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ALUMINUM ROLLING

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Session I

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AN INVESTIGATION OF DEFORMATION BEHAVIOR OF BIMETAL CLAD SHEETS BY ASYMMETRICAL ROLLING AT ROOM TEMPERATURE

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Abstract

The different thickness metals mild steel, aluminum and copper were bonded with each other by means of asymmetrical rolling at room temperature. The deformation behaviors, bonding conditions and interfacial layer thickness of the clad sheets were discussed. According to the slab stress in the plastic deformation region at the roll gap, the relations of bonding condition and metal flow were analyzed. The influence of cross shear on the bonding due to the roll speed mismatch is obvious. The large speed mismatch makes a good bonding and drops the critical reduction. The improvement of bonding is achieved with the increase of the total rolling reduction. The reduction of both layers increases in direct proportion with the total reduction, and the difference between hard and soft metals gradually diminishes. The large initial thickness ratio of hard and soft metal is unhelpful for the bonding due to the inconsistent deformation of bimetal.

Introduction

Roll bonding technique is a solid-state phase bonding process used to join similar or dissimilar metals. During the processes of multilayer clad sheet and strip production, it is the most economical and productive manufacturing process that can be applied to produce high bonding strength of various materials in continuous rolling and processing lines [1-2].

At present, there are many researches about roll bonding, mostly base on the hot or warm rolling. Some researchers make the experimental study on the cold roll bonding, using the symmetric rolling techniques [3-6]. According to the previous studies, the roll bonding strength is determined mostly by the roll temperature, but the high temperature makes the surface of bimetal clad sheets poor and causes the appearance of the intermetallic compounds on the interface of the two dissimilar metals. For the cold roll bonding, the thickness reduction plays a more important role for the effective bonding [1,7-8]. The bonding of the common metal and alloy can be achieved when the roll reduction reaches 50% [2,7,9], whereas the higher reduction imposes a strict demand for the equipments.

Asymmetrical rolling of bimetal clad sheet can significantly reduce the rolling force compared with conventional cold rolling, while still ensure the same primary bond strength[10]. In the asymmetrical roll bonding, there is a shear zone in the central region of roll gap due to the different peripheral speeds of two identical work rolls. The relative sliding on the interface between the two metals is enhanced at the entrance, whereas the plastic flow of the two metals becomes more homogenous at the exit of the roll gap[11]. The application of the cross shear roll bonding of the aluminum/stainless steel has shown the advantage of significantly reducing rolling load, while still guarantee equal (or even higher) primary bonding strength[12]. However, there is no complete analysis about the relation of stress state with deformation behavior of asymmetrical cold roll bonding for bimetal clad sheet.

In present work, it was intended to analyze the stresses on the interfacial zones of the component metals at the roll gap during an asymmetrical rolling, furthermore, the systemic experimental data of the aluminum/mild steel (Al/St), copper/mild steel (Cu/St) and aluminum/copper (Al/Cu) were attained to investigate the deformation behaviors, bonding conditions and interfacial layer thickness of the clad sheets by the asymmetrical roll bonding.

Experimental Procedure

The materials used in this investigation were commercial pure aluminum 1060, pure copper T2 and mild steel (0.14 wt. % C) of 25 mm width, 200mm length, respectively. The thicknesses of specimens are shown in the table 1.

The surface of specimen was degreased using acetone. NaOH (10% in mass) was used to remove the oxide coating of aluminum and copper, and H_2SO_4 (10% in mass) for the mild steel. The specimen was then scratched by a stainless steel circumferential brush with wires 0.3mm across running at a rotational speed of 1400 rpm. After surface preparation, the handling of the strips was performed carefully to avoid renewed contamination. Two pieces of the strips were stacked together by a soft aluminum wire. To investigate the effects of different parameters, a series of cold roll bonding experiments were made with the thickness reductions from 30% to 70% on the four-high reversing mill with roll diameter of 300 mm. The ratios of works roll speed, defined as speed mismatch ratio, were set as 1.06, 1.19 and 1.31. The specimen was fed into the roll gap while the hard component touched with the higher speed work roll. All the parameters of roll bonding are presented in the table 1.

