J. Cent. South Univ. (2024) 31: 369−383
DOI: https://doi.org/10.1007/s11771-023-5524-0

Springer

Optimization mechanism of matrix microstructure evolution on strength-plasticity of Mg/Al composite plate during hard-plate accumulative roll bonding

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Abstract: Mg/Al composite plate combines the light weight of Mg alloy and the plasticity and corrosion resistance of Al alloy, which significantly enhances its comprehensive performance. However, the long manufacturing cycle and high process requirements limit the rapid development of heterogeneous composite plate forming technology. Therefore, a new method of ARB (accumulative roll bonding) forming with hard plates is proposed in this paper. The results show that the tensile strength of Mg/Al composite plate can reach 235 MPa and the elongation is 14.7% at 3ARB. There are obvious dimples in the magnesium plate, which are ductile fracture characteristics, and the overall performance is the highest. Since the basal slip and non-basal slip of the Mg plate start at the same time, which promotes the formation of dynamic recrystallization. At this time, the recrystallization ratio of the Mg plate is 77.21%. With the progress of ARB, the high angle grain boundary increases and the grain refinement is obvious. The original grains have been basically broken and refined into equiaxed grains. The hardness fluctuation of Mg and Al matrix decreases gradually, and the internal structure of the composite plate tends to be stable. This provides a new idea for forming and manufacturing high-performance heterogeneous composite plates.

Key words: hard-plate accumulative roll bonding; Mg/Al composite plate; recrystallization; grain refinement; strength and plasticity

Cite this article as: ZHANG An-xin, LI Feng, NIU Wen-tao, GAO Rong-he, SUN Lu. Optimization mechanism of matrix microstructure evolution on strength-plasticity of Mg/Al composite plate during hard-plate accumulative roll bonding [J]. Journal of Central South University, 2024, 31(2): 369−383. DOI: https://doi.org/10.1007/s11771-023-5524-0.

1 Introduction

Energy conservation and emissions reduction are an effective means of achieving the national carbon policy goal, that is more consistent with the concept of green sustainability in manufacturing. Its importance is clear. The consumption of light alloys represented by Mg and Al has increased sharply in recent years [1 − 2], and has been applied in transportation, weaponry, electronic communication and other fields [3 − 5]. Taking Mg alloy as an

Foundation item: Project(JQ2022E004) supported by the Natural Science Foundation of Heilongjiang Province, China
Received date: 2023-07-22; **Accepted date:** 2023-09-12
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example, its forming performance and low corrosion resistance have been the bottleneck restricting its development [6]. If Mg and Al metals are combined [7 − 9], not only the corrosion resistance can be improved, but also the ductility of Mg alloy plate can be significantly improved by the introduction of Al alloy. At present, the forming methods of Mg/Al composite plate are extrusion [10], explosive welding [11], rolling [12] and so on.

WU et al [13] fabricated Mg/Al composite plate by using porthole die co-extrusion (PCE) technology. The relationship between the strength and volume fraction of the composite plate and the Mg and Al layers was studied. It was found that when the volume fraction of Al was 40.2%, the yield strength of the composite plate was greatly improved, and the weight was only increased by 19.8%. XIN et al [14] successfully formed Mg/Al multilayer composite plates with good bonding by co-extrusion (PCE). The results show that extrusion at 400 ℃ can make the grains of the matrix Mg layer more uniform, but can not further refine the grains. The yield strength of the composite plate does not increase, and the elongation is significantly improved. However, this method cannot carry out continuous large-scale production and requires a large power extruder.

CHEN et al [15] formed Mg/Al composite plate by explosive welding (EXW). It is found that the thickness of the interface diffusion layer increases with the increase of annealing temperature and holding time, while the mechanical properties are inversely proportional to it. The mechanical properties are the best when annealed at 200 ℃ for 2 h. FRONCZEK et al [16] used EXW to successfully form Al/Mg/Al composite plates. The results show that after annealing at 350 ℃ for 10 h, the $Mg_{23}Al_{30}$ phase is effectively promoted to form a discontinuous layer in the $Mg_{17}Al_{12}$ and Mg_2Al_3 phases, but the use of explosives during explosive welding will cause severe vibration and is easy to cause pollution.

NIE et al [17] hot rolled Al/Mg/Al composite plate with 48% reduction at 400 ℃ and annealed it. The results show that brittle intermetallic compounds appear when the annealing temperature exceeds 300 ℃, and the composite plate annealed at 200 ℃ for 1−4 h has better mechanical properties. CHANG et al [18] prepared Mg/Al composite plates at room temperature by accumulative roll bonding (ARB). The results show that with the increase of rolling passes, the grains of Al layer are continuously refined, while the grains of Mg layer are only homogenized and no longer refined after the first ARB refinement. The metal compounds at the interface show that the Mg/Al interface can also be metallurgically bonded at room temperature. The tensile strength of the composite plate increases significantly with the pass, and the interface bonding strength also increases, but the elongation decreases gradually.

By comparison, the ARB process has a low cost of production and is easy to use, which is one of the important ways to form and manufacture heterogeneous composite sheets, and due to severe plastic deformation [19 − 21], an ultrafine-grained lightweight composite plate can be prepared [22 − 23], but excessive deformation of ARB will make the composite plate strength increase and the plasticity decrease [24−25]. The shear stress of the composite plate can be reduced by adding hard plate during the ARB process, which greatly suppresses the edge crack phenomenon [26−27], improves the bonding strength and forming performance of the rolled composite sheet, and compensates for the defects of the traditional ARB process. It is difficult to optimize the matching of strength and plasticity in traditional ARB of heterogeneous composite plates [28 − 29]. It has been reported that the stress state, the state of interface contact and the law of co-ordination of deformation of the composite plate following the addition of the hard plate in the ARB process will change, which will have an important influence on the matrix grain morphology, interface structure, texture configuration and recrystallization behavior of composite plate, thus affecting the mechanical properties, interface bonding strength and processing capacity of rolling composite plate [30−31]. Inspired by this idea, this paper will focus on the study of Mg/Al metal multi-layer composite plate with excellent interface bonding ability and mechanical properties formed by hard plate accumulative roll bonding (HARB) process under the condition of adding hard plate.

2 Experimental

2.1 Process principle

Figure 1 shows the process flow of this experiment, it can be seen that the hard-plate ARB needs to be stacking, positioning, preheating, roll bonding, cutting, and the process of stacking to cutting is repeated. As shown in Figure 1(a)), the surface-treated Mg plate, Al plate and upper and lower lining plates are initially stacked, and the front end is fixed. After rolling, a composite plate with a thickness of about 1 mm is obtained. After proper correction, the plate is cut into two parts of the same size and shape along the middle, which are superimposed together, as shown in Figure 1(b)). Add hard plate to the upper and lower ends of the composite plate and repeat this process after fixation. A total of four passes of ARB were performed to finally prepare a multi-layer composite plate.

2.2 Research scheme

The research materials are as-rolled AZ31B plate (thickness t_1=1.5 mm) and AA1060 plate (thickness t_2=0.5 mm). The chemical composition is shown in Table 1, and the hard plate used is ASTM304 (thickness t_3=1 mm).

The AZ31B alloy plate and AA1060 alloy plate were cut into slabs with an initial size of 100 mm×60 mm. Before rolling, the slab needs to be polished with sandpaper to expose the fresh surface. After degreasing the surface with acetone solution, it is placed in alcohol solution for cleaning. In order to prevent the adhesion between the hard plate and the composite plate during the rolling process, it is necessary to spray a layer of high temperature isolation agent (boron nitride) on the inner surface of the lining plate and stack it in the above order. In order to prevent relative sliding between the initial slabs, it is pre-fixed with a thin wire. The heterogeneous composite slab was heated in the furnace at 350 ℃ for 20 min and then rolled. The single pass reduction was taken as h=50%, and air cooled to room temperature. The rolled Mg/Al clad plate (1ARB) was degreased and polished. After cleaning, it was cut into two halves and fixed together on average. Attention should be paid to the order in which the Mg layer is connected to the Al. After heat treatment, rolling is carried out with a reduction of 50%. This process is called an ARB cycle and needs to be repeated three times (2ARB, 3ARB, 4ARB). The experimental equipment is a two-roll mill, the model is PTM30, the machine tonnage is 6000 kg, and the speed is 6 rad/s.

