Bonding strength of Al/Mg/Al alloy tri-metallic laminates fabricated by hot rolling

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Abstract. One of major drawbacks of magnesium alloy is its low corrosion resistance, which can be improved by using an aluminized coating. In this paper, 7075 Al/Mg–12Gd–3Y–0·5Zr/7075 Al laminated composites were produced by a hot roll bonding method. The rolling temperature was determined based on the flow stresses of Mg–12Gd–3Y–0·5Zr magnesium alloy and 7075 Al alloy at elevated temperature. The bonding strength of the laminate composites and their mechanism were studied. The effects of the reduction ratio (single pass), the rolling temperature, and the subsequent annealing on the bonding strength were also investigated. It was observed that the bonding strength increased rapidly with the reduction ratio and slightly with the rolling temperature. The bonding strength increases with the annealing time until the annealing time reaches 2 h and then decreases. The mechanical bond plays a major role in the bonding strength.

Keywords. Laminated composite; bonding strength; hot rolling; Al/Mg/Al.

1. Introduction

One of major drawbacks of magnesium alloy in many applications is its low corrosion resistance. If aluminium alloys and magnesium alloys were fabricated as an Al/Mg/Al trilaminated composite using aluminium alloys as protective layers, improvement of the corrosion resistance of the magnesium alloys can be expected. Liu *et al* (2008) have recently shown that corrosion resistance of pure magnesium could be improved by using aluminized coating.

Many magnesium based laminated composites have been developed using various techniques. Usually, the laminated composites are fabricated by the solid-state joining techniques, such as diffusion bonding (Zhao and Zhang 2008). Roll bonding, as a solid phase welding method of bonding same or dissimilar metals by roll deformation at room temperature or elevated temperature, also has been applied to fabricate laminated composites. Matsumoto *et al* (2005) fabricated an Al/Mg–Li alloy clad layer by a cold rolling method. Ueda *et al* (2005) investigated the synthesis and hydrogen storage properties of Mg-based laminated composites prepared by repetitive-rolling. Takeichi *et al* (2007) reported the hydrogen storage properties of Mg/Cu and Mg/Pd laminated composites prepared by repetitive-rolling. However, there are few reports on Al/Mg/Al laminated composites fabricated by hot rolling.

The objectives of this study are to fabricate an Al/Mg/Al alloy tri-metallic laminated composite material by a hot rolling method, and investigate the bonding strength and the bond interface of the laminated composite. The effects of the reduction ratio, the rolling temperature and succeeding annealing treatments on the bonding strength were also studied.

2. Material and methods

The materials used were as-rolled Mg–12Gd–3Y–0·5Zr (in wt.%) magnesium alloy and 7075 aluminium alloy (Al 87·1–91·4 wt.%, Cr0·18–0·280 wt.%, Cu 1·20–2·0 wt.%, Fe ≤ 0·50 wt.%, Mg 2·10–2·90 wt.%, Mn ≤ 0·30%, Si ≤ 0·40 wt.%, Ti ≤ 0·20 wt.%, Zn 5·10–6·10 wt.%, Other, each ≤ 0·050 wt.% and total ≤ 0·15 wt.%). The Mg alloy and the Al alloy were cut into rectangular pieces of 100 mm × 75 mm × 10 mm and 100 mm × 75 mm × 5 mm, respectively. The two components were cleaned and mechanically ground orderly using 240 and 600 grit SiC papers to remove the oxidation films and bring forth a rugged surface. Subsequently, drying treatment was performed for both components after rinsing in ethanol.

The roller diameter was 450 mm, and the rotational speed of the roller was 60 rpm. The laminated composites were prepared at three reduction ratios (single pass) of 30%, 40% and 50%.

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Flow stress curve is a basic tool to select the rolling parameters. To select the rolling temperature, hot compression tests were conducted on a Gleeble-1500D thermal simulator testing machine to gain flow stress curves of the experimental alloys at elevated temperatures. Specimens were heated to test temperature, kept for 5 min for temperature equilibration. The specimens were compressed at the temperature and strain rate ranges of 300°C–475°C and 0·01 s^{-1}–20 s^{-1} respectively. In each case, the specimens were compressed to half their original height.

The shape and dimension of the specimens for the measurement of bonding strength of the composites are illustrated in figure 1. Because the thicknesses of the specimens, the Al alloy layer and the Mg alloy layer varied with the reduction ratio, there was no dimension in the thickness. The bonding strength test was performed at room temperature using the SANS-CMT5105 tensile testing machine with an initial strain rate of 1×10^{-3} s^{-1}. The average bonding strength was taken as

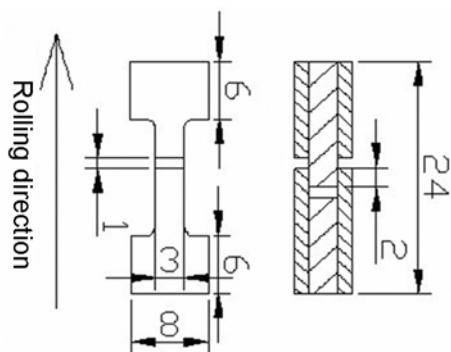Average bonding strength = peak load/
bond width × bond length.

Microstructure of the bond interfaces before and after the bonding strength test was observed by scanning electron microscopy (SEM) using a Philips Quanta200 instrument with an energy dispersive X-ray detector (EDX). The phase constitution near the interface was analyzed by means of XRD. Microstructure of the interface before and after annealing was examined by optical microscopy.

3. Results and discussion

3.1 *Typical flow stress of the experimental alloys*

Typical true stress–true strain curves of the experimental alloys are shown in figure 2. The flow stress decreased with deformation temperature and increased with strain rate. Uniform deformation is one of the primary require-

ments for the roll bonding. To ensure uniform deformation, the flow stress of Mg–12Gd–3Y–0·5Zr Mg alloys is required to be close to that of 7075Al alloy. Using Deform 2D software, the distribution of strain rate in the alloys plates was achieved. The strain rate of the plates approximated to 5 s^{-1}. The flow stress of Mg–12Gd–3Y–0·5Zr Mg alloy was near that of 7075Al alloy at the strain rate of 5 s^{-1}, as shown in figure 2c. In addition, the percentage elongation-to-failure of the experimental
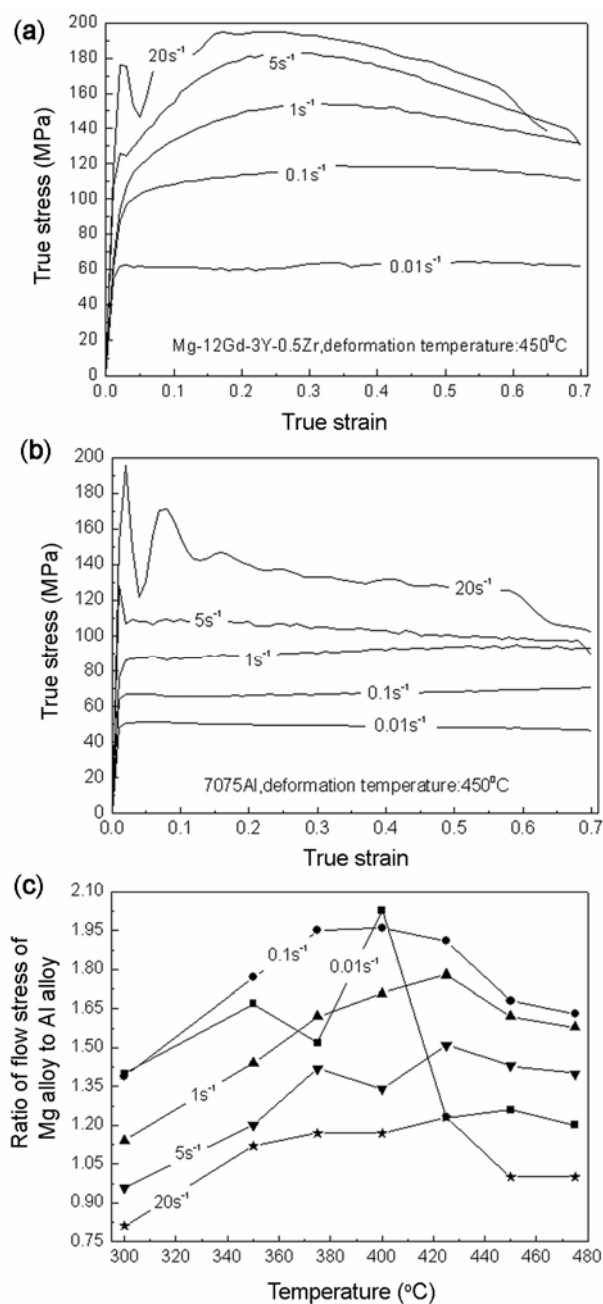
Figure 2. Typical flow stress curves of the experimental alloys and ratio of flow stress of the Mg alloy to the Al alloy: (**a**) Mg–12Gd–3Y–0·5Zr Mg alloy, (**b**) 7075 Al alloy, and (c) the ratio of the Mg alloy to the Al alloy.

Figure 1. A schematic view of the specimens for bonding strength test.

alloys increased with the deformation temperature. Because of the above mentioned reasons, the suitable rolling temperature of the experimentally laminated composite was in the range of 450–475°C. The rolling experiments were preformed at three temperatures of 450°C, 465°C and 475°C.

3.2 *Bonding strength and mechanism of bonding*

Figure 3 shows the Al/Mg/Al laminated composite fabricated by hot rolling at 465°C and reduction ratio of 50%. The laminated composite was about 10 mm in thickness, 450 mm in length and about 100 mm in width. A typical curve for the measurement of bonding strength is shown in figure 4. The shear stress necessary to separate the bond was about 40 MPa.

The bonding strength depended on the thermomechanical processing of the laminated composite. There are two types of solid-state bonding, i.e. diffusion bonding and mechanical bonding. A longer time is taken for diffusion bonding, and it involves the application of temperature and pressure (Chen *et al* 2007). Mechanical bonding occurs instantaneously or over a very short time and depends on the forces of attraction between the atoms (Mohsen and Mohammad 2010).

Figure 3. Appearances of Al/Mg/Al laminated composite fabricated by hot rolling.
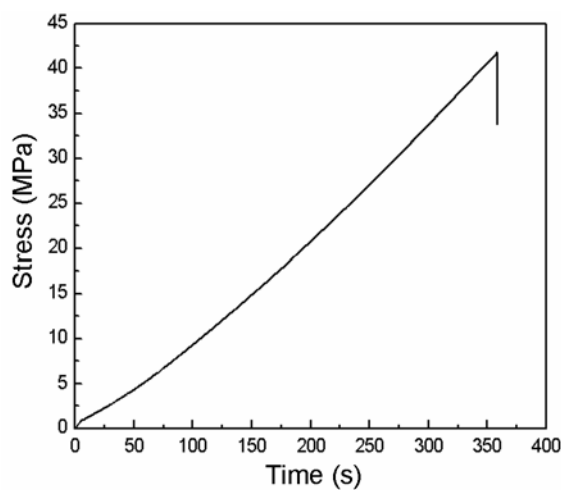
Figure 4. Typical bond strength curve of the experimental laminated composite obtained at room temperature.
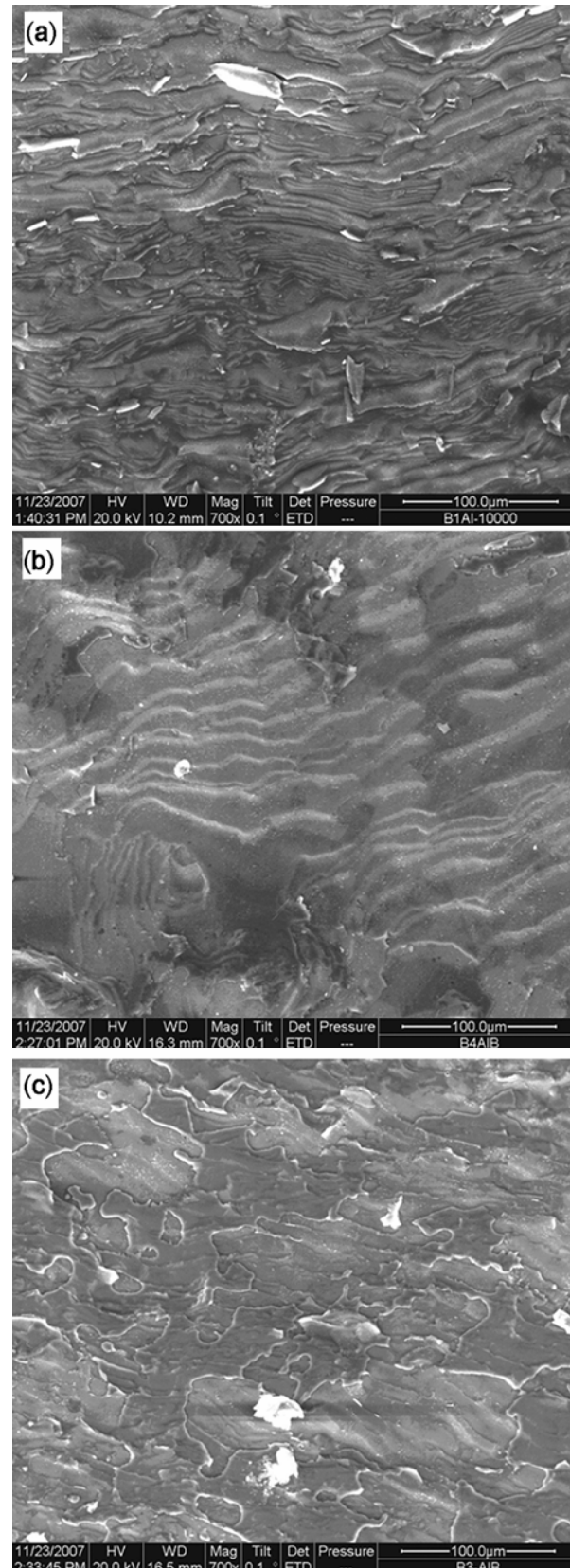

