldsymbol{v}_1$ at location $P_1$ and the speed is $\boldsymbol{v}_2$ at location $P_2$. The velocity components of $\boldsymbol{v}_1$ are $v_\alpha$ and $v_\beta$,

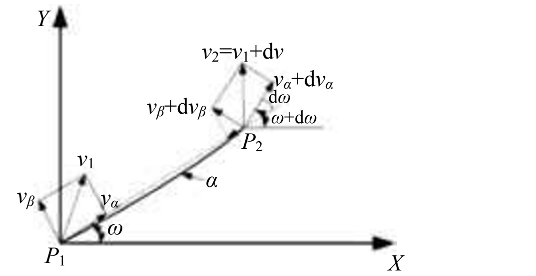


Fig.1 Decomposition of speed about two points on the slip line

along the slip line directions. The velocity components of $\boldsymbol{v}_2$ are $v_\alpha + \mathrm{d}v_\alpha$ and $v_b + \mathrm{d}v_b$, respectively, along the slip line directions. The angle is $\mathrm{d}\omega$ from $P_1$ to $P_2$. Because $P_1$ is infinitely close to $P_2$, we can think $\widehat{P_1P_2}$ overlaps with $\overline{P_1P_2}$. According to the not scalable characteristic of the slip line, we can realize that the velocity components of $P_1$ and $P_2$ are equal, on the direction of $\overline{P_1P_2}$ and on the direction which is perpendicular to $\overline{P_1P_2}$. The relations can be described by the following equations:

$$\left.\begin{aligned} v_\alpha &= (v_\alpha + \mathrm{d}v_\alpha)\cos\mathrm{d}\omega - (v_\beta + \mathrm{d}v_\beta)\sin\mathrm{d}\omega \\ v_\beta &= (v_\beta + \mathrm{d}v_\beta)\cos\mathrm{d}\omega + (v_\alpha + \mathrm{d}v_\alpha)\sin\mathrm{d}\omega \end{aligned}\right\} \quad (7)$$

because the $\mathrm{d}\omega$ is a very small value, these formulas are valid in Eq.(7): $\cos\mathrm{d}\omega \approx 1$, $\sin\mathrm{d}\omega \approx \mathrm{d}\omega$; at the same time, $\mathrm{d}v_\beta\sin\mathrm{d}\omega$ and $\mathrm{d}v_\alpha\sin\mathrm{d}\omega$ can be ignored. Eq.(7) can be described by the following equation:

$$\left.\begin{aligned} \mathrm{d}v_\alpha - v_\beta\mathrm{d}\omega &= 0 \\ \mathrm{d}v_\beta + v_\alpha\mathrm{d}\omega &= 0 \end{aligned}\right\} \quad (8)$$

Eq.(8) can be described by the corresponding difference equation:

$$\left.\begin{aligned} v_\beta &= \frac{\Delta v_\alpha}{\Delta\omega} \\ v_\alpha &= -\frac{\Delta v_\beta}{\Delta\omega} \end{aligned}\right\} \quad (9)$$

It can be shown very easily from Eq.(9) that if $v_\alpha$ and $v_\beta$ are known and the angle $\omega$ has an increment of $\Delta\omega$, the velocity values about $\boldsymbol{v}_{\alpha1}$ and $\boldsymbol{v}_{\beta1}$ of the next point on the slip line can be obtained.

At this point, the velocity of grid-point can be given by the following equation:

$$\boldsymbol{v} = \boldsymbol{v}_{\alpha1} + \boldsymbol{v}_{\beta1} \quad (10)$$

## 2 Velocity Field Analysis of Cold-rolled Bonding Process

### 2.1 Building model

The cold-rolled bonding process of copper/aluminum bimetal plate is a typical problem of material non-linearity,