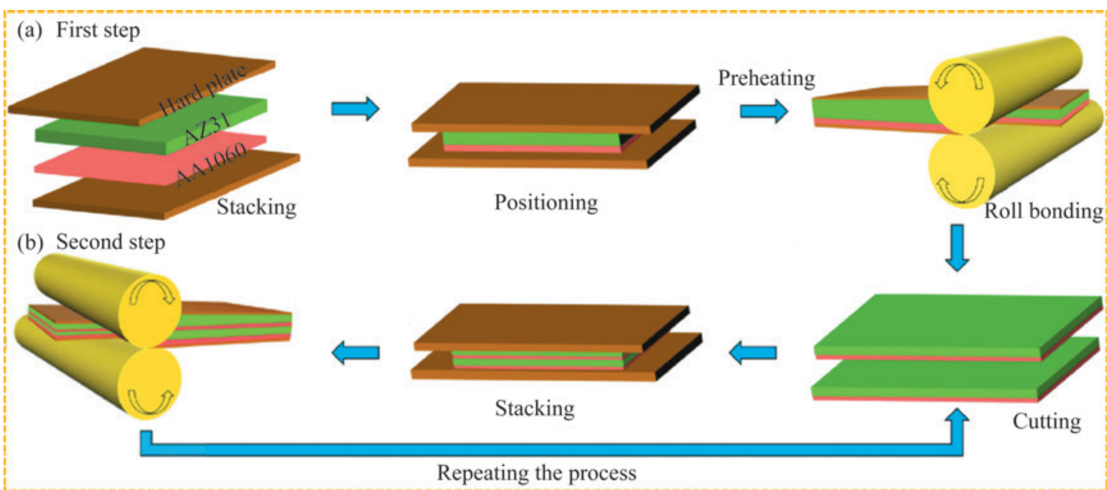

Figure 1 Process principle of hard-plate accumulative roll bonding composite plate: (a) Preparation of Mg/Al primary sandwich; (b) ARB procedure

Table 1 Compositions of AZ31B magnesium alloy and AA1060 aluminum alloy wt%

Material	Mg	Al	Mn	Cu	Fe	Zn	Ca
AZ31B	95.45	3.9	0.334	0.05	0.005	0.81	0.04
AA1060	0.03	99.6	0.03	0.05	0.35	0.05	---

2.3 Microstructure characterization

The optical microscope (OM) and electron backscatter detection (EBSD) were used to observe the metallographic structure of the matrix Mg. The interface morphology of the Mg/Al multilayer composite plate was characterized by scanning electron microscope (SEM). The scanning voltage was 20 kV, and the interface element distribution of the Mg/Al multilayer composite plate was analyzed by energy dispersive spectrometer (EDS). The size of the EBSD sample is 3 mm×5 mm×1 mm, and the sandpapers are used for grinding, and then the mechanical polishing is carried out to obtain the surface without scratches. Finally, electrolytic polishing is used, and the electrolytic polishing liquid is a mixed liquid of phosphoric acid and ethanol. X'Pert PRO diffractometer (XRD) was used to analyze the interface phase composition of Mg/Al multilayer composite sheet. The copper target K_{α} radiation was selected as the test target, the scanning range was set to 20°−80°, and the scanning speed was 0.03(°)/s.

2.4 Mechanical characterization

In order to evaluate the mechanical properties of the laminated Mg/Al composite plate, the samples were cut along the rolling direction on the formed plate. The tensile test used plate-like samples. The thickness of the sample was the same as that of the composite plate. The size was 10 mm× 70 mm. The tensile test was carried out on the universal testing machine at a loading speed of 1 mm/min. The average value of multiple experiments was taken to ensure accuracy. The preparation position and size of the tension samples are shown in Figure 5. In order to explore the change of hardness at the Mg/Al bonding interface of the composite plate, the HVS-1000A digital Vickers hardness tester was used to measure the sample. The loading load was 25 g and the holding time was 15 s.

3 Results

3.1 Macroscopic morphology of AZ31 and Al1060 layer after ARB processing

After ARB with additional hard plates, the change in the morphology of the interlayer interface will inevitably have a significant impact on the global performance of subsequent heterogeneous composite plates [32 − 33]. Consequently, the interface morphology of the SEM of the Mg/Al composite plates with different ARB cycles is analyzed, as shown in Figure 2.

It can be seen from the diagram that within a certain range, the number of composite plate interface layers increases with increasing loading cycles and accumulation of rolling deformation, the thickness of the Mg and Al layers is gradually decreasing, but there are no holes, separation and cracking at every cycle, and the interface between the layers is better. When condition 1ARB is depicted in Figure 2(a)), the interface between the layers of the Mg/Al composite plate is tight and straight, stating that the interface between the layers of the composite plate is better in this situation; with the increase in the number of ARB cycles, as shown in Figures 2(b) and (c)), the number of Mg and Al layers gradually increases and the strain increases, but the interface between the layers remains good continuity and relatively straight, indicating good uniformity and coordination of the overall deformation; When the number of layers is further increased to 4ARB, the cumulative strain of the composite plate has reached 93.8 %, resulting in a discontinued distribution of the Mg layer in the ND direction, as shown in Figure 2(d)). Although the Al layer can maintain a certain continuity, it emerges from the thickness distribution of the layer that it is an irregular form, meaning that the uniformity of deformation between the layers becomes worse.

In general, for Mg, Al dissimilar metals were rolled by ARB, because of the two types of plastic metal deformation, thickness, hardness and other kinds of difference. When the accumulated deformation of the Mg and Al layers increases, the inhomogeneity of the deformation between the two is aggravated. The unstable parts of the two metal interfaces will cause necking and fracture of the hard phase. Through comparison, it can be seen that the ARB cycle should be controlled within a certain range, otherwise, excessive cumulative deformation will aggravate the stress state and inhomogeneity of the deformation of each layer plate and will degrade the overall performance of the heterogeneous composite plate.

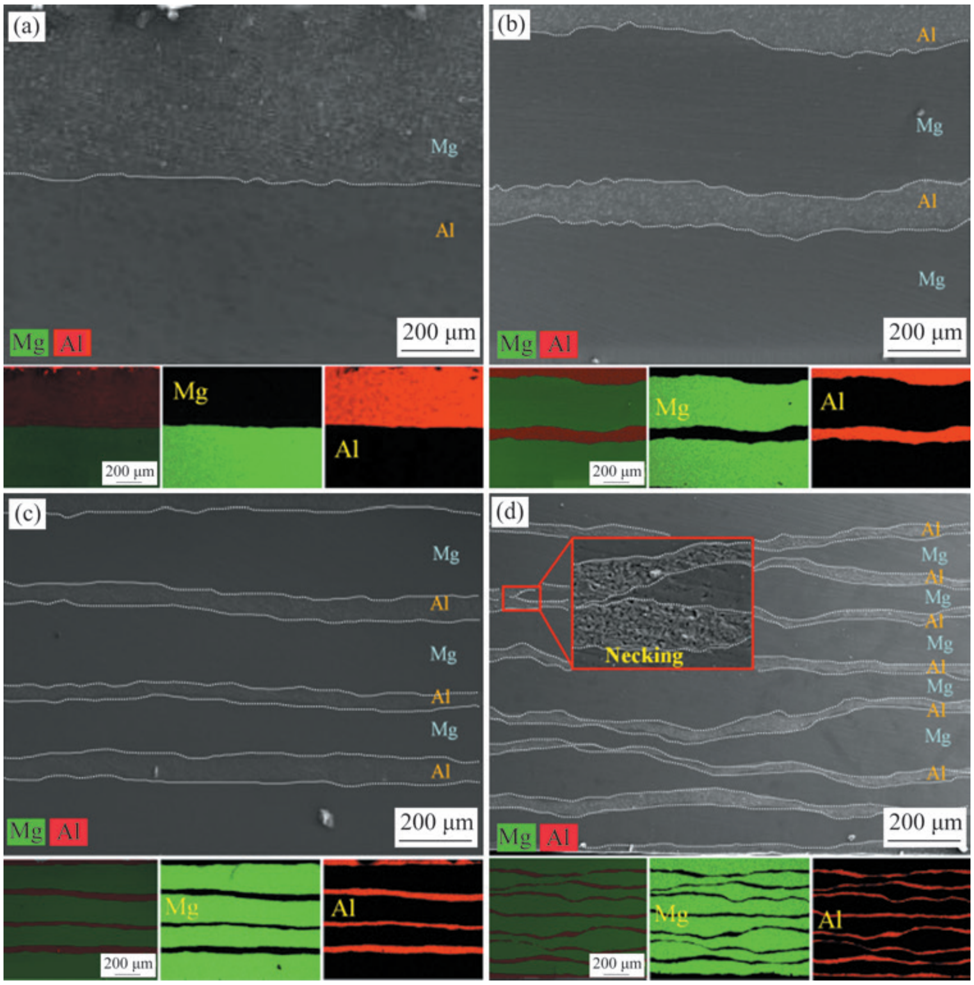

Figure 2 SEM micrographs of Mg/Al laminated composite on the RD-ND plane after ARB processing: (a) 1ARB; (b) 2ARB; (c) 3ARB; (d) 4ARB

3.2 EDS of Mg/Al composite

The characteristic of the ARB process is that the number of interlayer bonding interfaces increases with the increase of cycles, which significantly influences the phase structure, such as the element diffusion rate and the interface structure. The line scan analysis of the interface metal compounds of Mg/Al composite plates after different cycles is shown in Figure 3.

In the state of 1ARB, the EDS line scan curve at the composite plate linkage interface shows a “X” shape, as shown in Figure 3(e)), indicating that the atoms of Mg and Al have a certain degree of diffusion in the ARB process in a short time, but this is not apparent. The marked decrease in Mg and Al content at the interface indicates that no obvious intermetallic compounds are produced, and the thickness of the diffusion layer is approximately 2.91 μm. This is due to the fact that preheat before rolling intensifies the movement of some Mg and Al atoms, and that the solid solution is formed by mutual penetration during rolling. With the increase in the number of ARB cycles, the thickness of the interface diffusion layer changes, as shown in Figures 3(f) − (h)), and the diffusion layer is significantly thickened at 2 ARB, about 6.13 μm; As the cycles increased, the diffusion layers of 3ARB and 4ARB reached 12.14 and 12.30 μm, respectively. Figure 3(i)) is the comparison of the thickness of the diffusion layer at each interface. The existing diffusion layer can be seen to be significantly thicker than the newly formed interface during the ARB process. For the existing Mg/Al interface, the metals which come into contact and diffuse with each other at the beginning of the composite plate are prolonged to obtain a solid contact of great surface and a metallurgical bond. At the same time, preheating prior to each ARB also

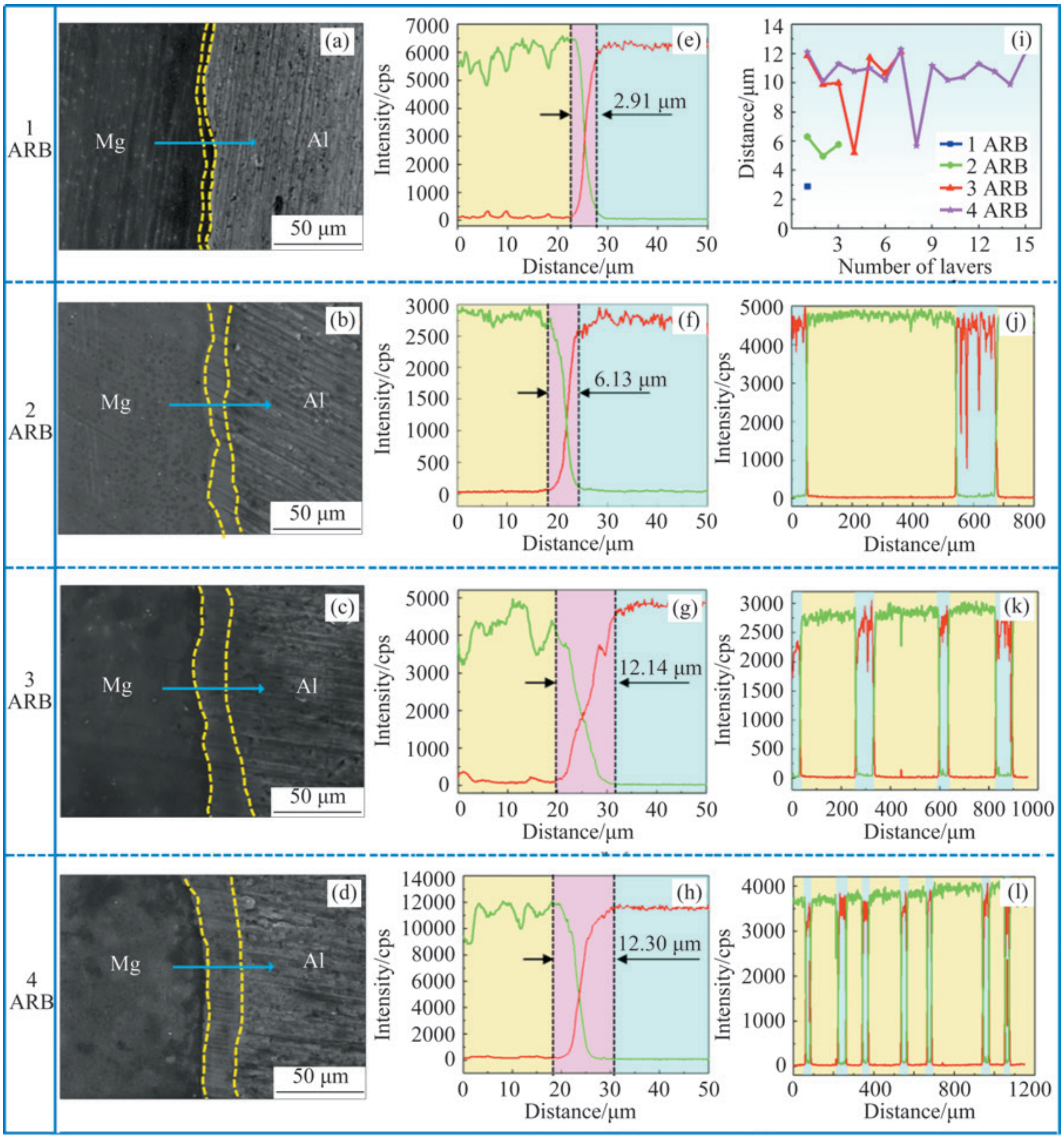

Figure 3 Microstructure and EDS line scan analysis of Mg/Al interface: (a−d) Interface morphology of 1ARB to 4ARB; (e−h) EDS line scan of 1ARB to 4ARB; (i) Schematic diagram of diffusion layer thickness at each interface; (j−l) Local magnifications of (f−h)

plays some role in promoting the thickening of the diffusion layer.

3.3 Microhardness of Mg/Al composite

Hardness may reflect the organization structure difference of metallic materials, so that it is widely used to assess the properties of heterogeneous composite plates. Figure 4 shows the comparison of the Vickers hardness values of the Mg/Al composite plates following different ARB cycles.

The figure shows that the Vickers hardness of the Mg/Al composite plate increases significantly during the original ARB process, from HV 64.37 of 1ARB to HV 71.65 of 2ARB. In the subsequent ARB process, the hardness of the composite sheet increases with increasing cycle, but the increase is small, reaching HV 74.06 after 4ARB, and the Mg and Al matrix also show the same trend as the average hardness. The reason for the evident increase in hardness after 2ARB is that the grain is relatively coarse, the grain is refined during the deforming process, the internal dislocation density

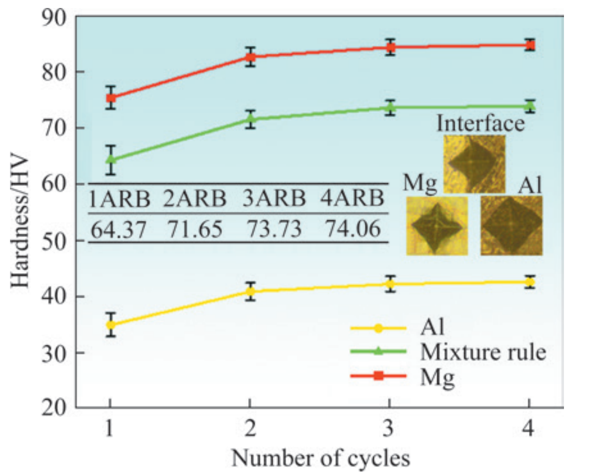

Figure 4 Changes in microhardness of Mg / Al composite plates after ARB treatment

increases and work hardening occurs, thus enhancing the ability of the Mg/Al composite plate to withstand deformation; In the subsequent deformation process, the grains have been refined, the dislocation value increases slowly, so the hardness value increases slowly. We can see from the progressive shortening of the error bar in each passage in the number which with the accumulation of the ARB cycle, the variation in hardness of the matrix Mg and Al progressively decreases, and the internal structure of the composite plate progressively tends to be stable, this is mainly due to the gradual homogenisation of the grains, with the exception of the homogenisation of the grains caused by a large deformation, the ARB front preheat treatment makes the surrounding recrystallized fine grains engulf coarse grains, and the grains are equiaxed, which can also improve the uniformity of the microstructure.

3.4 Mechanical property of Mg/Al composite

The cumulative deformation of the ARB process has a great influence on the microstructure after rolling, which will lead to the change of the mechanical properties of the Mg/Al composite plate. Figure 5 shows the engineering stress−strain curve of the Mg/Al composite plate following various ARB cycles.

It is clear from the figure that with the rise in the number of ARB cycles, the tensile strength and elongation of the composite sheet increases first and subsequently decreases, which differs from the rapid increase in strength and the sharp decrease in the plasticity of the traditional ARB. During the 3ARB process, with the increase in cumulative deformation, the resistance and plasticity of the composite plate gradually increase due to the effect of fine grain strengthening and strain hardening. The tensile strength increased from 103 to 228 MPa, and the elongation increased from 8.8% to 12.6%. This is due to the introduction of a large number of dislocations, leading to a rapid increase of the density of dislocation within the grains. Due to dislocation interaction and entanglement, internal stress is generated, so that the tensile strength increases rapidly. The increase of plasticity is mainly due to the larger Schmid factor of the slip system of the cylindrical and conical surfaces of the Mg plate. Opening the non-basal slip system during the tensile process is beneficial in improving plasticity. At the same time, the strengthening of the

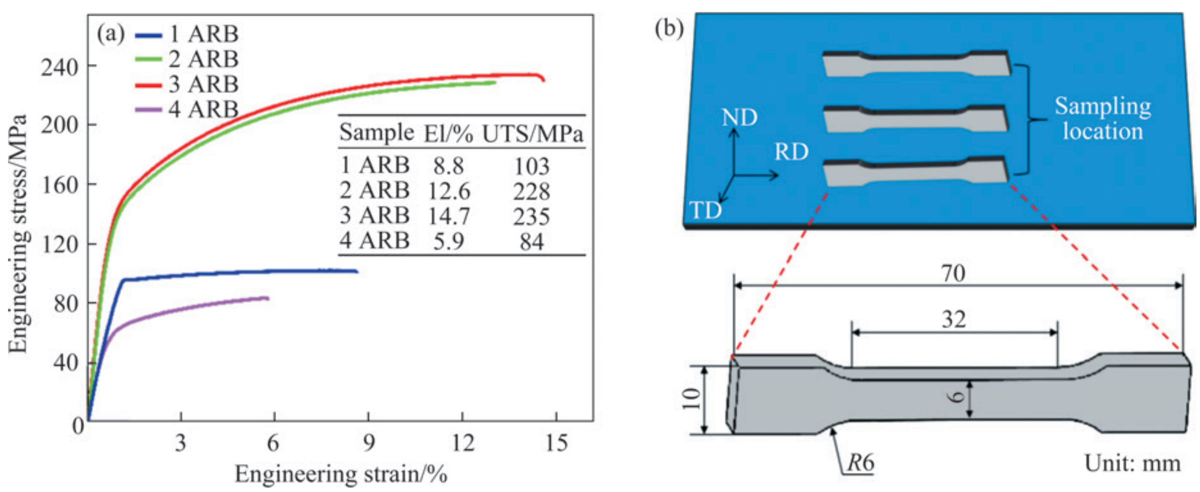

Figure 5 Mechanical property test: (a) Engineering stress−engineering strain curve; (b) Size diagram of tensile specimen

interface bonding ability of the Mg/Al interface inhibits the separate fracture coalescence and promotes the increase of the elongation of the composite plate.

After 4ARB, the tensile strength began to decrease, and the elongation also decreased. This is because when the cumulative strain increases to a certain extent, the strain of the composite plate is large at this time, and the Mg layer and the metal of the Al layer cannot be uniformly deformed as above, and the release of stress can only take place through “necking”, cracks and other pathways of instability. Due to the effect of the rolling force, cracks, holes and other defects at the interface lead to a decrease in tensile strength. Grain refining, the ability to account for dislocations is significantly reduced, and dislocations cannot be activated, which is also a major reason for the decrease in plasticity.

Figure 6 shows the tensile fracture morphology of Mg/Al composite plate. It can be seen from the figure that the Mg and Al layers of the composite plate after 1ARB are broken independently, and the Mg and Al plates are separated. After 2ARB, the necking of Mg layer and Al layer can be clearly observed. Under the condition of 3ARB, the Mg/Al layer is well bonded away from the fracture, and no delamination parallel to the tensile axis is produced. The small degree of interface cracking also indirectly indicates that the hard plate accumulative roll bonding composite plate has a strong interface bonding effect. After rolling, obvious dimples appear in the Mg plate, showing ductile fracture characteristics, while a large number of dissociation steps can be seen at the necking of the Al plate, and the number of dimples is small.

4 Discussion

The above analysis shows that when the Mg/Al composite plate is treated through various ARB cycles, the comprehensive performance is the best under the condition of 3ARB, and the volumetric fraction of the Mg plate used in this article is much greater than that of the Al plate. Thus, the Mg plate has an important influence on the performance of the composite plate. In order to clarify the evolutionary law of the microstructure of the laminated composite plate by the hard plate ARB, the modification of the matrix structure of the Mg plate is discussed in detail.

4.1 Microstructure of Mg matrix

Each cycle of ARB deformation has a significant effect on the evolution of the microstructure of built-up composite plates Mg/Al. Figure 7 shows the metallographic structure of Mg plate after different ARB cycles. The grain size measurement method is the intercept line method.

As shown in Figure 7(a), due to the fact that AZ31 alloy is HCP structure alloy with less slip

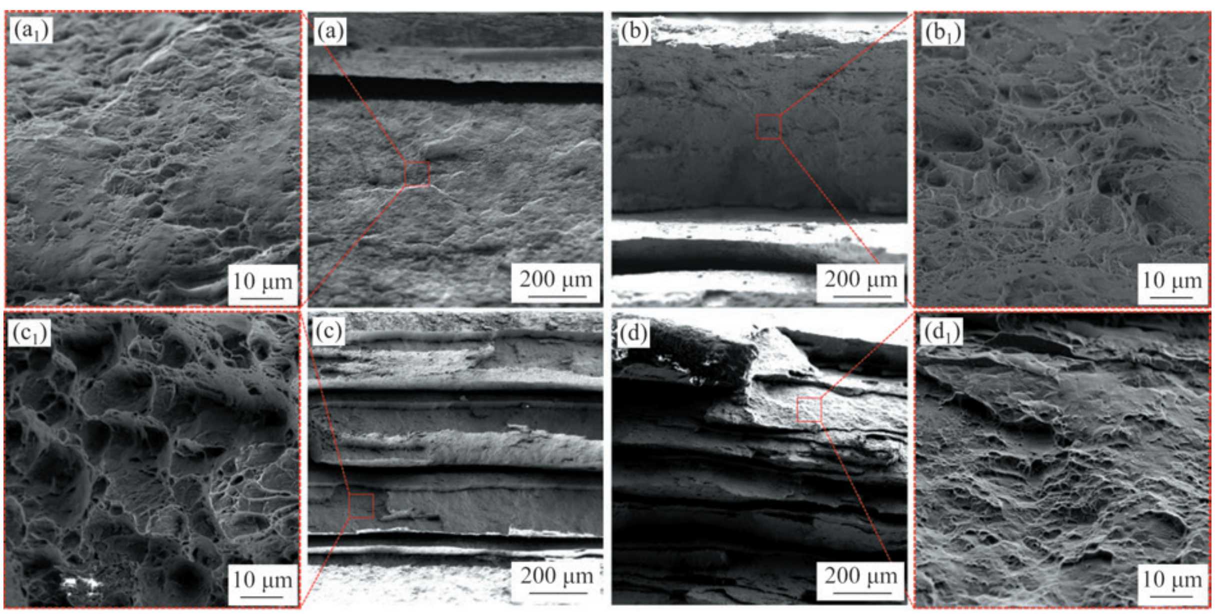

Figure 6 Tensile fracture morphology: (a) 1ARB; (b) 2ARB; (c) 3ARB; (d) 4ARB; (a_1−d_1) are the amplification region of (a−d) respectively

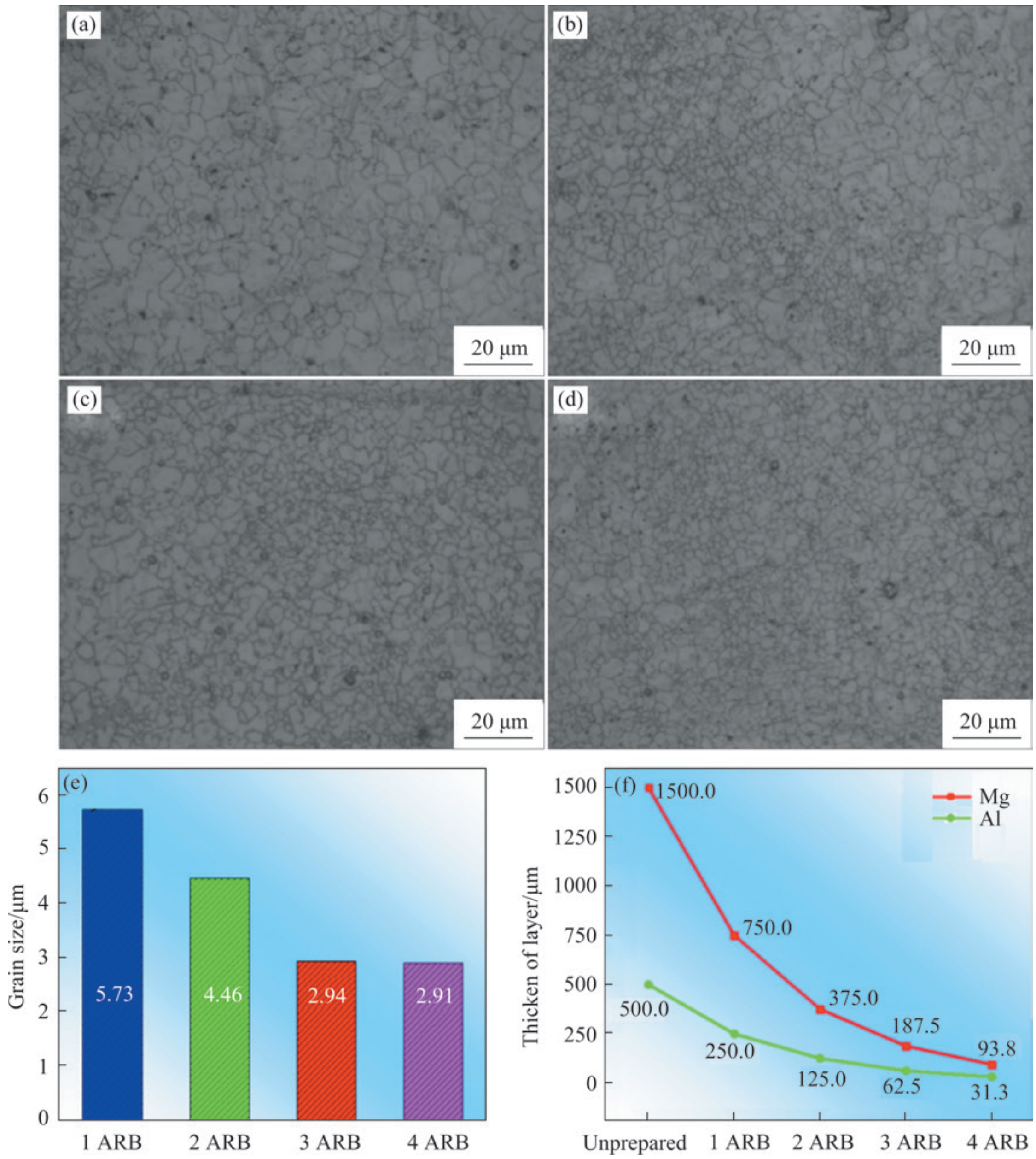

Figure 7 Comparison of Mg microstructure under different conditions: (a) 1ARB; (b) 2ARB; (c) 3ARB; (d) 4ARB; (e) Grain size; (f) Thickness variations of Mg and Al layers

system, after rolling, the microstructure of the composite plate in 1ARB condition is uneven on the rolling plane, and there are many coarse grains, with an average grain size of 5.73 μm. As shown in Figure 7(b), with the increase in cumulative deformation after 2ARB deformation, the grains of Mg layer are obviously refined, but the uniformity of the microstructure is still low, and coarse and fine grains coexist, with an average grain size of 4.46 μm. In the state of 3ARB, the Mg layer grains of the composite plate are deformed by ARB, as shown in Figure 7(c). Large grains are gradually segmented and broken, the number of fine grains increases, and the microstructure is more consistent. The average grain size reaches about 2.94 μm; in the process of ARB, with increasing cycles, the high angle grain limit increases and grain refinement is evident, and the original grain is essentially split into equiaxed grains. When the cycle is increased again, the 4ARB structure is more uniform, but the refining effect of the grain is not obvious, as shown in Figure 7(d).

From the above comparative analysis that the accumulated deformation increases gradually when the reduction by cycle is 50% in the ARB process. The large deformation is easy to induce the formation of HAGBs, which promotes progressive fragmentation and grain refinement. The average thickness changes of Mg and Al layers are shown in Figure 7(f). As the cycles increase, the deformation of the Mg and Al layers increases gradually, and the thickness of the diffusion layer decreases gradually. Before rolling, the thickness of the Al layer is only 1/3 of that of the Mg layer, but after 4ARB cycles, the thickness of the two layers tends to be the same.

4.2 Recrystallization structure

During the hard-plate ARB, new fine grains are formed at the grain boundary due to the effect of dynamic recrystallization [34]. The dynamic recrystallisation process will greatly affect the morphology of the microstructure. Figure 8 shows the distribution of recrystallization, subgrain and deformed grains in different ARB cycles.

Due to the addition of hard plates during the ARB process, the stress state of the composite sheet has been altered, and the "necklace" structure and coarse grains in the traditional rolling process did not appear. The recrystallization of the Mg/Al composite plate counts for 39.13% and the deformed grain is 57.36% after 2ARB. As the cycles increase, the proportion of the recrystallization volume fraction increases progressively, and the proportion of 3ARB is 77.21%. Compared with the previous cycle, it increased by 97%. This is because for HCP metals, the stacking fault energy of the matrix Mg alloy is low. When the deformation is large, because of the high dislocation density of the sub-grain limit in relation to the sub-grains on both sides, the sub-grain positions on both sides are very different, which is easy to induce grain boundary migration into high-angle grain boundaries. HAGBs can become the potential core of dynamic recrystallization grains. The subgrains are formed by polygonization. In the low energy region without dislocation, they become the effective core of recrystallization by deformation energy storage. With the increase of deformation, more subgrains

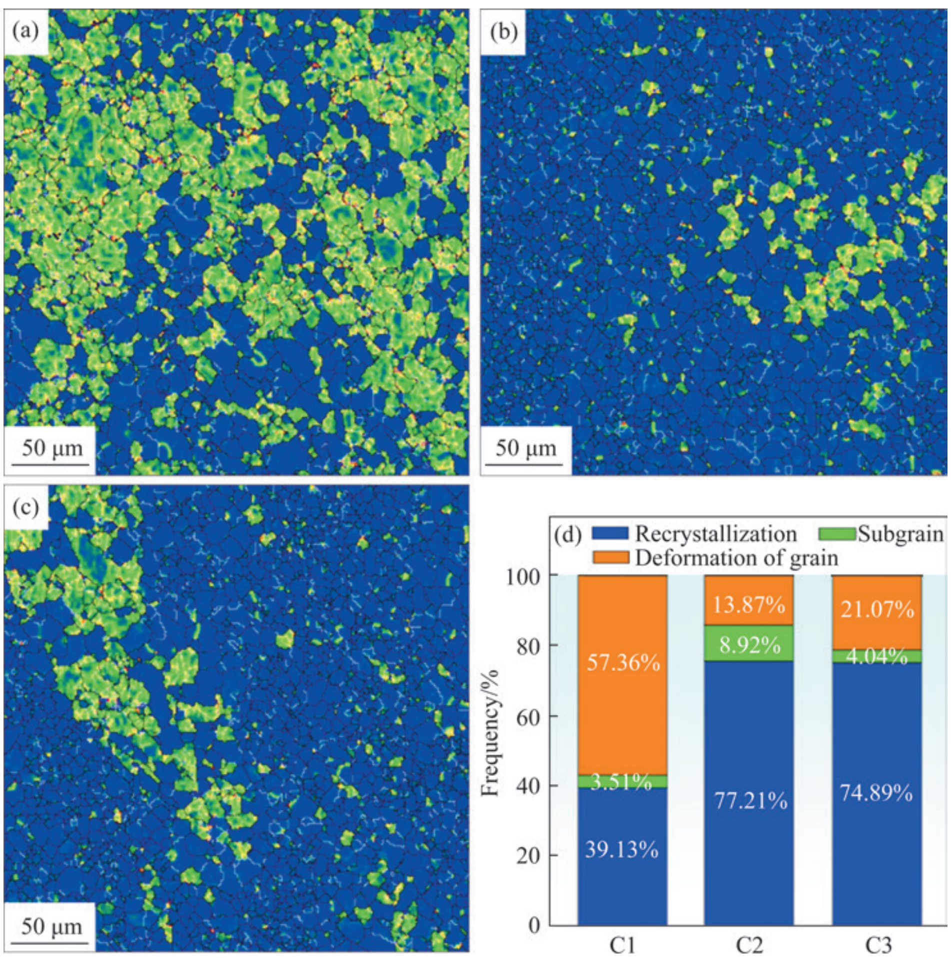

Figure 8 Recrystallization structure: (a) 2ARB; (b) 3ARB; (c) 4ARB; (d) Percentage of grain type

will be formed to facilitate nucleation. Therefore, the proportion of recrystallization increases significantly. After 4ARB, the proportion of recrystallization volume fraction basically did not change, indicating that all dynamic recrystallization had been completed in the previous cycle.

