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Materials

Mathematical modeling and simulation of the interface region of a tri-layer composite material, brass-steel-brass, produced by cold rolling

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Abstract: The object of this study was to find the optimum conditions for the production of a sandwich composite from the sheets of brass-steel-brass. The experimental data obtained during the production process were used to validate the simulation program, which was written to establish the relation between the interface morphology and the thickness reduction amount of the composite. For this purpose, two surfaces of a steel sheet were first prepared by scratching brushing before inserting it between two brass sheets with smooth surfaces. Three sheets were then subjected to a cold rolling process for producing a tri-layer composite with various thicknesses. The sheet interface after rolling was studied by different techniques, and the bonding strength for each rolling condition was determined by peeling test. Moreover, a relation between interfacial bonding strength and thickness reduction was found. The simulation results were compared with the experimental data and the available theoretical models to modify the original simulation program with high application efficiency used for predicting the behavior of the interface under different pressures.

Key words: sandwich composite; cold rolling; mathematical simulation; metallic bonding; interface

Nomenclature:

B: Width of strips;
n: Rotational velocity of the roll, r/min;
R_0: Radius of rolls;
υ^*: Shear velocity;
α_n: Contact angle related to neutral points;
α_2: Entrance point angle;
U: Linear velocity of the roll;
τ_s: Shear stress;
P: Pressure;
$\bar{\sigma}$: Average stress;
ε^0: Strain rate;
m_1: Friction coefficient between the roll surface and the outer surface of the upper layer;
m_2: Friction coefficient between the roll surface and the outer surface of the underneath layer;
t_{01}: Original thickness of the upper brass layer;
t_{02}: Original thickness of the middle steel layer;
t_{03}: Original thickness of the lower brass layer;
σ_{01}: Yield strength of the upper layer;
σ_{02}: Yield strength of the middle layer;
σ_{03}: Yield strength of the lower layer;
t_{f1}: Final thickness of the upper brass layer;
t_{f2}: Final thickness of the middle steel layer;
t_{f3}: Final thickness of the lower brass layer;
R_t : Reduction percentage of the total thickness.

1. Introduction

Cold roll welding is one of the solid state welding processes that can be used for joining two or more sheet metals by passing them through the gap space of two prefect rolls at ambient temperature. This technique is used in the production of composite sheet materials for various applications [1-3]. The mechanism of joining sheet metals in this process is said [4] to be primary due to metallic bonding between the surface atoms of the sheets. Since this process is performed at room temperature, the effect of rolling pressure on joining sheet metals becomes very crucial as there is no any conventional diffusion at this temperature [5]. In fact, in the cold roll welding process, a certain amount of rolling pressure can cause the atoms within the interface region of sheets to settle in such a way that an equivalent atomic distance to those of sheet metals involved be established at the interface [6]. The preparation of metal sheets before rolling is one of the most important factors for joining. This can be carried out either by coating the surfaces of the harder layer or

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by scratch brushing its surfaces [7-10]. In the scratch brushing method, asperities (*i.e.* scratches consisted of peaks and troughs) are produced during brushing the surface. The peaks undergo the maximum deformation during rolling; hence, it becomes harder and subsequently some microcracks appear in the surfaces. The surfaces of these microcracks consist of virgin metals (*i.e.* non-oxide surfaces), so when they come in contact with the softer metal extruded through microcracks during cold rolling, some metallic bonds can be established between the two metals [3, 8].

2. Experimental work

Before the application of cold rolling process in the present work, the surfaces of steel cores of the three-layer composite, brass-steel-brass were prepared by the scratch brushing technique. Then a sheet of brass with smooth surfaces was put over each side of the brushed steel sheet before rolling the three sheets at room temperature. Different thickness reductions (R_t=12%-71%) were applied to investigate the effect of rolling pressure on bonding strength and to find the optimum pressure for the production of the composite with enough bonding strength suitable for the next stage of operation, which was deep drawing after the annealing stage. The details of material compositions, the joining operation, and the peeling test for the evaluation of bonding strength can be found else where [11-12]. However, in this article, the mechanism of locking at the interface region has been simulated adequately, so that it can properly justify the relation between the observed microstructural changes during rolling and the pressure used for the cold welding process. To make these ends meet, the pressures applied for a certain amount of thickness reduction were established from the laboratory data, and then by use of Ansys-7.1 software, the variation of interface morphology for different thickness reductions was estimated. Finally, the relation between the bonding strength of the interface and thickness reduction was established, and an efficient mathematical model for this relationship was proposed.

