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ARTICLE

Effect of Intermetallic Compounds on the Fracture Behavior of Mg/Al Laminated Composite Fabricated by Accumulative Roll Bonding

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Abstract: We observed massive cracked intermetallic compounds at the interface of the laminated Mg/Al composite fabricated by accumulative roll bonding and investigated the effect of the compounds on the fracture process of the Mg/Al composite. Scanning electron microscopy observation reveals that these cracked intermetallic compounds dominate the fracture behavior of the accumulative roll bonded Mg/Al composite during uniaxial tensile testing. The results indicate that obvious Mg/Al interface delamination is promoted by the cracked intermetallic compounds, and the cracks propagate into the softer Mg layer and lead to the rupture of Mg layer. These two factors result in the premature failure of the laminated Mg/Al composite.

Key words: accumulative roll bonding; Mg/Al laminated composite; intermetallic compounds; crack; tensile test; fracture

Multilayered metal composites or laminates consisting of alternately packed layers of different metals or alloys have shown many unique properties combining the ones of the constituent materials, such as fracture toughness, fatigue behavior, impact behavior, wear and corrosion [1]. The multi-layered composites of bimetal systems [2-4] can be fabricated by accumulative roll bonding (ARB) which consists of multiple cycles of rolling, cutting, stacking and solid-state deformation bonding. The advantage of producing multilayered composites through ARB is that the composites can be refined to ultra-fine grained (UFG) microstructure without any geometrical changes. Foremost ARB is easy to carry out and has a good prospect for commercialization [5-7].

Nowadays, clad rolling and ARB were employed to prepare the Mg/Al clad plate and multilayered composite to improve the corrosion resistance and the mechanical properties of Mg sheet[8-10]. Properties of the multilayered composite are significantly influenced by bonding quality [11-13]. However, there are few reports on mechanical properties of the ARB-processed multilayered composite correlating with the bonding quality. In our previous work, the intermetallic compounds were observed appearing at the Mg/Al interface of the ARBed Mg/Al composite, which were verified to be an important factor affecting the tensile property[14]. Effect of these intermetallic compounds on the fracture behavior was still not investigated in detail. The present work is a following research designed to record the fracture history of this kind of ARBed Mg/Al composite during a uniaxial test and to reveal the effect of intermetallic compounds on mechanical properties.

1 Experiment

In this study, a laminated Mg/Al composite (containing 17 layers) was fabricated by ARB processing at 400 ℃ for 3 cycles using the commercial pure magnesium (99.8 wt %) and Al 5052 alloy sheets. The detailed ARB processing and the global microstructure of the laminated sheet were shown in Ref. [14]. A dog-bone shape tensile sample was machined along the rolling direction from the sheet ARBed for 3 cycles and then annealed at 150 ℃ for 10 min to release residual

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stress. The gauge dimension of the tensile samples was 10 mm×6 mm×1 mm. Prior to the tensile test, the longitudinal plane of the tensile sample was mechanically ground and polished carefully on the abrasive papers of grit size 1000, 2000 and 4000. Then the starting microstructure on the longitudinal plane was observed by HITACHI S3000 scanning electron microscopy (SEM) with EDS. After that, the uniaxial tensile test was carried out on the Instron5569 testing machine at ambient temperature with a ram speed of 1 mm/min. In order to record the facture history of this ARBed Mg/Al laminates, tensile loading was stopped and released at three strain levels after obvious yield during the tensile test. The test was stopped for the first time after obvious yielding (Recorded as Level 1). The last temporary stop was designed to ~0.5% ahead of failure (Recorded as Level 3) while the second was in the middle of Levels 1 and 3 (Recorded as Level 2). The elongation and yielding point were obtained from the continuous tensile test. At each strain level, the tensile sample was removed from the testing machine and one same area on the polished longitudinal plane around necking was observed by SEM. After observation, the tensile test was re-conducted on this sample till next strain level. At last, the fracture profile of the specimen after failure was also examined by SEM.

2 Results and Discussion

The stepped engineering stress-strain curves are plotted in Fig.1. The composite shows a very limited elongation, which is similar to our previous work [14]. Fig.2 displays the SEM microstructure of the longitudinal plane of the specimen before the tensile test. A large number of massive intermetallic compound particles (indicated by the black arrows) with obvious cracks are observed at the Mg/Al interface. The particle was characterized by EDS line analysis (Fig.3) and identified as Al_3Mg_2 at the side of Al layer and $Mg_{17}Al_{12}$ next to the Mg layer. The similar results were reported in Chen's work [10]. The particles formed between layers are thought to be due to the large rolling strain and the high temperature [15], which accelerate the diffusion at the Mg/Al interface. These intermetallic compounds nucleate and grow rapidly during

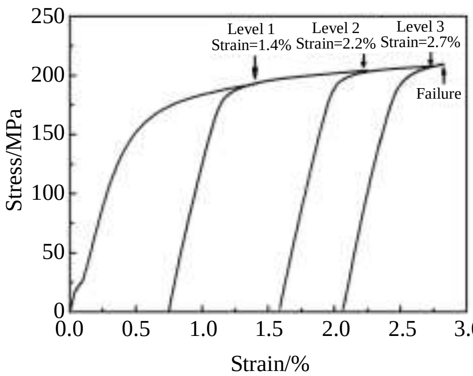

Fig.1 Stepped engineering stress-strain curves of the uniaxial tensile test

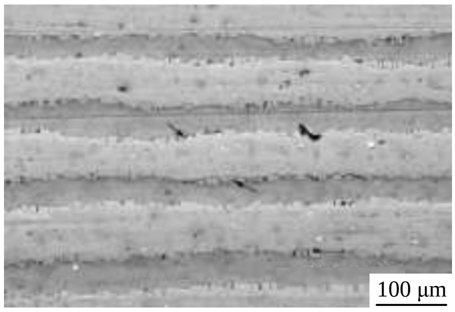

Fig.2 SEM microstructure on the longitudinal plane of the tensile sample before tensile test

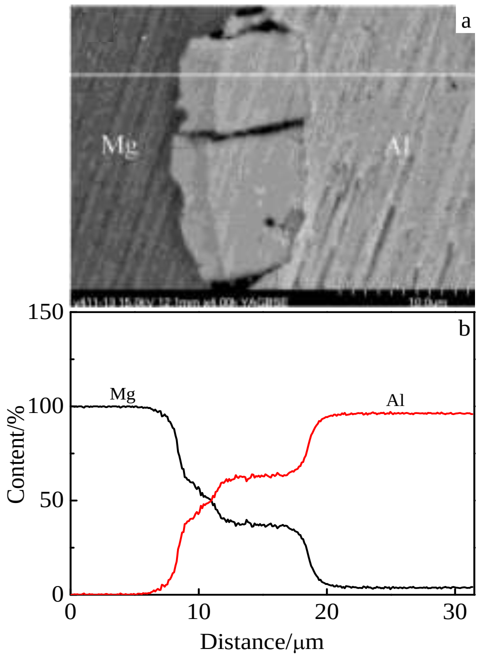

Fig.3 SEM image of an intermetallic compound (a) and EDS line analysis along the intermetallic compound (b)

pre-heating in initial circles of ARB. Then the coarsened particles fracture during the following circles of ARB.

The detailed tensile fracture behavior of the ARBed Mg/Al composite is presented in Fig.4. At strain level 1, an obvious crack is observed along the Mg/Al interface, possibly because of the linkage of cracks in neighbouring intermetallic compounds (see Fig.4a and 4d). This interface crack has not propagated into the intermetallic compounds "1" and "2" which are located ahead of the interface crack-tip at this strain level (Fig.4g). It is worth noting that some incipient crack points marked by the black arrows in Fig.4d are observed in the Mg layer, at the region close to the crack opening of the intermetallic compounds. Above observations show that the pre-existing cracks of the intermetallic compounds cause a crack initiation in the Mg layer at this strain level. On further straining from stain level 1 to strain level 2, the newly introduced micro-cracks locating at the edge of the Mg layer