Figure 5. The separated surface of 7075 Al alloy at three reduction ratios: a) 50% (the bonding strength is 44 MPa), (**b**) 40% (the bonding strength is 20 MPa) and (**c**) 30% (the bonding strength is 9 MPa). Rolling temperature is 465°C.

It was believed that the mechanical bond played a major role in the bonding strength. The separated surface of 7075 aluminium alloy is shown in figure 5a. There were many significant permanent deformations of the asperity tops, giving rise to relatively large true areas of contact. The tendency of the separated surface of magnesium alloy was the similarity. As roll bonding started at a high temperature, elemental concentration gradients played a role in driving certain elements from the layers to the interfaces. However, the rolling time was too short to generate strong inter-diffusion. EDS line analysis, as shown in figure 6, revealed that the elemental distribution at the interfaces was not strictly steep, and occurred at a distance of about 4 μm, indicating the occurrence of physical mixing and/or atomic inter-diffusion at the Mg/Al interfaces.

3.3 *Effects of reduction ratio and rolling temperature on the bonding strength*

Typical effect of reduction ratio (single pass) on the bonding strength of the laminates is shown in figure 7,
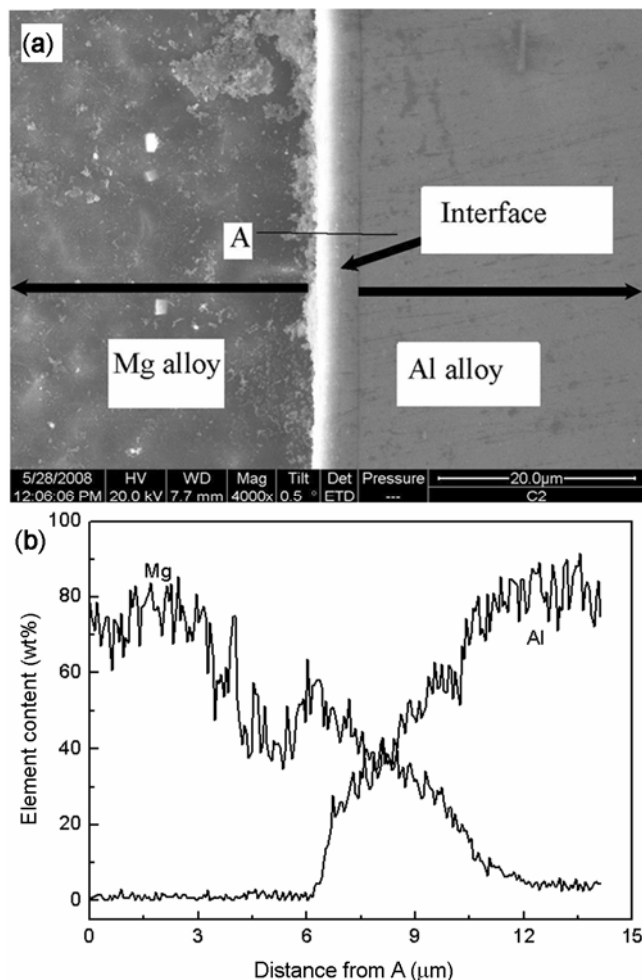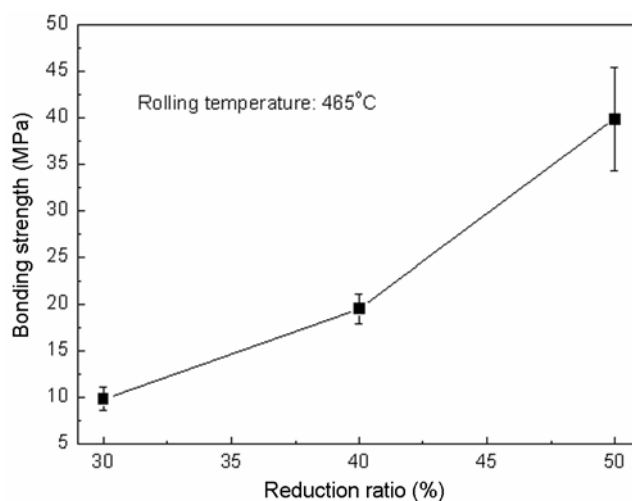

the bonding strength increased rapidly with the reduction ratio. When the reduction ratio was 30%, the bonding strength was only about 10 MPa. When the reduction ratio was 50%, the bonding strength was more than 40 MPa.

The separated surfaces of 7075 aluminium alloy after the bonding strength test at different reduction ratios are shown in figure 5. The difference as a function of the bonding strength was clearly observable. Figure 5a shows a maximal bonding strength, i.e. 44 MPa, which indicates significant permanent deformation of the asperity tops, giving rise to relatively large 'true' areas of contact, resulting in a large number of adhesive bonds. Figure 5b demonstrated average bonding strength, indicating similar behavior but the contact surfaces are smaller than those in figure 5a. The surface of the poorly bonded samples is shown in figure 5c demonstrating much lower roughness and a noticeably smaller 'true' area of contact. The appearance of the separate surface suggested little permanent deformation of the asperity peaks and that bonding only occurred at the top of the asperities. The tendency of the Mg alloy was similar.

The reduction ratio is one of the most important parameters affecting bond formation in hot rolling. According to the film theory mechanism in roll bonding (Bay 1986), the surface layers of the Al plate and the Mg plate were subjected to increasing normal pressure to deform in the rolling direction. Therefore, some cracks were produced in the surface layer of the plates. Then, the underlying metals were exposed through these cracks and virgin metal surfaces were extruded. In addition, the high normal roll pressure on the surfaces lead to cracking in the brittle surface layers, so that extrusion of these virgin metals was convenient for metal-to-metal and atom-to-atom bonding, thus metallic bonds were produced. Increase in the bonding strength on increasing the reduction

Figure 6. Elemental distributions across a Mg/Al interface of the laminated composite. (**a**) Interface of the Al plate and the Mg plate and (**b**) elemental distributions.

Figure 7. Typical effect of reduction ratio on bonding strength of the experimental laminates.

ratio was due to the increase of contact mean pressure and the overlapping surface exposure at the interface, as described by Danesh Manesh and Karimi Taheri (2005). Moreover, with increase in the reduction ratio, the number of cracks increase and therefore more virgin metal surfaces are exposed in the contact surfaces. Then the area available for atom-to-atom bond was extended, and accordingly the bonding strength between layers increased. Therefore, increased bonding strength as a result of increase in reduction ratio was due to the enhancement of the rolling pressure, increased surface area, area fraction of cracks, and weld area percentage (Mohsen and Mohammad 2010).

In general, enhancement of the rolling temperature increases the bonding strength. At higher rolling temperatures, the difficulty and the formability of virgin metals in

the underlying surfaces increase and enhances their extrusion through more cracks in the contact surfaces (Mohsen and Mohammad 2010).

