Formability and interface structure of Al/Mg/Al composite sheet rolled by hard-plate rolling (HPR)

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Abstract
How to improve the bonding ability and quality performance of heterogeneous plates has always been one of the difficult problems in the field of high-performance heterogeneous composite sheet forming and manufacturing. In this paper, a new manufacturing method of heterogeneous clad plate, hard plate rolling clad plate, is proposed. The hot rolling process of Al/Mg/Al composite slab with or without hard plate was studied. The results show that the shear stress in the rolling direction (RD) can be transformed into the compressive stress in the normal direction (ND), and then the welding pressure between different composite layers can be increased. This method can suppress the bending and edge crack defects and significantly improve the shape quality and forming ability. At the same time, through the study of the interface structure of the composite plate, it can be known that the metallurgical bonding can be achieved with a small reduction after adding the hard plate. Two clear layers of Al₃Mg₂ and Al₁₇Mg₁₂ intermetallic compounds appear at the Al/Mg interface. The thickness of the diffusion layer is significantly larger than that of the traditional hot-rolled clad plate, and the thickness of the diffusion layer can reach 38 μm when the reduction is 60%. The yield strength is 172.3 MPa and the elongation is 21.5%. To sum up, the hot rolling of hard-plate provides a new idea for the forming and manufacturing of high performance heterogeneous composite plate.

Keywords Hot-rolled · Composite plate · Al/Mg/Al · Metallurgical bonding · Joint strength

Light weighting is one of the ideal first-choice ways to achieve energy saving, emission reduction, and cost reduction and efficiency enhancement. Therefore, the amount of lightweight materials such as Al/Mg/Ti [1, 2] has increased significantly. However, the use of a single material is often prone to disadvantages. For example, magnesium (Mg) alloy [3–5] is the lightest metal structural material currently available, but there are bottlenecks such as poor corrosion resistance and low strength in actual engineering applications. The composite use of the above materials will achieve the effects of “complementing each other's strengths and avoiding weaknesses.” Therefore, layered composite components or products such as Al/Mg/Ti [6], Steel/Al [7], and Al/Cu [8] continue to emerge. And it has been widely used in aerospace, rail transit, military weapons, and other fields. Taking the preparation of Al/Mg/Al laminates [9] method, explosive compounding method, hot rolling method, and rolling compounding method have emerged one after another. As an example, there are many bottlenecks in the preparation, such as low bonding strength, easy edge cracking, poor plate shape, and so on. How to improve the forming performance and quality of composite plates has become one of the research hotspots in this field. [10, 11]

Plastic processing and preparation methods for composite plates such as extrusion compounding method explosive compounding method, hot rolling method, and rolling compounding method have emerged one after another.

Chen et al. [12] proposed a shunt die co extrusion (PCE) process to prepare Al/Mg/Al laminates. The results show that there are no voids and cracks at the Al/Mg interface. The
thickness of the transition layer increases with the increase of temperature. The design of the diverting die greatly improves the connection strength of the extruded composite plate, and the Al/Mg composite plate achieves metallurgical bonding. Yan et al. [13] prepared magnesium alloy (AZ31B) and aluminum alloy (7075) composite plates by explosive welding. The research results show that the “metallurgical bonding” of explosive welding interface is realized by local diffusion, and the diffusion layer is about 3.5 μm, and the bonding interface is wavy. Although Al/Mg composite plate achieves metallurgical bonding, the bonding strength is slightly inferior to that of extruded composite plate. Zhang et al. [14] prepared Al/Mg/Al composites by hot rolling method. The research results show that with the increase of reduction ratio and rolling temperature, the grain size and diffusion layer width increase, and the bonding strength decreases with the increase of reduction ratio and rolling temperature; traditional hot rolling can achieve effective connection between interfaces at a small reduction, but there will still be side cracks and other adverse effects when the thinning is too large. Motevali et al. [15] processed Al/Ti/Mg ternary composites by ARB method. The research results showed that after five ARB cycles, Al/Ti/Mg ternary multilayer composites were obtained and formed uniform distribution, and the hardness increased gradually. The elongation at break decreases with the increase of ARB cycles.

In recent years, rolling method is the research focus of heterogeneous laminate in the forming and manufacturing. However, the shortcomings of traditional rolling process are gradually highlighted. Therefore, it is urgent to improve the traditional process.

