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Bonding evolution of bimetallic Al/Cu laminates fabricated by asymmetric roll bonding

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Abstract. Roll bonding (RB) process of bi-metal laminates as a new noble method of bonding has been widely used in the production of bimetal laminates. In the present study, asymmetric roll bonding process as a new noble method has been presented to produce Al/Cu bimetallic laminates with the thickness reduction ratios 10%, 20% and 30% together with mismatch rolling diameter ($\frac{R_2}{R_1}$) ratio 1:1, 1:1.1 and 1:1.2. ABAQUS as a finite element simulation software was used to model the deformation of samples. The main attention in this study focuses on the bonding properties of Al/Cu samples. The effect of the $\frac{R_2}{R_1}$ ratios was investigated to improve the bond strength. During the simulation, for samples produced with $\frac{R_2}{R_1} = 1:1.2$, the vertical plastic strain of samples was reach the maximum value with a high quality bond. Moreover, the peeling surface of samples after the peeling test was investigated by the scanning electron microscopy (SEM).

Keywords: asymmetric roll bonding; mismatch roll diameter; peeling test; bimetal laminates; numerical simulation

1. Introduction

Nowadays the need of bimetal laminates is growing. A metal or alloy itself cannot has a group of desirable properties together. So, bimetal laminates become increasingly popular in various fields such as automobile, electrical industries and aerospace due to excellent properties such as strength, forming ability, wear and corrosion resistance and economic efficiency. Among various cladding techniques, roll bonding (RB) technique has been adopted in various industrial areas because of its capability of continuous and efficient production of clad sheets. Roll bonding process is used to fabricate many kinds of laminated composites such as Copper (Abbasi and Toroghinejad 2010), Copper/Iron (Arabi *et al*. 2009), Titanium/ Aluminum (Chaudhari and Acoff 2010), Iron/Aluminum (Kang *et al*. 2007, Nezhad and Ardakani 2009), Aluminum/Steel (Manesh and Shahabi 2009), Aluminum/Zinc (Movahedi *et al*. 2008), Titanium/Iron (Zhao *et al*. 2009),

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Aluminum/Magnesium (Zhang *et al*. 2010), Steel/Brass (Kavarana *et al*. 2000), Copper/Silver (Ohsaki *et al*. 2007) and Aluminum/Nickel (Mozaffari *et al*. 2010) laminated composites. Accumulative roll bonding (ARB) process as a severe plastic deformation (SPD) has been invented and presented by Saito in 1999. Roll bonding (RB) as the first pass in the ARB process is a continuous and cost efficient bonding mechanism of solid welding processes. The asymmetric roll bonding is a new noble method and has been the subject of some researches (Yu *et al*. 2014). There are four theories presented about the welding mechanism in the RB. The major mechanism theory in the RB process is the film theory (Vini *et al*. 2017a). Based on this theory, during the rolling process, by breaking off the brittle layers of surfaces during the rolling process, the virgin material is extruded across the strips due to the rolling pressure. To investigate the FEM aspects of the asymmetric rolling process, several finite element method investigations have been done. Reyds *et al*. (2003) investigated the outgoing curvature of bimetallic aluminum-copper sheets using FEM method. Tadanobu *et al*. simulated the ARB process up to three rolling cycles. They showed the effect of ARB cycles on the equivalent strain of aluminum layers (Tnoue *et al*. 2013). In this study, the finite element simulation and experimental investigation of the asymmetric RB process of bimetallic Al/Cu samples have been presented. The mismatch ratio of lower to upper roll diameter $(\frac{R_2}{R_1})$ was quantitatively analyzed. Also, the finite element (FEM) and experimental methods are used to investigate the bond strength of Al/Cu bimetallic laminates produced by the asymmetric RB process with various thickness reduction pct. and $(\frac{R_2}{R_1})$ ratios. Cross section and peeling surface of the peeling test specimens were investigated by the scanning electron microscopy (SEM). The investigations were used to enhance the bond strength.

2. Materials and processing

2.1 Experimental investigations

In the present study, the asymmetrical roll bonding as a new noble technique is used to fabricate bimetallic Al/Cu laminates. RBed samples were strips of annealed commercial pure Al and Cu with dimensions of 100 × 30 × 1 mm where annealed preciously. The mismatch ratio of

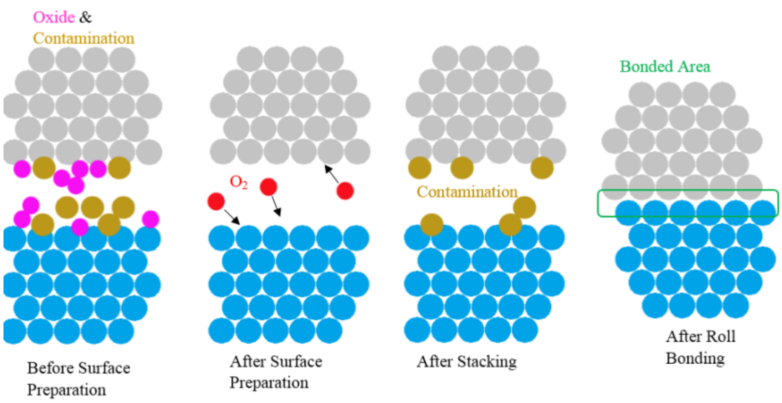

Fig. 1 Atomic arrangement during the RB process

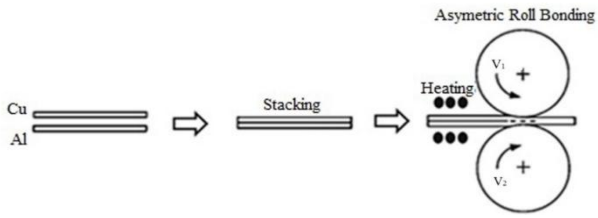

Fig. 2 Schematic illustration of asymmetrical RB process

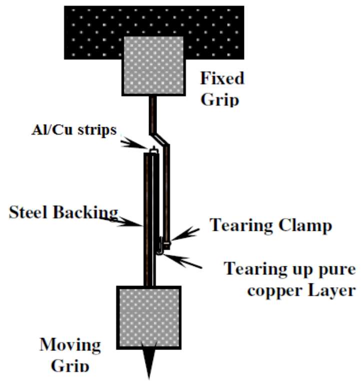

Fig. 3 Schematic illustration of the peeling test fixture

lower to upper roll diameter $(\frac{R_2}{R_1})$ was set to 1:1, 1:1.1and 1:1.2. Before the RB process, surface brushing of strips to be joined is necessary. As can be seen in Fig. 1, there might be some greases, contaminations, dust particles, adsorbed ions and oxides to exist on the metal surfaces. Thus, the metal surfaces were degreased in the acetone bath for ten minutes and scratch brushed. According to Fig. 2 after fastening one strip of Al and the other of Cu by steel wires, they were roll-bonded with thickness ratios 10%, 20% and 30% at 300℃, respectively.

An Intron tensile testing machine with 100 kg load cell was used to set up the asymmetric RB process. Fig. 3 shows the peeling test fixture. According to Fig. 3, the peeling speed in the peeling test was 20 mm/min. the peeling test of samples were performed according to ASTM-D903-93 standard. Also, the average peel strength was (Vini *et al*. 2017a)

$$\text{Average bond strength} = \frac{\text{Average load}}{\text{Bond width}}$$

2.2 Numerical simulation

Fig. 4 shows a schematic diagram of the asymmetric roll bonding process of Al/Cu bimetallic laminates. In the two dimensional FE simulation, the initial thickness of both layers was 1 mm. To solve the process, dynamic explicit solver is used. For applying the boundary conditions on the rolls, the centers of them were regarded as reference points. Also, as mentioned before in the experiments, the thickness reduction ratios selected were 10%, 20% and 30% at 300℃ with the roll mismatch diameter ratios $(\frac{R_2}{R_1})$ 1: 1, 1: 1.1 and 1: 1.2, respectively. During the asymmetric roll

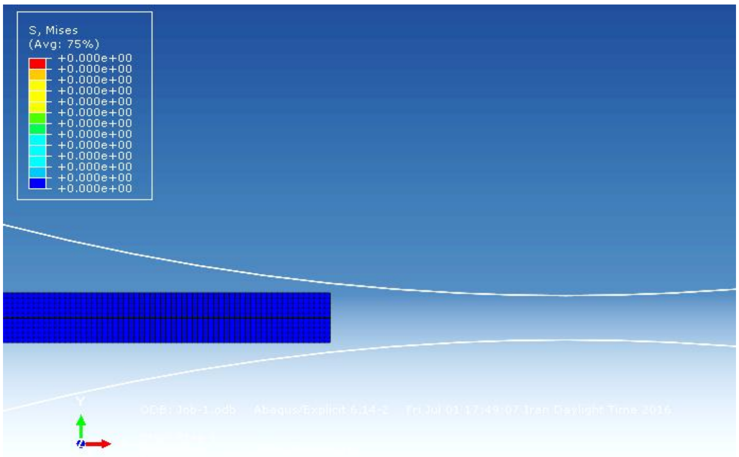

Fig. 4 FE meshing of the asymmetric roll bonding process

Table 1 Mechanical and physical properties of Cu and Al strips

Elastic modulus (GPa)	Poisons ratio	Yield strength (MPa)	Density (Kg/m^3)	Strip
110	0.3	33.2	8900	Cu
70	0.3	10	2700	Al

bonding process, the plane strain condition was regarded for the plastic deformation and rolls were defined as rigid. Also, strips have been meshed with CPE4R elements (Vini *et al*. 2017b). Al and Cu layers defined by the isotropic material model. Also, width spread and temperature change were neglected during the RB. After doing the mesh sensivity analysis, the geometric models were meshed with 1250 square elements. Fig. 4 shows the FE meshing of bimetallic strips for the roll bonding process. As mentioned before in the experiment, the rolls rotated with a constant angular velocity 40 rpm in the rolling process. Table 1 shows the mechanical and physical properties of Cu and Al strips used in the experiment.

3. Results and discussions

3.1 FE simulation results

In the FE simulation the dynamic explicit solver in the ABAQUS software is used. The problem is 2D modeled and the rolls regarded as rigid bodies. Fig. 5 shows the asymmetrical roll bonding process of bimetal Al/Cu laminates. As can be seen in Fig. 5, the difference of the yield stress of Al and Cu strips generates a curved product and an asymmetrical strain distribution along the thickness of strips. Moreover, Figs. 5(a)-(d) show the vertical strain amount of Al/Cu strips after rolling with $(\frac{R_2}{R_1})$ 1:1 and 1:1.2, for the reduction ratios of 10% and 30%, respectively. According to Fig. 5, increasing the $(\frac{R_2}{R_1})$ ratios increases the radius of the final rolled bimetal curvature.

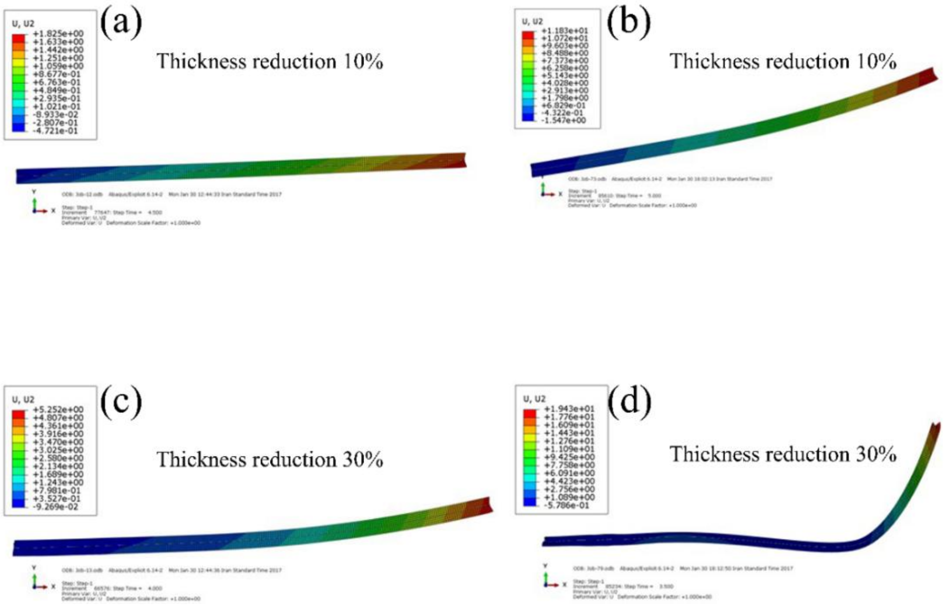

Fig. 5 Maximum vertical strain exerted on the bimetal strips with $(\frac{R_2}{R_1})$ (a, c) 1:1 and (b, d) 1:1.2

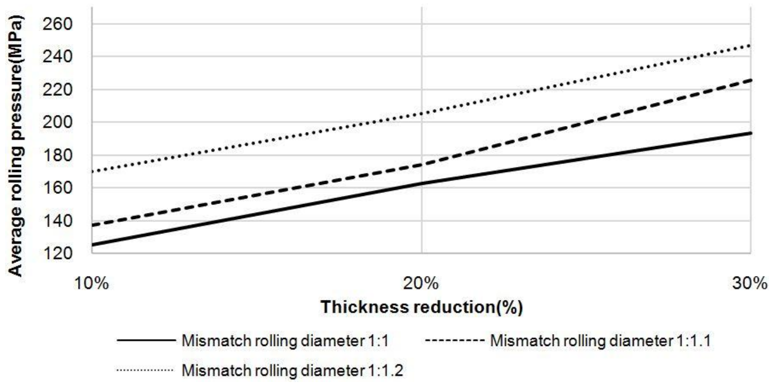

Fig. 6 Maximum rolling pressure of samples with different $(\frac{R_2}{R_1})$ ratios

By increasing the roll diameter ratio up to 1.2, the curvature radius attains a maximum value. So, increasing the curvature radius generates the higher shear strain at the interface of Al/Cu bimetal laminates. The maximum rolling pressure for the roll bonding process of bimetal laminates with 10%, 20% and 30% of reduction ratio and with different $(\frac{R_2}{R_1})$ ratios is shown in Fig. 6. As can be seen in Fig. 6, increasing the $(\frac{R_2}{R_1})$ ratios leads to a lightly increasing rate of the forming stress. Thus, shear stresses increase along the rolling length of contact which improves the rolling pressure.

3.2 Bonding interface

It is useful to investigate the interface of samples which was studied by SEM. Figs. 7(a) and (b) show the interface between Al and Cu with different $(\frac{R_2}{R_1})$ ratios 1:1 and 1:1.2 with the thickness reduction ratios 30%. According to Fig. 7(a), by increasing the $(\frac{R_2}{R_1})$ ratio, the interface gap becomes more and clear and the interface contains some residual voids. Also, by increasing the $(\frac{R_2}{R_1})$ ratio up to 1.2, the interface bond quality between Cu and Al component improves greatly. Thus, the interface gap vanishes and the microstructural analysis shows an apparent soundness (no pores or cracks). According to Fig. 7, the interfaces are all very thin (less than 1 μm) and is influenced by three parameters of the roll bonding process, (I). Rolling thickness reduction ratio, (II). Roll bonding temperature and (III). Mismatch diameter ratios. In fact, the higher mismatch diameter ratios favor the bonding process enabling to achieve sound joints (Li *et al*. 2011). Also, the results are good consistent with the analysis of stress state of asymmetric RB shown in Fig. 5. Also, Arrows in Fig. 7 show the residual voids generated during the roll bonding process which decreases in amount by increasing the rolling pressure by increasing $(\frac{R_2}{R_1})$ ratios.