As shown in figure 8, the effect of the rolling temperature (ranging from 450–475°C) on the bonding strength of the experimental laminates was very slight due to the narrow temperature ranges.

3.4 *Effect of the succeeding annealing treatment on the bonding strength*
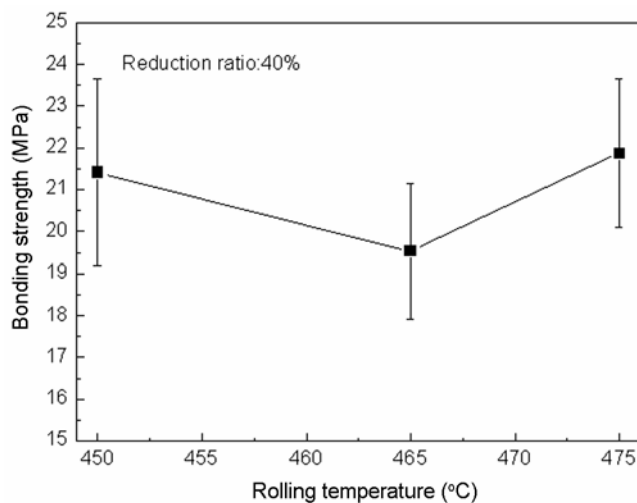
Figure 9 indicates that the annealing time affects the bonding strength of the laminated composite. The bonding strength increased with the annealing time until the annealing time reached 2h and thereafter decreased. This may be the result of appearance of Al_3Mg_2 precipitates, confirmed by XRD later.

The interfaces of the plates varied with the annealing time are shown in figure 10. The interface expands with the annealing time related to the atomic diffusion phenomenon at the interface. The XRD results of the interface are shown in figure 11. It is clear that Al_3Mg_2 phase formed at the interface of Al and Mg alloy plates, and the content of the Al_3Mg_2 phase increased with the annealing time. As a brittle phase, the effect of the Al_3Mg_2 on the bonding strength was like that of Fe_3C phase on the strength of ferrous alloy. When the content of Al_3Mg_2 phase was at a lower level, the Al_3Mg_2 phase could be considered as a reinforced phase, the bonding strength increased with the content of Al_3Mg_2 phase, as reported by Li *et al* (2008). However, when the content of Al_3Mg_2 phase reached a higher level, the brittleness of the Al_3Mg_2 phase decreased the bonding strength because multiple cracking was initiated in Al_3Mg_2 during a tensile test and subsequently a main crack propagates throughout the fragmented Al_3Mg_2, not along the interfaces, thereby leading to macroscopic deboning, as reported by Matsumoto *et al* (2005). In this paper, the preferable annealing time was 2h with annealing temperature of 350°C.

4. Conclusions

An Al/Mg/Al alloy tri-metallic laminate composite material was fabricated by hot rolling. Based on the flow stresses of Mg–12Gd–3Y–0·5Zr magnesium alloy and 7075 Al alloy at elevated temperature, the suitable rolling temperature of the experimentally laminated composite is in the range of 450–475°C for uniform deformation.