3. Theoretical work

3.1. Calculation of pressure by the upper bound theorem

The upper bound theorem for the calculation of the required pressure for a certain amount of thickness reduction was used in the following way. According to Ref. [13], the total power by the outer force=the internal power for heterogeneous deformation + the required power for ideal deformation.

$$PU = \sigma_{\text{avr}} A U \le \int_v \bar{\sigma}\, \varepsilon^0 \mathrm{d}v + \int_s \tau_s \upsilon^* \mathrm{d}s \tag{1}$$

where P is the upper bound force or the roll separating load. This force is higher than the actual force required for deformation and is a function of rolling variables. By minimizing this equation on the base of independent variables, the predicted required force can come near to the actual force.

(1) Calculation of power.

Fig. 1 shows a schematically deformation pattern produced during the rolling of sandwich layers. The calculation of power for rolling three layers, that is the estimated upper bound power required for the deformation (J) of the three layers, was determined by using Eq.(1) in the following way [14-15]. The total required power during rolling according to the upper bound theorem can be expressed as

$$J = W_{\text{it}} + W_{\text{st}} + W_{\text{sf}} \tag{2}$$

where, W_{it}, W_{st}, and W_{sf} are the internal power dissipated during the process, the shear power due to velocity discontinuity in neighboring fields, and the shear power losses due to the friction between brass sheets and rolls, respectively. The detailed expressions of the individual terms in Eq. (2) are as follows.

(a) Internal ideal power (W_{it}) of deformation:

$$W_{\text{it}} = \frac{2b}{\sqrt{3}} U \cdot \frac{\dfrac{t_{\text{f1}}+t_{\text{f2}}+t_{\text{f3}}}{R_0} + \alpha_n^2}{\dfrac{t_{\text{f1}}+t_{\text{f2}}+t_{\text{f3}}}{R_0}} \cdot \left[\sigma_{01} t_{\text{f1}} \cdot \ln\frac{t_{01}}{t_{\text{f1}}} + \sigma_{02} t_{\text{f2}} \cdot \ln\frac{t_{02}}{t_{\text{f2}}} + \sigma_{03} t_{\text{f3}} \cdot \ln\frac{t_{03}}{t_{\text{f3}}}\right] \tag{3}$$

(b) Shear power (W_{st}) due to the velocity discontinuity in neighboring fields:

$$W_{\text{st}} = bU\left(1 + \frac{R_0}{t_{\text{f1}}+t_{\text{f2}}+t_{\text{f3}}}\alpha_n^2\right) \cdot \frac{(t_{\text{f1}}+t_{\text{f2}}+t_{\text{f3}})^{\frac{3}{2}} \sqrt{\dfrac{t_{01}+t_{02}+t_{03}}{t_{\text{f1}}+t_{\text{f2}}+t_{\text{f3}}} - 1}}{(t_{01}+t_{02}+t_{03})^2 \sqrt{R_0}} \cdot \left\{\frac{\sigma_{01}}{\sqrt{3}}(t_{02}+t_{03}) \cdot t_{01} + \frac{\sigma_{02}}{4\sqrt{3}}\left[(t_{02}+t_{03}-t_1)^2 + (t_{01}+t_{02}-t_{03})^2\right] + \frac{\sigma_{03}}{\sqrt{3}} \cdot t_{03}(t_{01}+t_{02})\right\} \tag{4}$$

(c) Shear power losses (W_{sf}) due to the friction between brass sheets and rolls: