Study of Deformation Behavior of 4A60 Aluminum Alloy/08Al Steel Clad Material During Cold Roll Bonding

Bo Wu, Long Li, Chuang Gao, Zhenming Yang and Dejing Zhou

ABSTRACT

The deformation behaviors of 4A60 aluminum alloy/08Al steel clad materials with different thickness of each layer were investigated in this study. The amounts of residual aluminum and cracks on the steel surface of deformation zone after peeling were measured, and the morphologies of steel surfaces after peeling and caustic wash were observed by scanning electron microscope (SEM), respectively. In addition, the mechanical of aluminum/steel roll bonding was discussed. The results showed that the deformation of aluminum alloy has precedence over steel layer, and the stable thickness reduction of collaborative deformation of aluminum layer and steel layer decreased along with the thickness of steel layer increase, and increased with the thickness of aluminum layer. The effect of ditches generated by steel brush on bonding strength of the aluminum/steel composite materials of CRB was larger than transverse cracks growth along rolling direction.

INTRODUCTION

Bimetal clad materials composed of two dissimilar metal layers such as aluminum and steel are commonly used in a number of fields such as aerospace, automobile, and electrical industries due to their high strength, electrical conductivity and corrosion resistivity [1-3]. The methods of manufacturing clad sheet include explosion welding, hot pressure welding, diffusing welding or bonding, hot roll bonding and cold roll bonding (CRB)[4]. Compared with other methods, CRB is simple and automated, and considered as one of the promising methods of bonding materials from foils [1,5]. In the clad rolling process, the variation between the yield stresses of strip layers results in the different reductions in each layer. Hence, the deformation study of bimetal strip rolling is more complicated than compared to single layer sheet/strip rolling. Maleki[1] studied the effect of thickness reduction on rolling force, reduction of each layer and peeling
strength by analytical model, and the model was applicable for simulating the cold rolling process of two-layer strips. Tzou and Huang[4] based on analytical modified model found that the increase of thickness reduction, frictional coefficient, thickness ratio and back tension et al were beneficial to increase the bonding length. Tang et al[6] studied the effect of surface treatment on the bonding strength of CRB, and found that the longitudinal surface texture was more advantageous for bonding.

The precise mechanism for the interfacial bonding of bi-metal by CRB were unclear, over the past decades, many attempts have made to explain the mechanisms of CRB such as the film theory[7], energy barrier theor[8], diffusion bonding theory[9] and recrystallization theory [10]. Ref [11] have expressed that the film theory is the major mechanism of CRB due to the low rolling temperature. It indicated that bonding should be obtained when deformation causes fresh metal surfaces to be exposed and that the deformation reaches a value sufficiently large to establish contact bonding between the two sheets.

The objective of this study was investigated the deformation behavior of this clad material with different layer thickness, and found the optimization of thickness ratio of aluminum layer to steel layer, which may provide a guidance of selecting proper thickness ratio of aluminum layer and steel layer for enhancing the bonding strength of the aluminum clad steel sheets.

EXPERIMENTAL PROCEDURE

Materials. Complete recrystallized aluminum alloy sheets (4A60) and hot rolled low carbon steel sheets (08Al) were used in this study. The aluminum alloy sheets and steel sheets were 250mm in length, 100mm in width, while the thickness of each sheet varied from 1mm to 4mm. The chemical compositions of the aluminum alloy sheet and the steel sheet were listed in Table 1.

<table>
<thead>
<tr>
<th>Materials</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ti</th>
<th>Fe</th>
<th>Al</th>
</tr>
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<tbody>
<tr>
<td>4A60</td>
<td>-</td>
<td>0.83</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
<td>0.32</td>
<td>Bal.</td>
</tr>
<tr>
<td>08Al(steel)</td>
<td>0.007</td>
<td>0.019</td>
<td>0.25</td>
<td>0.011</td>
<td>0.004</td>
<td>0.0004</td>
<td>Bal.</td>
<td>0.004</td>
</tr>
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</table>

Surface preparation. The aluminum alloy sheets were degreased by acetone to remove the dust particles and greases. The steel sheets were pickled by 5 wt% hydrochloric acid solution to remove the grease and oxide. And the surface of aluminum alloy sheets and steel sheets which to be bonded were scratched by steel brush, respectively. The steel circumferential brush was 90mm in diameter with Φ 0.3mm.

Cold roll bonding process. The heads of the aluminum sheet and the steel sheet were riveted after surface preparation to avoid drifting. The bimetal sheets were then cold roll bonded at the total reduction of 45% without lubrication, a four-high laboratory rolling mill with a loading capacity of 2000kN was used. Diameters of the backup roll and work roll were 350mm and 170mm, respectively, and the roll width was 500mm. The rolling speed of 3m/mm was employed. The samples were cut by liner cutting from roll deformation zone along rolling direction with 50mm in length, 10mm in width. All samples named after the thickness of each layer before CRB, for example, sample cut from composite sheet made from
1mm thickness aluminum alloy sheet and 2mm thickness steel sheet was named as Al1St2.

**Thickness measurement and Vickers hardness test and surface morphology observation.** The samples were peeled by manual, and then immersed in the 30 wt% sodium hydroxide solution for 5 hours to remove the residual aluminum on the steel surface and ultrasonic cleaning was carried out to wipe out the sodium hydroxide residual on samples surface. The thickness of samples of deformation zone was measured by ZEISS Imager A2m optical microscope (OM). Micro Vickers was employed to test the hardness of samples. The morphology of the steel surface after peeling was examined by ZEISS scanning electron microscope (SEM). The chemical composition was detected by energy dispersive spectrometer (EDS).

### RESULTS

**The effect of component layer thickness on 4A60 aluminum alloy /08Al steel cold roll bonding.** Fig.1 showed the bonding results of 4A60 aluminum/08Al steel clad sheets with different layer thickness. It can be seen that increase the aluminum ratio was facilitated to bond successfully. According to the results, drew an imaginary line on the diagram, and indicating that above the line, the sheets could be bonded, instead, the sheets could not be bond.

![Figure 1](image.png)

**Figure 1.** The result of aluminum/steel bond with different thickness under total reduction of 45%.

**Effect of steel layer thickness on 4A60 aluminum alloy /08Al steel cold roll bonding.** The variations of the reduction of aluminum layer and steel layer with total reduction were shown in fig.2. It can be seen that the reduction of each layer increased with total reduction. Due to the difference of yield stress of the component layers, the thickness reductions of component layers were dissimilar. As can be seen, the reduction of aluminum layers was always larger than the reduction of steel layers. That was probably because of the poor resistance to deformation of aluminum. The difference of thickness reduction between aluminum alloy layer and steel layer was more significant while the total reduction was small. Inversely, the thickness reduction of steel reduction became significant where the total reduction was more than 18%. Over the interval of 45% thickness reduction of aluminum, the decrease of thickness of aluminum layer trended to slow down. In addition, in the range of total of total reduction from 0% to 20%, the thickness reduction of
aluminum layer increased with the original thickness of steel layer, while above this range, the thickness reduction of steel layer increased rapidly. Meanwhile, the reduction rate of each layer tends to be consistent. Fig.3 showed the variations of the clad ratio of aluminum layer with the total reduction, it can be seen that the clad ratio of aluminum layer decreased with the increase of total reduction and the thickness of steel layer. In addition, the stable point of collaborative deformation of aluminum layer and steel layer decreased with the increase of the thickness of steel layer.

**Figure 2.** Variations of each layer reduction with total reduction.

**Figure 3.** Variations of clad ratio of aluminum layer with total reduction and thickness of steel layer.

**Effect of aluminum alloy layer thickness on 4A60 aluminum alloy /08Al steel cold roll bonding.** The variations of the thickness reduction of aluminum layer and steel layer with total reduction and thickness of aluminum layer (Al1St3, Al2St3 and Al3St3) were shown in fig.4. As can be seen, the thickness reduction of aluminum layer increased rapidly at low total reduction, as can be seen in section I. In section II, this reduction growth tended to slow down, which is similar with Fig.2. In section III, where the thickness reduction of aluminum was above 50.2%, despite of the origin thickness, the deformation behavior of aluminum layers tend to be consistent. Apparently, the thickness reductions of steel layers were less than aluminum layers. Among these samples, steel layers started to deform with a reduction of 10%, meanwhile, the increment of thickness reduction of the steel layers decreased with the original thickness of aluminum layer. Fig.5 showed the variations of the clad ratio of aluminum layer with total reduction. The clad ratio
decreased with total reduction, but increased with the original thickness of aluminum. In addition, different to Fig.3, the stable point of collaborative deformation of aluminum layer and steel layer increased with the thickness of aluminum.

**Figure 4.** Variations of each layer reduction with total reduction.

![Graph showing variations of each layer reduction with total reduction.](image)

The hardness distributions of deformation zone of steel layers at different total reduction were shown in Fig.6. It displayed that the hardness of steel layers increased with total reduction, but decreased with thickness of aluminum layer. As stated above, the reduction of steel risen up rapidly after a total reduction of 10%, and then the deformation resistance of steel increased due to the dislocation increased, and the hardness of steel layer increased with total reduction as well.

**Figure 5.** Variations of clad ratio of aluminum layer with total reduction and thickness of aluminum layer.

![Graph showing variations of clad ratio of aluminum layer with total reduction.](image)
Effect of layer thickness with same clad ratio on 4A60 aluminum alloy/08Al steel cold roll bonding. Fig.7 showed the relationship between layer reduction and total reduction. All these samples had the same clad ratio of 1:1. As can be seen, the deformation behaviors of all aluminum layers and steel layers were approximately the same, respectively, despite of their different original thickness. The residual aluminum and cracks on the steel surface were shown in Fig.8. Fig.8 (a) showed the variations of residual aluminum and cracks relative area with total reduction. As can be seen, the area of aluminum and cracks increased with total reduction. Moreover, it was found that the area of residual aluminum were more than that of cracks on the steel surface. Fig.8 (b) displayed the critical reduction where residual aluminum and cracks first appeared. It can be seen that the critical reduction increased with thickness of samples, meanwhile, the residual aluminum were found at a smaller critical reduction than that of cracks. This phenomenon was investigated in detail in the following research.
The steel layer surface morphology of deformation zone after peeling. In order to study the influence of reduction on bonding strength of deformation zone, morphologies of steel surfaces in deformation zone cut from Al2St2 sample after peeling were shown in Fig.9. It can be seen that in the deformation zone, the area of residual aluminum in the steel layer surface after peeling tended to grow with the increase of the reduction. However, it was found that there were 23.4 wt% mass fraction of aluminum (detected by EDS) in the surface of steel layer where the total reduction was 1.7%, as shown in Fig.9 (a). Constantly, the aluminum sheet and steel sheet could not bond at such a small thickness reduction. It was inferred that these residual aluminum after peeling were not resulted from aluminum/steel interface bonding, it was probably caused by relative friction motion between aluminum sheet and steel sheet on the entry side of roll bite during which some soft aluminum were grinded by hard steel [12]. It can be seen in Fig.9 (a) and (b) that the morphologies of residual aluminum mainly presented as blocks and bits of ridges, which were indicative of a small bonding force between aluminum and steel with a reduction of 1.7% and 18.6%, respectively. Few cracks were found on the surface of steel layer, indicated that the steel layer had not performed severe deformation along rolling direction. Steel surface with total reduction of 35.5% and 39.8% in deformation zone were shown in Fig.9 (d) and (e), respectively. As can be seen, the morphologies of residual aluminum on the surfaces of steel layer mainly consist of ridges which were parallel to the scratches caused by steel brush as lined out in Fig.9 (d). Meanwhile, a multitude of cracks were observed, while few residual aluminum were found in these cracks. This phenomenon was more pronounced in the zone with larger reduction. Fig.9 (f) displayed the surface morphology of steel after peeled with a reduction of 45.5%, it showed that the peeled surface of steel was almost covered by ridge-like residual aluminum, and the distribution arrangement of the aluminum was also paralleled to polished direction of steel brush. Inversely, there were few aluminum existed in cracks which was perpendicular to the rolling direction. According to the film theory, the hardened surfaces layer will be broken during CRB, which is beneficial to the contact and bonding of virgin metals. In this study, however, the results indicated that the hardened surface layers fracture contributed little to the interface bonding force.
In order to study the effect of total reduction on hardened surface layer fracture of steel, steel layer was etched by sodium hydroxide solution to remove residual aluminum after peeling. The morphologies of surfaces of steel after caustic wash were displayed in Fig.10. There were no distinct cracks on steel surface where the reduction is less than 25.6%, as shown in Fig.10 (a), (b) and (c), which had a close relationship with the results of fig.9. It was indicated that the residual aluminum on the surfaces of steel layer at a reduction less than 25.6% have no relationship with transverse cracks. Although cracks were increased significantly with the total reduction, there were no obvious sign of residual aluminum in the cracks, as shown in Fig.10 (d), (e) and (f). On the contrary, the ditches produced by steel brush existed in all reduction, and with reduction increased, the ditches were widened. In addition, there were some obvious signs appeared on surfaces of steel layer sample before alkali etched, as shown in Fig.10 (d), (e) and (f).
Figure 10. SEM images of steel sides of Al2St2 sample with different thickness reductions after caustic wash: (a) 1.7%; (b) 18.2%; (c) 25.6%; (d) 35.5%; (e) 39.8%; (f) 45.4%.