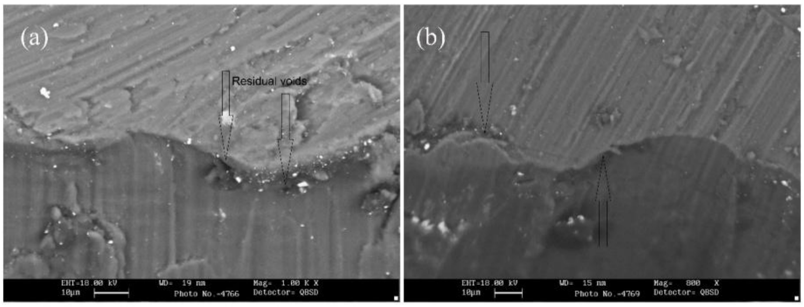

Fig. 7 SEM microstructure of asymmetric RB processed samples with different $(\frac{R_2}{R_1})$ ratios: (a) 1:1 and (b) 1:1.2

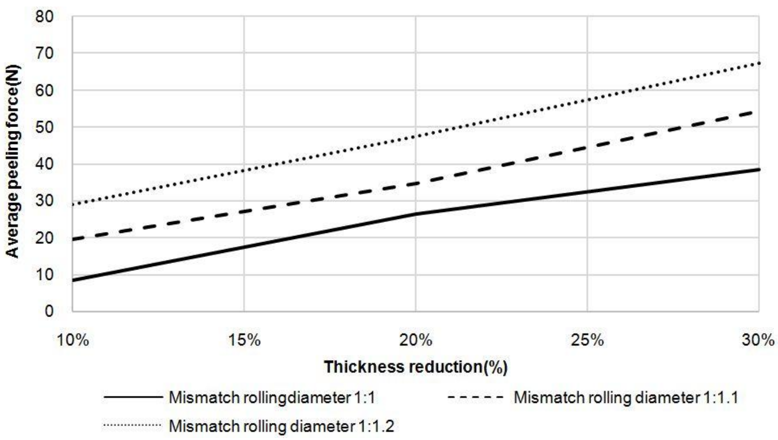

Fig. 8 Effect of $(\frac{R_2}{R_1})$ ratio on the average peeling force of samples

3.3 Effect of $(\frac{R_2}{R_1})$ ratios on the peeling strength

Fig. 8 shows the bonding strength of samples in the peeling test. According to Fig. 8, the larger $(\frac{R_2}{R_1})$ ratio causes an improvement in the peeling force and hence the bond strength. Also, According to Figs. 5 and 6, FE simulation shows that by increasing the $(\frac{R_2}{R_1})$ ratio, the rolling pressure increases considerably. For example, the average peeling strength of Al/Cu samples improves from 8.4 N up to 28.9 N and 38.4 N up to 67.4 N for samples fabricated with $(\frac{R_2}{R_1})$ ratio 1:1 and 1:1.2 and with 10% and 30% of thickness reduction ratio registering 244% and 75.5% improvement, respectively. According to Fig. 8, this improvement is due to (I): increasing the amount of shear deformation at the interface of samples, (II): surface expansion of Al and Cu strips normal to the rolling direction and size of crack and finally (III): extrusion of the virgin metal during the asymmetrical roll bonding process.