Some tests were conducted to try to enhance bonding on the interface by annealing at various temperatures for 20 min. The temperature deviation of the furnace was ±5□.

The cross sections of specimens, transverse to the rolling direction, were mechanically polished and buffed. They were then etched at room temperature using a solution of 5 ml HNO_3+100ml C_2H_5OH for Al/St and Cu/St specimens for 30 s, and of 2 ml HF+3 ml HCl+5 ml HNO_3+95 ml H_2O for the Al/Cu specimens for 30 s.

The microstructures of the interfacial zone and intermetallic compound layers were identified by optical microscope, scanning electron microscope with energy disperse spectroscope.

Table1. Thickness of Specimens and Parameter of Roll Bonding

No.	Component thickness			Speed ratio	Thickness reduction/%
	Mild steel /mm	Copper /mm	Aluminum /mm		
1	-	1.50	1.00	1.06	48

2	-	0.50	1.00	1.06	48
3	-	1.50	1.00	1.19	48
4	-	0.50	1.00	1.19	79
5	-	0.50	1.00	1.19	53
6	-	0.50	1.00	1.19	64
7	-	1.50	1.00	1.31	48
1	1.50	-	1.00	1.06	30
2	1.50	-	1.00	1.19	30
3	1.50	-	1.00	1.31	40
4	1.50	-	1.00	1.31	30
1	1.20	0.50	-	1.19	50
2	1.20	0.50	-	1.31	50
3	1.50	0.50	-	1.31	50

Deformation Stress Analysis

The deformation behavior of roll bonding is difficult to perform. Some researchers develop various theories and establish the mathematical model to perform the experiment [7,13-17]. Figure 1 shows a schematic illustration of asymmetrical roll bonding under constant shear friction. It is assumed that the process of roll bonding is plane strain state and accordant with slab method, and distribution of normal stress at upper and lower work rolls is homogeneous. The material just makes rigid plastic deformation.

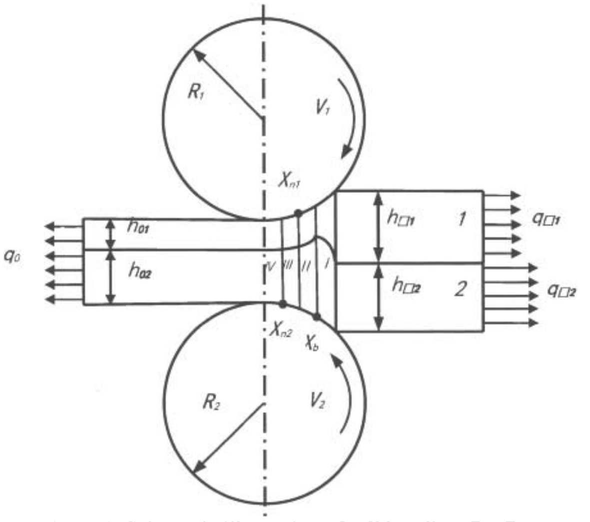

Figure 1. Schematic illustration of roll bonding. $R_1=R_2$, V_2□V_1, the deformation zone at the roll gap is divided into four distinct subzones I, II, III and IV.

The Figure 1 reveals the geometry at the roll gap. Unbounded clad sheet is initially bit into the roll gap, the soft sheet (layer 1) is yielded and the hard sheet (layer 2) is not yet yielded. Thus, this region (zone I) belongs to the unbounded region. The slab stress state in zone I is shown in Figure 2(a), where the shear stress on the interface is τm. As the harder sheet is yielded, the clad sheet begin to bond, the bonding point (x_b) is generated. The plastic deformation region at the roll gap can be divided into four distinct subzones along with rolling direction[13], zone I($x_b \le x \le L$) for the unbounded region; zone II ($x_{n1} \le x \le x_b$), zone III ($x_{n2} \le x \le x_{n1}$) and zone IV ($0 \le x \le x_{n2}$) for the bounded regions. The slab stress state of the clad sheet in zone II is shown in Figure 2(b), zone III is the cross shear region where the frictional shear stresses are reverse as showed in Figure 2(c), and the frictional shear stresses in zone IV are opposite to that in zone II. The direction of the shear stress on the interface changes along with the rolling direction due to the mismatch speed Zone II, III, and IV for the shear stress on the interface (τm) should be determined by the model.