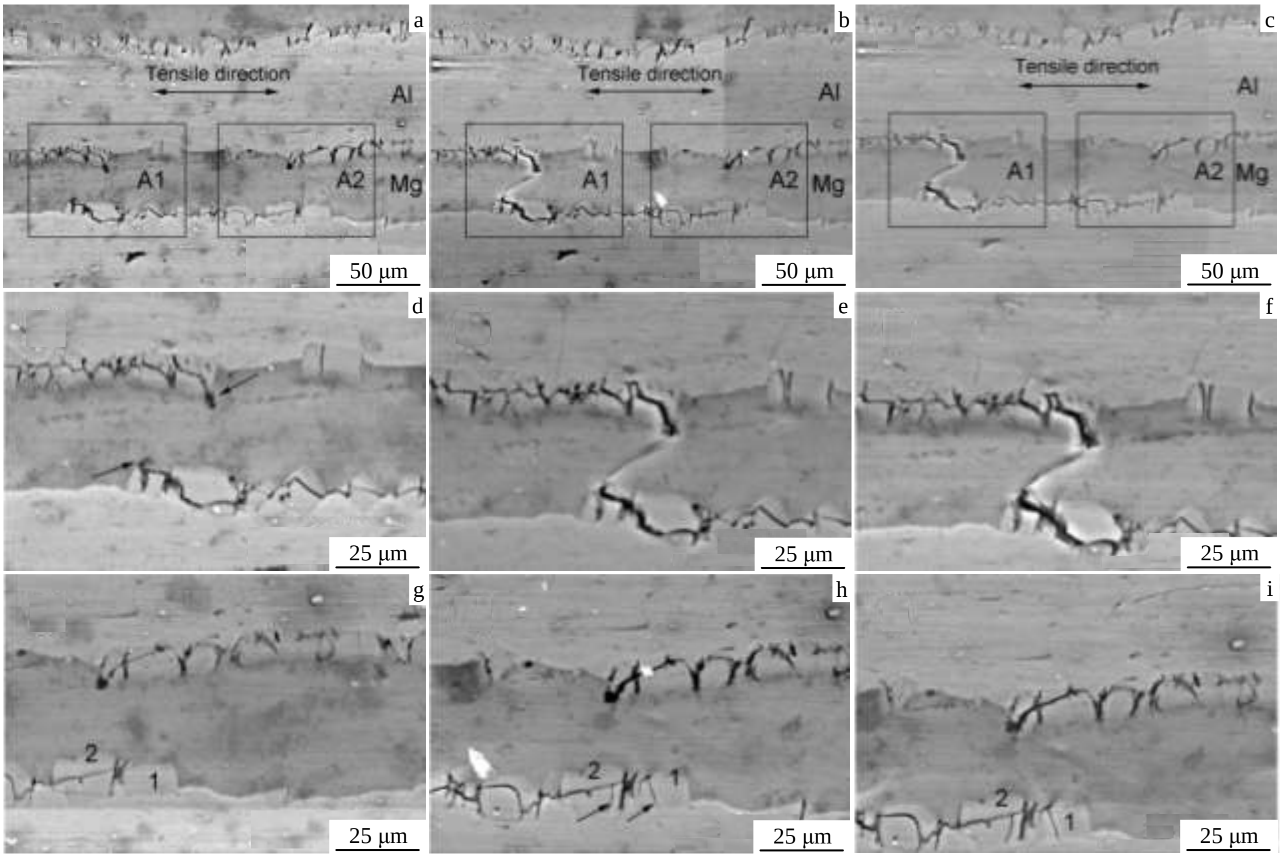

Fig.4 SEM microstructures of the selected observation area at different strain levels: (a) level 1, (b) level 2, and (c) level 3; (d, e, f) and (g, h, i): enlarged regions "A1" and "A2" in Fig.4a~Fig.4c, respectively

have been propagated into the center of Mg layer and a severe local 45° shear deformation could be observed at strain level 2, as shown in Fig.4e. Simultaneously, new cracks, pointed out by the black arrows in Fig.4h, occur on both intermetallic compounds "1" and "2". As similar as Matsumoto's work [8], the interface crack could readily propagate in the intermetallic compounds and finally to an interface delamination. With strain increasing up to strain level 3, crack width of the Mg layer keeps increasing and the Mg layer is completely ruptured, which are shown in Fig.4f. Accordingly, the sample shows a very limited strain increment and fails in a sudden manner after strain level 3, as shown in Fig.1.