4.3 Texture evolution of Mg layer

Figure 9 shows the orientation angle distribution and pole figure of the Mg layer after the ARB. It appears from the figure that the Mg alloy grains at each pass are relatively uniform, the orientation distribution map is predominantly red, and the orientation is obvious, mainly in the [0001] direction. A large number of white lines can be observed from the deformed grains in Figure 9(a). During the ARB process, the source of dislocation within the deformed grains is activated by the rolling force, and a large number of subgrains are formed by dislocation accumulation. The orientation difference angle corresponding to the right side can also be known. The LAGBs content is relatively more than 50%, because the number of stacking passes is less, and the accumulation of deformation is insufficient, resulting in insufficient internal recrystallization and insufficient formation of HAGBs. As shown in Figure 9(b), with the increase of the ARB passes, Mg/Alcomposite plate produces a serious deformation under the action of strong compression and shear stresses. Multiple slip systems are activated at the same time, and the

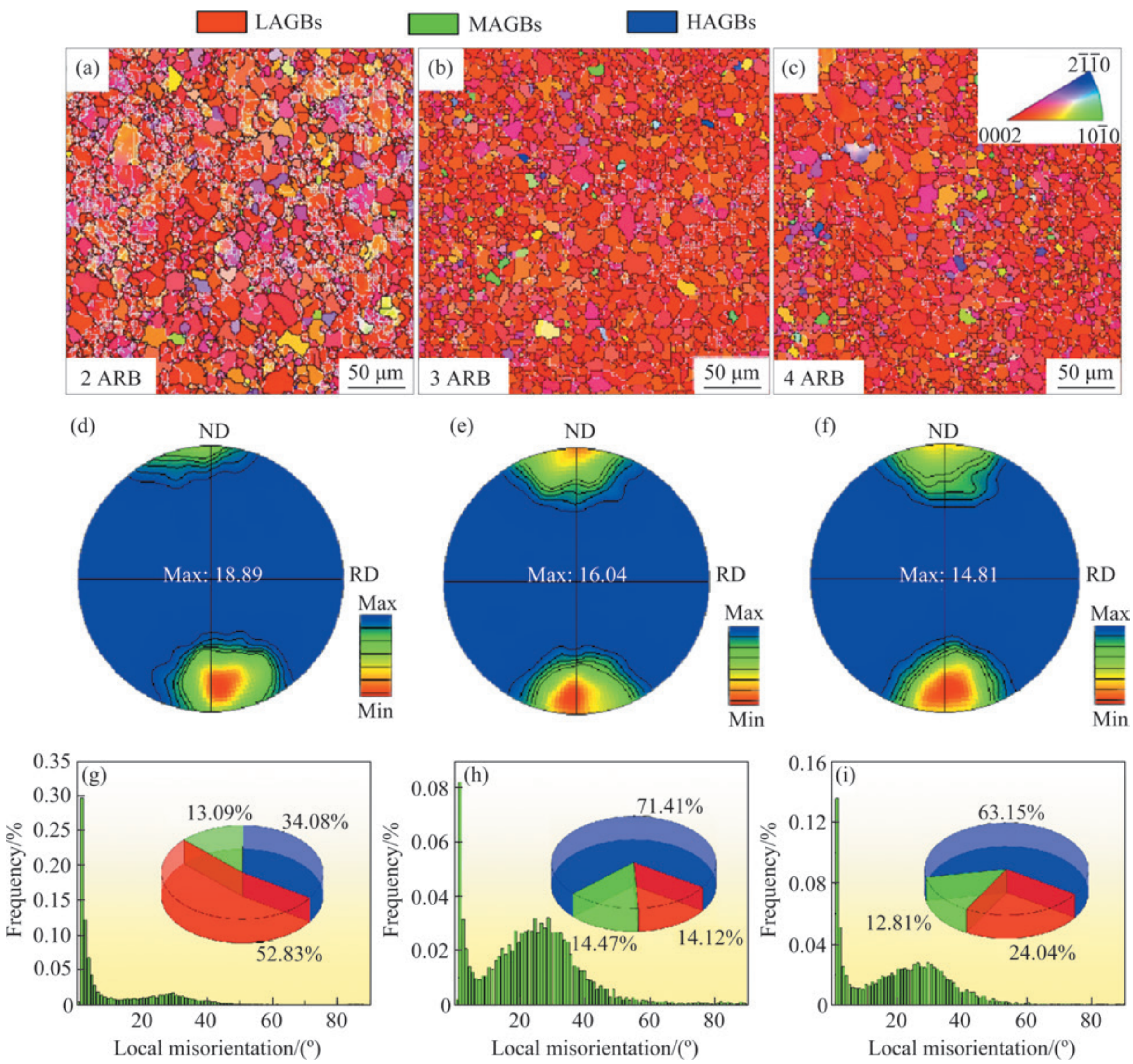

Figure 9 Texture evolution of Mg layers: (a−c) IPF maps from 2ARB to 4ARB; (d−f) Pole figures from 2ARB to 4ARB; (g−i) Orientation angle distribution diagram from 2ARB to 4ARB

dislocation proliferation is intensified, resulting in a large number of defects. As a result, the lattice becomes more serious, and the interaction between defects and crystal lattices increases, which makes the orientation difference of grains appear preferred orientation compared with the initial rolling [35]. At this time, LAGBs decreased from 52.83% to 14.12%, HAGBs increased from 13.09% to 71.41%, and the grains in the Mg matrix were mainly composed of HAGBs. It is worth noting that after 4ARB, the dislocation source restarts again during the ARB process, resulting in dislocation cells and subgrains, which makes the proportion of LAGBs rise again. The texture of the as-cast Mg alloy is slightly tilted from ND to TD. From the pole figure, it can be seen that the texture type of Mg plate does not change significantly during the accumulative rolling process. After 4 cycles, the overall trend shows that the matrix texture intensity decreases with the increase of ARB cycles.

4.4 Schmid factor

Slip is the principal mechanism of deformation of the magnesium alloy during the ARB process, and the orientation factor determines the difficulty of opening the crystal slip. KAM reflects the level of homogenisation of the plastic strain. Figure 10 shows the Schmid factor and KAM distribution of different ARB cycles. In the KAM diagram, the rainbow color from red to blue represents the value of the Schmid factor from high to low.

It can be seen from Figures 10(a)−(c) that with the increase of ARB cycles, the color of KAM diagram changes from green to blue with relatively