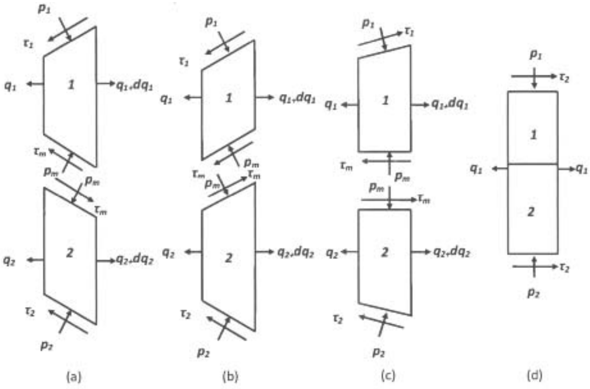

Figure 2. Stress state of distinct regions at roll gap, (a) (b) (c) (d) represents the subzone of I, II, III, IV respectively.

The slab stress state presents the metal flow tendency. In zone I and zone II, the shear stress both promotes the hard metal to deform. Unlike layer 2, layer 1 gets little shear effect, because of the same direction of shear stress on roll direction. Simultaneously, both layers take a large thickness reduction, the interfacial zones get enormous metal flow. When the metals come into zone III, the cross shear stress cause both layers to shear deform, an amount of metal flow is made on the interfacial zone. Afterward, cracks appear on the interface, the fresh virgin metals are extruded. In zone IV, the virgin metals achieve a mechanical bonding due to the metallic atoms bonding under load and thermal energy. After that, the component layer is thrown out the roll gap as an integral sheet. It should be noted that this analysis has discussed only the stress direction, not involve the value and relation of each other.

Results and Discussion

Effect of Speed Mismatch Ratio on Bonding

Figure 3 represents the effect of speed mismatch ratio on the interfacial bonding of bimetal clad sheets. The diffusion thickness on the interface increases clearly with the speed mismatch ratio varying. When the speed ratio increases from 1.06 to 1.31, the thickness of the interfacial zone of Al/Cu clad sheet and Al/St clad sheet grows from 2.8µm and 1.8µm to 3.5µm and 2.1µm, respectively. Similarly, that of Cu/St clad sheets increases from 6.4µm to 7.5µm with speed ratio varying from 1.16 to 1.31.

The large speed mismatch ratio causes a dramatic cross shear stress state on the interfacial zone, which has been analyzed in part of stress analysis. It is noted that the experimental results agree with the analysis. In the process of asymmetrical bonding, the way that the hard metal touch with the higher speed roll and the soft metal with the low speed roll enables the metal flow of both metals to uniform. Figure 3 shows that the morphology of interfacial zone of bimetal clad sheets has an improvement with increasing speed mismatch ratio.

In addition, the temperature increase induced by deformation and friction, due to the large speed mismatch ratio of asymmetrical rolling, play an important role on interface diffusion.