The bonding strength of the laminate composite depends mainly on the reduction ratio and annealing time, and slightly on the rolling temperature. The bonding strength increased rapidly with the reduction ratio due to the enhancement of the rolling pressure, increased surface area, area fraction of cracks, and weld area percentage.
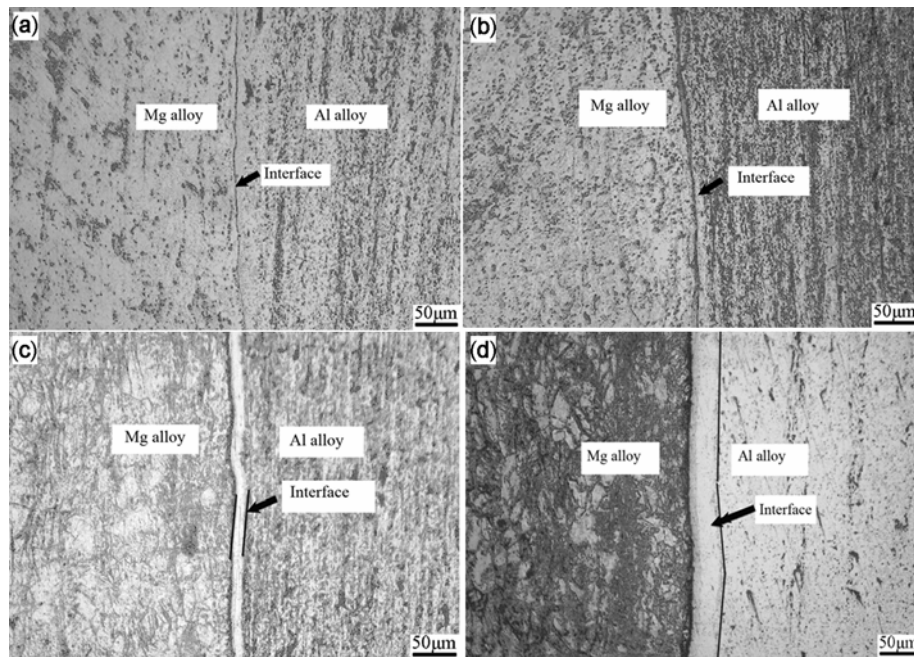
Figure 8. Typical variations in bonding strength of the experimental laminates versus rolling temperature.
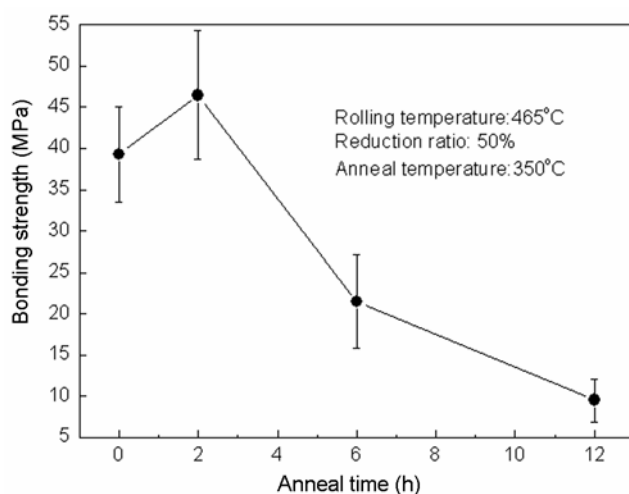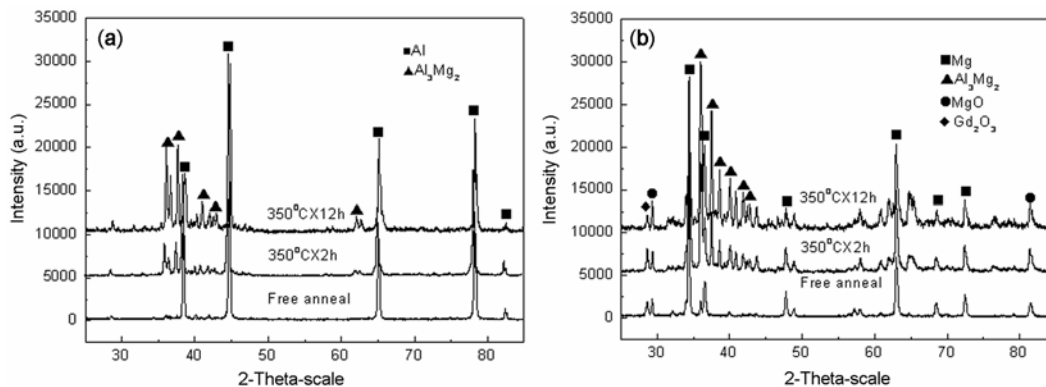
Figure 9. Bonding strength of the laminated composite vs. the annealing time.

Figure 10. Effects of annealing on the interface of the Al plate and the Mg plate: (**a**) original, (**b**) 350°C + 1 h, (**c**) 300°C + 2 h and (**d**) 350°C + 12 h.

Figure 11. XRD results of the interface of (**a**) the Al alloy plate and (**b**) the Mg alloy plate.

With increase of the annealing time, the bonding strength increases until the annealing time reaches 2h and thereafter decreases. This may be due to the appearance of Al_3Mg_2 precipitates. The mechanical bond plays a major role in the bonding strength.

Acknowledgements

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