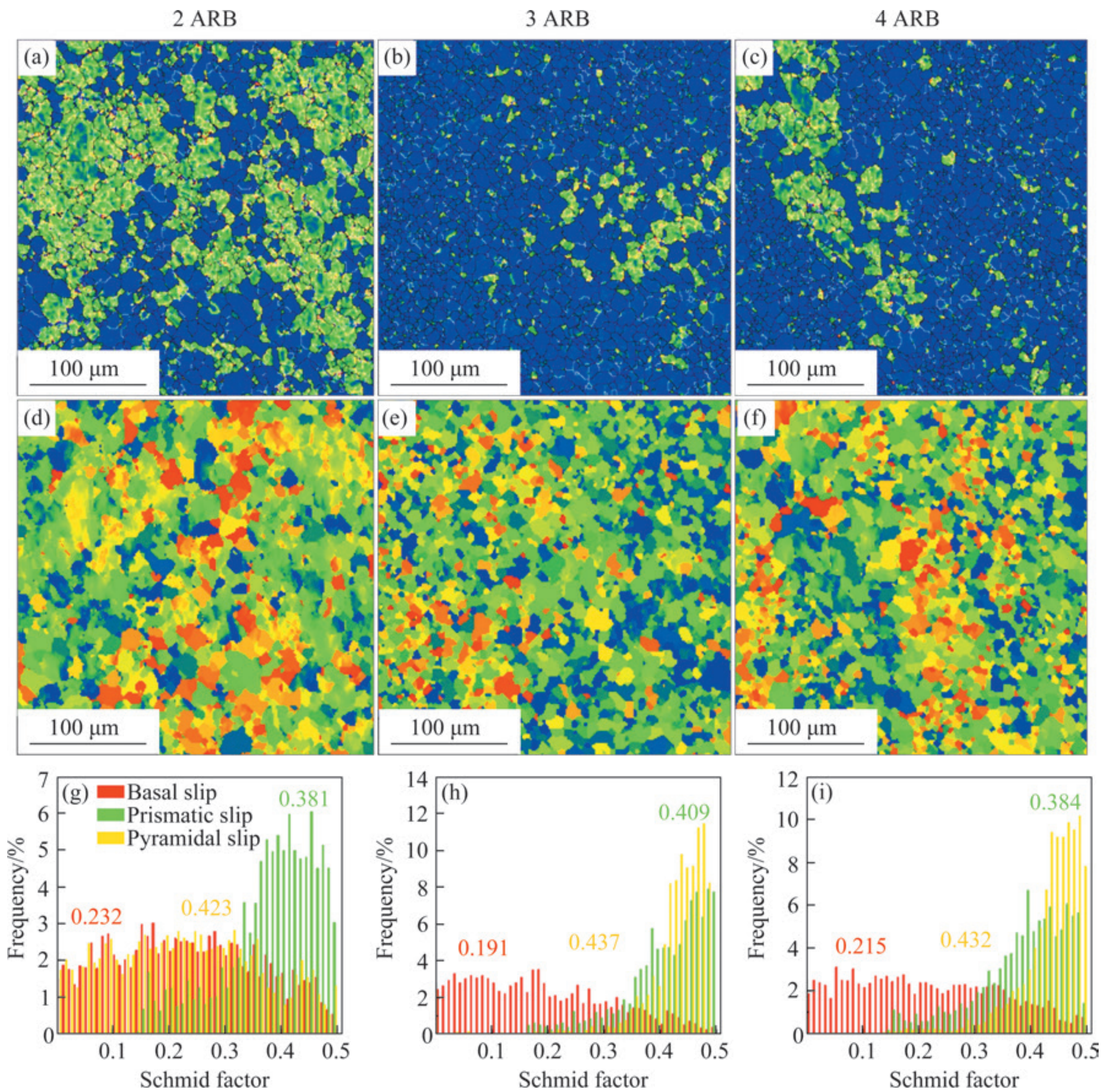

Figure 10 Comparison of Schmid factor distribution: (a−c) KAM figures; (d−f) Schmid factor; (g−i) Schmid factor distribution curve

low value. For 2ARB, there are still many deformed grains in its interior, and the KAM value is larger. At this time, the deformation energy stored in the Mg plate is higher, and the recrystallization is used as the nucleation force to replace the deformed grains in the subsequent ARB process. After 3ARB, it can be seen that the residual strain energy is low, the uniformity of plastic deformation is improved, and the recrystallization is sufficient. By comparing Figures 10(d)−(f) and the corresponding histogram, it can be seen that the main slip system of each cycle is cylinder slip and cone slip. Due to the close-packed hexagonal structure, the basal slip system is the main slip mode of Mg alloy deformation at room temperature, while Mg alloy can simultaneously activate basal slip and non-basal slip when rolling at high temperature. After 3ARB, the Schmid factor of cylindrical and conical slip of Mg alloy is higher than that of other passes. The opening of non-basal slip system is very important, which can make the number of independent slip systems meet the von-Mises criterion, promote the plastic deformation ability of Mg alloy, coordinate the stress and reduce the anisotropy.

5 Conclusions

1) The research results of Mg/Al composite plate formed by hard-plate ARB method show that the change of loading passes significantly affects the microstructure and mechanical properties of the composite plate. Before 3ARB, the interface bonding quality increases with the increase of the number of ARB passes, and the atoms of each layer diffuse each other to form intermetallic compounds, which makes the metallurgical bonding more sufficient;

2) In comparison to other cycles, continuous dynamic recrystallization is the main fine-grained mechanism in the 3ARB state, and the proportion of the recrystallization volumetric fraction of the composite plate increases significantly to 77.21%. Subgrain boundary dislocation density increases. For 4ARB, the proportion is fundamentally unchanged, indicating that dynamic recrystallization was completed in the previous pass, and that grain refinement and homogenization are achieved;

3) As the cycles increase, the tensile strength and elongation of Mg/Al composite plate increase first and then decrease, and the hardness fluctuation of Mg and Al matrix decreases gradually. The tensile strength of the composite plate after 3ARB is 235 MPa and the elongation is 14.7%, and there are obvious dimples in the Mg plate, showing ductile fracture characteristics. It is suggested that the follow-up researchers should discuss the Mg/Al interface problem in depth.

Contributors

ZHANG An-xin performed the experiments, analyzed the data and wrote the manuscript. LI Feng developed the overarching research goals and edited the draft of manuscript. NIU Wen-tao validated the proposed method and edited the draft of manuscript. GAO Rong-he performed the experiments and edited the draft of manuscript. SUN Lu validated the proposed method with practical experiments.

Conflict of interest

ZHANG An-xin, LI Feng, NIU Wen-tao, GAO Rong-he and SUN Lu declare that they have no conflict of interest.

References

[1] VAHID A, HODGSON P, LI Yun-cang. Effect of high-energy ball milling on mechanical properties of the Mg-Nb composites fabricated through powder metallurgy process [J]. Advanced Engineering Materials, 2018, 20(3): 1700759. DOI: 10.1002/adem.201700759.

[2] LI Yuan-qi, LI Feng, KANG Fu-wei, et al. Recent research and advances in extrusion forming of magnesium alloys: A review [J]. Journal of Alloys and Compounds, 2023, 953: 170080. DOI: 10.1016/j.jallcom.2023.170080.

[3] ZHANG Liu-yan, WANG Xiu-jin, WU Hui-shu, et al. High densification and anti-corrosion of graphene-coated aluminum coating deposited on AZ31B magnesium by low-pressure cold spray [J]. Carbon Letters, 2020, 30(5): 581−584. DOI: 10.1007/s42823-020-00128-y.

[4] GUO Shao-fei, LIU Xue-song, ZHANG Hong-xia, et al. Thermographic study of AZ31B magnesium alloy under cyclic loading: Temperature evolution analysis and fatigue limit estimation [J]. Materials, 2020, 13(22): 5209. DOI: 10.3390/ma13225209.

[5] YANG Xin-he, JIN Yang, WU Rui-zhi, et al. Simultaneous improvement of strength, ductility and damping capacity of single Β -phase Mg-Li-Al-Zn alloys [J]. SSRN Electronic Journal, 2022: 159. DOI: 10.2139/ssrn.4272731.

[6] TAYYEBI M, ALIZADEH M. A novel two-step method for producing Al/Cu functionally graded metal matrix composite [J]. Journal of Alloys and Compounds, 2022, 911: 165078. DOI: 10.1016/j.jallcom.2022.165078.

[7] ROUZBEH A, SEDIGHI M, HASHEMI R. Comparison between explosive welding and roll-bonding processes of AA1050/Mg AZ31B bilayer composite sheets considering microstructure and mechanical properties [J]. Journal of Materials Engineering and Performance, 2020, 29(10): 6322−6332. DOI: 10.1007/s11665-020-05126-9.

[8] ZHANG An-xin, LI Feng, PENG Da-huo, et al. Response mechanism of matrix microstructure evolution and mechanical behavior to Mg/Al composite plate by hard-plate accumulative roll bonding [J]. Journal of Materials Research and Technology, 2023, 23: 3312−3321. DOI: 10.1016/j.jmrt.2023.01.227.

[9] PRIEL E, UNGARISH Z, NAVI N U. Co-extrusion of a Mg/Al composite billet: A computational study validated by experiments [J]. Journal of Materials Processing Technology, 2016, 236: 103−113. DOI: 10.1016/j.jmatprotec.2016.05.007.

[10] WANG Yu, CHEN Gang, CHEN Zeng-kui, et al. Electropulsing assisted aging with ultrafast hardening rate for AerMet100 steel [J]. Materials Science and Engineering A, 2022, 841: 143066. DOI: 10.1016/j.msea.2022.143066.

[11] ZHANG Nan, WANG Wen-xian, CAO Xiao-qing, et al. The effect of annealing on the interface microstructure and mechanical characteristics of AZ31B/AA6061 composite plates fabricated by explosive welding [J]. Materials & Design, 2015, 65: 1100−1109. DOI: 10.1016/j.matdes.2014.08.025.

[12] LIU Shou-fa, TAYYEBI M, ASSARI A H, et al. Microstructure, texture and tensile properties of nickel/titanium laminated composites produced by cross accumulative roll bonding process [J]. Metals and Materials International, 2023: 1 − 15. DOI: 10.1007/s12540-023-01461-3.