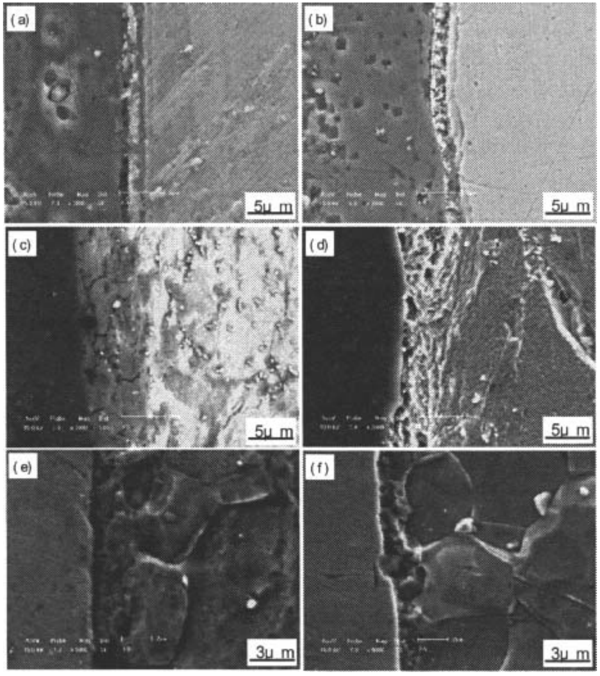

Figure 3. SEM image of the morphology of interfacial zone with different speed mismatch ratio. (a) (b) shows that of Al/Cu sheet with annealing at 400□; (c) (d) represents the Al/St sheet with annealing at 350□; (e) (f) is the Cu/St sheet with annealing at 750□.

Effect of Thickness Reduction on Bonding

In cold bonding processes like rolling, the total thickness reduction is one of the most important parameters that affect bonding strength. On the other hand the large normal roll pressure on the surfaces leads to produce cracks on the brittle surface layers. Thus extrusion of these virgin metals is convenient to get metallic atoms bonding in the deformation region at the roll gap.

Figure 4 shows the interfacial zone variation of the clad sheet with rolling thickness reduction. It is found that morphology of the clad sheet is significantly improved with increasing rolling thickness reduction. As the rolling reduction increases from 53% to 79%, the interfacial zone thickness of Al/Cu clad sheet is, to some extent, improved. The improvement is similar for the Al/St clad sheet, the interfacial zone grows into a continuous layer, and the thickness increases from 4μm to 7μm when the reduction increases from 30% to 40%.

The deformation of hard metal is delayed to the soft metal because of their different deformation resistance. So normally, the soft metal has a larger deformation accumulation during the whole roll bonding reaching the maximal strain hardening first. Afterward, the deformation rates of soft metal reduce, therefore, the deformation distribution of hard metal increase at the later stage of bonding. Figure 5 represents the deformation distribution of both metals variation with the total deformation. The reduction of both components of Al/Cu as well as Al/St clad sheet increased in direct proportion with the total reduction, and the difference between hard and soft metal gradually diminished. The higher deformation uniformity of both metals is useful for the metal atoms to make metallic bonding and the improvement is corresponding to the higher rolling reduction.

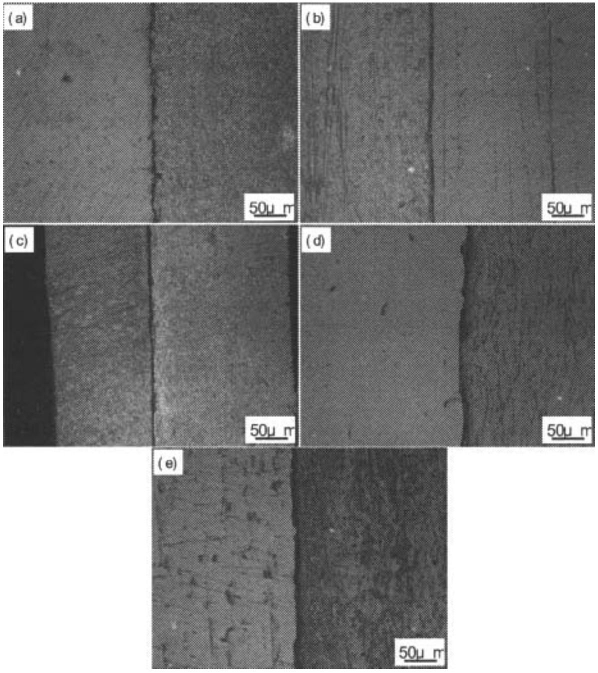

Figure 4. Micrograph of interfacial zone variation with different reduction. (a), (b), (c) represents 53%, 64% and 79%, respectively, of Al/Cu sheet with annealing at 400□; (d) (e) is for Al/St sheet with 30% and 40% followed annealing 400□.