3.4 Effect of $(\frac{R_2}{R_1})$ ratios on the peeling surface

The microstructure of peeled surface of asymmetric roll bonded Cu/Al clad sheets is shown in Fig. 9. According to Fig. 9, increasing the $(\frac{R_2}{R_1})$ ratio leads to enhancing the size of extrusion of the base metal (virgin metal) and hence the bond strength improves. Based on the Figs. 5 and 8,

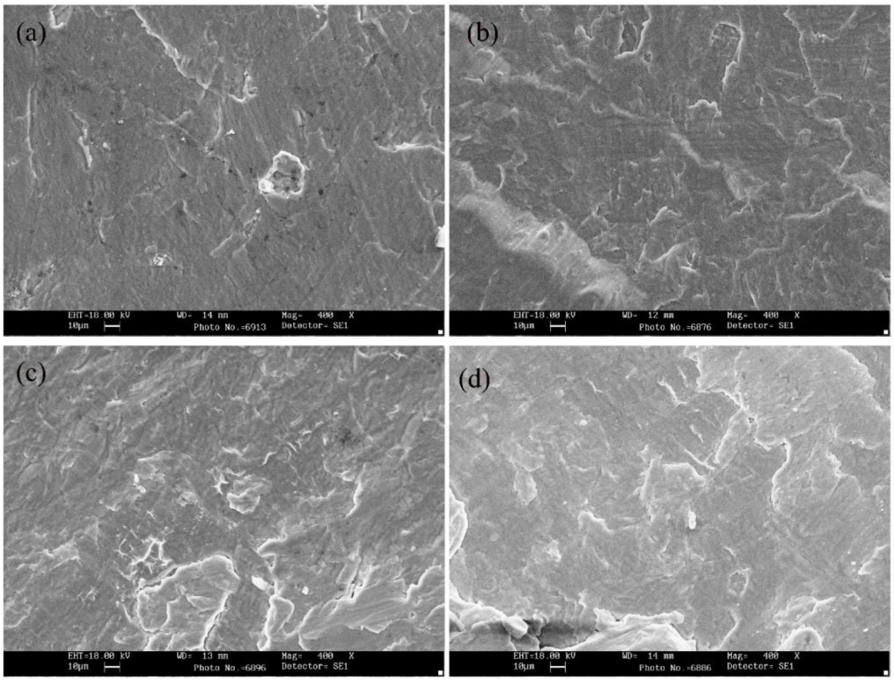

Fig. 9 SEM microstructure of peeled surface of samples with thickness reduction ratios (a, b) 10% and (c, d) 30%. Also, with $(\frac{R_2}{R_1})$ ratios as (a) 1:1; (b) 1:1.2; (c) 1:1; and (d) 1:1.2

increasing the $(\frac{R_2}{R_1})$ leads to introducing the plastic strain and the normal rolling pressure which generates higher surface expansion of Al and Cu strips. Moreover, based on the film theory, the higher is the surface expansion along the rolling direction the more are cracks on the metal surfaces which are the extrusion channel. Thus, in Fig. 9, a lot of underlying virgin metal which are look like small isolated islands are extruded by the rolling pressure. Finally, increasing the $(\frac{R_2}{R_1})$ ratio leads to the enhancing of number and area of them.

4. Conclusions

In the present study, the experimental and finite element investigation of the asymmetric roll bonding process of bimetal Al/Cu laminates were successfully conducted. The following results may be drawn from the present investigation:

- Due to the asymmetric geometry of the asymmetric RB process of Al/Cu laminates, this process affects the final geometry of the rolled sample.
- Asymmetrical RB creates a noticeable cross shear strain and promotes the Al and Cu surfaces to deform.
- With increasing the $(\frac{R_2}{R_1})$ ratio from 1:1 up to 1:1.2, the interface bond quality improves and the number of visible cracks decreases considerably. Thus, number and area of bonding areas which are looks like isolated islands increases considerably.
- Increasing the strain at the bimetal interface due to increasing the $(\frac{R_2}{R_1})$ ratio, leads to improvement of the bonding quality.

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