[13] WU Yang, FENG Bo, XIN Yun-chang, et al. Microstructure and mechanical behavior of a Mg AZ31/Al 7050 laminate composite fabricated by extrusion [J]. Materials Science and Engineering A, 2015, 640: 454 − 459. DOI: 10.1016/j.msea.2015.05.094.

[14] XIN Yun-chang, HONG Rui, FENG Bo, et al. Fabrication of Mg/AL multilayer plates using an accumulative extrusion bonding process [J]. Materials Science and Engineering A, 2015, 640: 210−216. DOI: 10.1016/j.msea.2015.06.008.

[15] CHEN Zhi-qing, WANG Dong-ya, CAO Xiao-qing, et al. Influence of multi-pass rolling and subsequent annealing on the interface microstructure and mechanical properties of the explosive welding Mg/Al composite plates [J]. Materials Science and Engineering A, 2018, 723: 97−108. DOI: 10.1016/j.msea.2018.03.042.

[16] FRONCZEK D M, CHULIST R, LITYNSKA-DOBRZYNSKA L, et al. Microstructure and kinetics of intermetallic phase growth of three-layered A1050/AZ31/A1050 clads prepared by explosive welding combined with subsequent annealing [J]. Materials & Design, 2017, 130: 120−130. DOI: 10.1016/j.matdes.2017.05.051.

[17] NIE Hui-hui, LIANG Wei, CHEN Hong-sheng, et al. Effect of annealing on the microstructures and mechanical properties of Al/Mg/Al laminates [J]. Materials Science and Engineering A, 2018, 732: 6 − 13. DOI: 10.1016/j.msea.2018.06.065.

[18] CHANG H, ZHENG M Y, XU C, et al. Microstructure and mechanical properties of the Mg/Al multilayer fabricated by accumulative roll bonding (ARB) at ambient temperature [J]. Materials Science and Engineering A, 2012, 543: 249−256. DOI: 10.1016/j.msea.2012.02.083.

[19] WANG Yin-wei, TAYYEBI M, TAYEBI M, et al. Effect of whisker alignment on microstructure, mechanical and thermal properties of Mg-SiC_w/Cu composite fabricated by a combination of casting and severe plastic deformation (SPD) [J]. Journal of Magnesium and Alloys, 2023, 11(3): 966−980. DOI: 10.1016/j.jma.2022.11.004.

[20] RAHMATABADI D, TAYYEBI M, SHEIKHI A, et al. Fracture toughness investigation of Al1050/Cu/MgAZ31ZB multi-layered composite produced by accumulative roll bonding process [J]. Materials Science and Engineering A, 2018, 734: 427−436. DOI: 10.1016/j.msea.2018.08.017.

[21] WANG Yin-wei, HUANG Peng-fei, LIU Shou-fa, et al. Microstructural evolution, shielding effectiveness, and the ballistic response of Mg/Al7075/B_4C/Pb composite produced by combination of coating and severe plastic deformation (SPD) processes [J]. Journal of Manufacturing Processes, 2022, 84: 977−985. DOI: 10.1016/j.jmapro.2022.10.062.

[22] SAITO Y, TSUJI N, UTSUNOMIYA H, et al. Ultra-fine grained bulk aluminum produced by accumulative roll-bonding (ARB) process [J]. Scripta Materialia, 1998, 39(9): 1221−1227. DOI: 10.1016/S1359-6462(98)00302-9.

[23] YE Qing, LI Xue-jun, TAYYEBI M, et al. Effect of heat treatment parameters on microstructure evolution, tensile strength, wear resistance, and fracture behavior of Ni-Ti multilayered composites produced by cross-accumulative roll bonding [J]. Archives of Civil and Mechanical Engineering, 2022, 23(1): 1−19. DOI: 10.1007/s43452-022-00557-8.

[24] SAITO Y, UTSUNOMIYA H, TSUJI N, et al. Novel ultra-high straining process for bulk materials—Development of the accumulative roll-bonding (ARB) process [J]. Acta Materialia, 1999, 47(2): 579−583. DOI: 10.1016/S1359-6454(98)00365-6.

[25] ZHAN Mei-yan, ZHANG Wei-wen, ZHANG Da-tong. Production of Mg-Al-Zn magnesium alloy sheets with ultrafine-grain microstructure by accumulative roll-bonding [J]. Transactions of Nonferrous Metals Society of China, 2011, 21(5): 991 − 997. DOI: 10.1016/S1003-6326(11)60811-X.

[26] HUO Peng-da, LI Feng, WANG Ye, et al. Corrugated interface structure and formation mechanism of Al/Mg/Al laminate rolled by hard plate [J]. Transactions of Nonferrous Metals Society of China, 2023, 33(4): 1038−1053. DOI: 10.1016/S1003-6326(23)66164-3.

[27] HUO Peng-da, LI Feng, NIU Wen-tao, et al. Microstructure characteristics and corrugation interface behavior of Al/Mg/Al composite plate rolled under large strain [J]. Acta Metallurgica Sinica (English Letters), 2023, 36(5): 827−838. DOI: 10.1007/s40195-022-01486-4.

[28] HABILA W, AZZEDDINE H, MEHDI B, et al. Investigation of microstructure and texture evolution of a Mg/Al laminated composite elaborated by accumulative roll bonding [J]. Materials Characterization, 2019, 147: 242−252. DOI: 10.1016/j.matchar.2018.11.010.

[29] NIE Jin-feng, LIU Ming-xing, WANG Fang, et al. Fabrication of Al/Mg/Al composites via accumulative roll

bonding and their mechanical properties [J]. Materials, 2016, 9(11): 951. DOI: 10.3390/ma9110951.

[30] RONG Jian, WANG Peng-yue, ZHA Min, et al. Development of a novel strength ductile Mg-7Al-5Zn alloy with high superplasticity processed by hard-plate rolling (HPR) [J]. Journal of Alloys and Compounds, 2018, 738: 246−254. DOI: 10.1016/j.jallcom.2017.11.348.

[31] WANG Hui-yuan, YU Zhao-peng, ZHANG Lei, et al. Achieving high strength and high ductility in magnesium alloy using hard-plate rolling (HPR) process [J]. Scientific Reports, 2015, 5: 17100. DOI: 10.1038/srep17100.

[32] AVAZZADEH M, ALIZADEH M, TAYYEBI M. Structural, mechanical and corrosion evaluations of Cu/Zn/Al multilayered composites subjected to CARB process [J]. Journal of Alloys and Compounds, 2021, 867: 158973. DOI: 10.1016/j.jallcom.2021.158973.

[33] LIU X B, CHEN R S, HAN E H. Preliminary investigations on the Mg-Al-Zn/Al laminated composite fabricated by equal channel angular extrusion [J]. Journal of Materials Processing Technology, 2009, 209(10): 4675−4681. DOI: 10.1016/j.jmatprotec.2008.11.034.

[34] LIU C Y, WANG Q, JIA Y Z, et al. Microstructures and mechanical properties of Mg/Mg and Mg/Al/Mg laminated composites prepared via warm roll bonding [J]. Materials Science and Engineering A, 2012, 556: 1−8. DOI: 10.1016/j.msea.2012.06.046.

[35] YU Jin-cheng, SONG Bo, XIA Da-biao, et al. Dynamic tensile properties and microstructural evolution of extruded EW75 magnesium alloy at high strain rates [J]. Journal of Magnesium and Alloys, 2020, 8(3): 849−859. DOI: 10.1016/j.jma.2020.02.013.

(Edited by HE Yun-bin)

中文导读

衬板叠轧Mg/Al复合板基体组织演变优化强塑性机制

摘要：Mg/Al复合板兼并了镁合金的轻质性及铝合金的可塑性、耐腐蚀等性能，显著增强了其综合性能，但制造周期长、工艺要求高等不足制约了异质复合板成形技术的快速发展。为此，本文提出一种衬板辅助叠轧成形新方法。研究结果表明：3ARB时Mg/Al复合板抗拉强度可达235 MPa，伸长率为14.7%，镁板中出现明显的韧窝，呈韧性断裂特征，综合性能为最佳。由于此时Mg板基面滑移与非基面滑移同时开动，促进了动态再结晶的生成，此时Mg板再结晶比例为77.21%。随着累积叠轧的进行，大角度晶界增加和晶粒细化明显，原始晶粒已经基本破碎细化成等轴晶，Mg、Al基体硬度波动逐渐减小，复合板内部结构逐渐趋于稳定。本研究可为高性能异质复合板成形制造提供了一种新思路。

关键词：衬板叠轧；Mg/Al复合板；再结晶；晶粒细化；强塑性