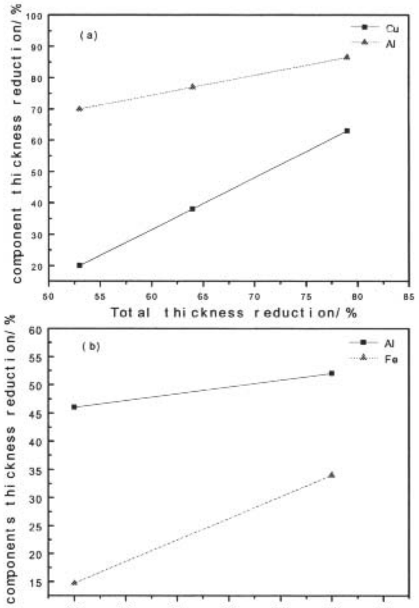

Figure 5. Variation of components thickness reduction with total thickness reduction. (a) represents that of Al/Cu clad sheet, (b) represents that of Al/St clad sheet.

Effect of Initial Thickness on Bonding

When the rolling force is constant, the sheet with thin initial thickness has a small contact area with the rolls and suffers a higher rolling stress, ultimately the metal yields rapidly. The couple of metals have an asynchronous deformation owing to their different resistance. Generally, the plastic deformation of soft metal is higher distinctly than that of the hard metal. By decreasing the initial thickness of hard metal strips, the shear stress of the deformation region at roll gas may cause hard metal to yield easily. In this way, the deformation uniformity of both metals is achieved. The bonding is, therefore, improved.

Figure 5 shows the experiment results, which are agreement well with above theory. The initial thickness ratio is expressed by the ratio of hard and soft metal, shown as S_h/S_s. It can be seen that the interfacial layer thickness increases from 3μm to 7μm, when the initial thickness ratio of Al/Cu clad sheet changed from 1.5 to 0.5 with the initial thickness of aluminum strip constant. The trend is similar for the Cu/St clad sheet, the initial thickness ratio changed from 3 to 2.4 results in the improved interfacial diffusion.

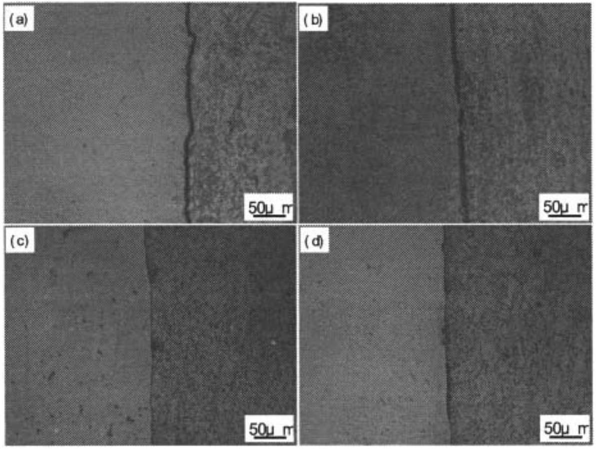

Figure 6. Micrograph of interfacial zone with initial thickness ratio S_h/S_s varying. (a) (b) is Al/Cu sheet with S_h/S_s as 1.5 and 0.5 annealed at 500□, (c) (d) represents Cu/St sheet with S_h/S_s varying from 3 to 2.4 annealed at 600□.

Conclusions

According to the deformation stress analysis and microstructure on the interfacial zone, the deformation behavior and bonding of bimetal clad sheets in the asymmetrical cold roll bonding process were analyzed. The following conclusions may be drawn from the present work:

1. The deformation zone at roll gap is constituted of four districts, and the stress analysis shows that the hard metal touched with the higher speed roll has a beneficial stress field.
2. The larger speed mismatch ratio of work rolls is helpful for the couple metals to achieve a fine interfacial diffusion layer for good bonding.
3. The bonding of clad sheet is improved due to increasing thickness reductions, and the reduction of both layers increases in direct proportion with the total reduction, simultaneously, the difference between hard and soft metal gradually diminishes.
4. Reducing the initial thickness of hard metal improves the deformation uniformity of both metals to accomplish a good rolling.

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