Fig.5 shows a SEM image taken at the area close to the fracture. Many cracks in Mg layers and Mg/Al interface delamination are observed in this area near the main fracture. Thus, one can conclude that a number of ruptures in Mg layers and interface delaminations take place simultaneously at different locations in the sample during initial straining. Then some of them propagate together and cause the sudden failure of the sample. Fig.6 presents the fracture profile of the tensile sample along the transverse direction after the tensile test. A clearer crack could be observed along the Mg/Al interface. It is evident that the intermetallic compounds do also affect the fracture behavior of the Mg/Al laminated composite along the transverse direction, which as same as that along the rolling direction.

Moreover, it is interesting that the slope in the first curve for strain level 1 is different from the slope for the other strain levels, as shown in Fig.1. According to the present work, one possible explanation for this behavior could be proposed as: the delamination of Mg/Al interface occurs after the global yielding (or at the strain level 1). This might result from cracked intermetallic compounds and different deformation properties of Mg and Al layer. When loading further, the Al layer mainly endures loading while the Mg layer yields. Thus, the slope for the following strain level is steeper than the slope of the

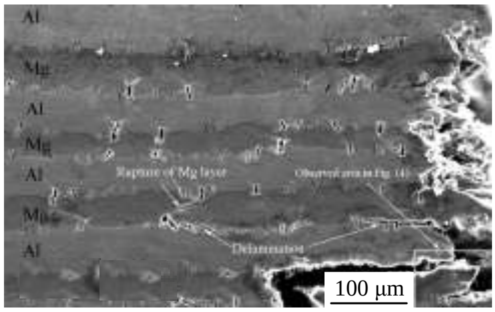

Fig.5 Fracture profile of the tensile specimen after failure

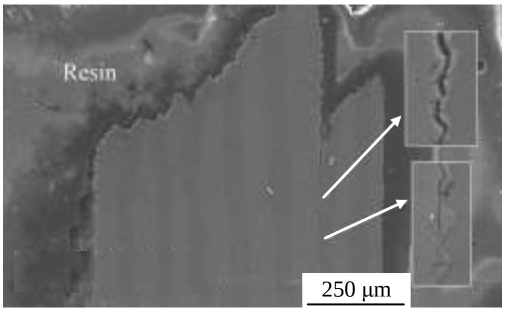

Fig.6 Fracture profile of the tensile specimen along the transverse direction after failure

first curve due to the high modulus of Al. However, this immature assumption needs further proofs.

To sum up, the fracture behavior of the ARBed Mg/Al laminated composite during the tensile test is described as: (a) An interface crack forms along the Mg/Al interface due to linkage of the existed cracks in intermetallic compounds. Then the pre-existing crack of intermetallic compounds starts to propagate into the pure Mg layer. (b) The delamination occurs due to the propagating of the interface crack along the Mg/Al interface and the pure Mg layer ruptures because of the local shear deformation introduced by cracking. (c) A sudden failure eventually appears in the laminated composite due to the non-uniform deformation introduced by the Mg/Al interface delamination and the rupture of the Mg layer.

3 Conclusion

The Mg/Al interface delamination and the premature rupture of the Mg layer which mainly results from the existed cracks of the intermetallic compounds lead to the sudden failure of the laminated Mg/Al composite.

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金属间化合物对累积叠轧 Mg/Al 多层复合板材断裂过程的影响

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摘　要：采用分步拉伸观测的方法研究了累积叠轧 Mg/Al 多层复合板材中界面金属间化合物对复合板材断裂过程的影响。结果表明：在单向拉伸过程中，Mg/Al 界面处金属间化合物导致了裂纹的萌生和扩展，从而导致 Mg/Al 界面的分离；在后续拉伸过程中，由于 Mg 层强度较低，首先产生颈缩失效，致使整个样品提前断裂。

关键词：累积叠轧；Mg/Al 多层复合板材；金属间化合物；裂纹；拉伸试验；断裂

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