DISCUSSION

Fig.11 showed the interface morphologies of deformation zone of Al2St2 sample where thickness reduction is 45%. As can be seen, the interface morphology of transverse plane was relatively flat, and no obvious crack gaps were found between hardened surface layer and steel matrix which was different with related elaboration in Ref [2], as shown in Fig.11 (a). On the contrary, few mechanical locks were found on the interface, and the morphology of the interface was more undulated. Moreover, some aluminum bulges embedded in the steel matrix were observed, as shown in Fig.11 (b). It is the common sense that, surface mechanical preparation before CRB is an effective method to improve the bonding strength of bimetal composite sheet. Proper surface mechanical preparation can not only decrease the threshold reduction but also increase the bonding strength of the composite sheet [13]. Scratch brushing can not only cleans the metal surface but also forms a work hardened surface layer. During CRB, the hardened surface layer fractures, virgin metals exposed near the interface were extruded from the cracks to be contacted and bonded together. When new metal surfaces of two materials are in contact with each other and atoms of the two are close to each other, interatomic attraction acts[14]. Observed from Fig.9 to Fig.11, the effect of ditches generated
by steel brush on increase bonding strength of the aluminum/steel clad materials of CRB was more than transverse cracks growth along RD direction.

![Figure 11](image)

**Figure 11.** The interface morphologies of Al2S12 sample with different face (a) transverse plane; (b) rolling plane.

Fig.12 gave the schematic diagram for the CRB of the aluminum-steel clad sheet. Compared with transverse plane, there were some pre-ditches existed in the interface morphologies of rolling plane, as shown in Fig.12 (b). During CRB, with the reduction increased, the hardened steel surface layer generated by surface mechanical preparation was broken, meanwhile the transverse cracks occurred and expanded with reduction increasing. However, the crack gaps were too narrow and shallow to establish good bonding between aluminum and fresh steel matrix, as shown in Fig.12(c). By contrast, more soft aluminum were squeezed into the ditches, contacted and bonded with the virgin steel, which gave rise to the bimetal interface, as shown in Fig.12 (d).

![Figure 12](image)

**Figure 12.** Schematic diagram of cold roll bonding of 4A60/08Al composite sheet.

### 5. CONCLUSION

Aluminum clad steel sheets composed of different thickness sheets were developed by cold roll bonding method. The experimental work was conducted using rolling deformation zone of 4A60 aluminum alloy sheet/08Al steel sheet. The following were the results obtained:
The thickness reductions of the component layers were dissimilar while the reduction of aluminum layers was always larger than the reduction of steel layers.

The value of stable point of collaborative deformation of aluminum layer and steel layer decrease with the thickness of steel layer, and increase with the thickness of aluminum.

The deformation behaviors of aluminum layers and steel layers with different original thickness of same clad ratio were similar.

The critical reduction where residual aluminum and cracks first appeared increased with thickness of samples, respectively. Meanwhile, the residual aluminum was found at a smaller critical reduction than that of cracks.

The effect of ditches generated by steel brush on increase bonding strength of the aluminum/steel clad materials of CRB was larger than transverse cracks growth along RD direction.

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