Wang et al. [16] in this paper, a new method of corrugated + plate rolling was used to prepare Cu/Al composites. The research results show that the Cu/Al composites with wavy interface prepared by this method have good tensile properties. Compared with the traditional rolling clad plate, the innovation and optimization of this process can improve the mechanical properties of the formed plate; Zhao et al. [17] rolled Al/Mg composite plate by asymmetric metal packaging. The research results show that the elongation of Al/Mg composite plate prepared by this method is 24%, and the bonding property is better than that of traditional rolling composite plate. The mechanical properties of the cladding rolling are greatly improved, but the preparation process is slightly complicated.

The existing research results show that the application of hard plate to the rolling of magnesium alloy plate can increase the single-pass reduction, form bimodal grain structure [18], and improve the elongation. However, the effect of hard-plate on composite plate connection is still in the exploratory stage. In this paper, the rolling process of clad plate with additional hard-plate (HPR) is studied. After adding the hard plate, the composite plate does not directly contact with the roller but is transferred through the hard plate. The contact between the hard plate and the roller transforms most of the shear stress into compressive stress [19]. Due to the change of stress state, the composite bonding ability and quality of heterogeneous materials have an important impact.

1 Research plan

1.1 Process principle

The process principle of hard-plate rolling clad plate (HPR) is shown in Fig. 1, which consists of roller, hard plate, and clad slab. It can be seen from Fig. 1a that hard plates are respectively added on the two outer sides of the composite slab, and the dimension of the hard plate is slightly larger than that of the composite slab. Figure 1b shows the morphological characteristics of the composite plate and hard plate after rolling deformation. It can be seen from the figure that the hard plate will separate from the clad plate after rolling, which has no effect on the subsequent study of clad plate. At the same time, it can be known the sampling position of mechanical properties, SEM and XRD.

Adding hard plate can change the stress state of clad plate in rolling process, and transform the shear stress into compressive stress. On the one hand, this method can not only enhance the welding pressure between heterogeneous clad plates caused by rolling deformation, but also reduce the edge crack defects under the condition of large reduction, and fully improve the forming ability and performance of clad plates; on the other hand, the traditional hot-rolled clad plates will inevitably be oxidized and the temperature will decrease in the rolling process, resulting in poor forming quality and useless energy consumption. In this paper, the process of clamping composite plate with upper and lower hard plates is adopted, and the elongation of composite plate is considered. The size of hard board is larger than that of composite board, which can play the role of anti-oxidation and heat preservation.

1.2 Experimental program

The test uses commercial aluminum plate AA1060 and magnesium alloy plate AZ31B, the composition of which is shown in Table 1.

The upper and lower layers of the composite slab are AA1060 plate with the dimension of length (l) × width (w) × height (h) of 6 mm × 3 mm × 1 mm; the middle layer is AZ31B plate with the dimension of 6 mm × 3 mm × 1.5 mm; the hard plates on both sides are stainless steel plate ASTM304 with the dimension of 12 mm × 6 × 1 mm. As shown in Fig. 2, the slab should be pretreated before rolling. Firstly, the surface of the composite slab should be scrubbed with acetone solution to remove oil stains. Secondly, the
surface of the slab should be polished with coarse sandpaper to remove the oxide layer on the metal surface and expose the fresh metal. Then, the metal surface should be cleaned with alcohol and dried. In order to prevent the hard plate from detaching after rolling, a thin layer of high temperature isolating agent is sprayed evenly on the interface between the hard plate and the aluminum plate. Arrange according to the stacking order shown in Fig. 2a and fix the other side of the laminated plate. Preheating treatment is needed before rolling, and the preheating temperature is 350 °C for 0.5h. The rolling reduction is 40%, 60% and 80%, respectively, and the connection quality and interface structure of hot-rolled clad plate with or without hard plate are compared. After preheating, take out the clad plate from the heat treatment furnace and quickly put it into the rolling mill, then put the fixed end into the rolling mill firstly, and wait for the rolling mill to bite one end of the clad plate until the rolling is completed.

As shown in Fig. 2b, compared with the traditional hot rolling of clad plate, the hot rolling of clad plate with hard plate can change the stress state and heat preservation of clad plate. The microstructure and interfacial phases of hot-rolled Al/Mg/Al composite plates were analyzed by scanning electron microscopy and X-ray diffraction. Quanta 200F field emission scanning electron microscope was used to observe the morphology and diffusion layer thickness of aluminum magnesium bonding interface. The scanning voltage was 20 kV, and energy-dispersive spectrometer (EDS) was equipped to conduct line scanning on one side of the bonding interface, so as to characterize the existence of second phase between metals. Under x’pert Pro X-ray diffractometer, the tube voltage is 40 kV, the tube current is 40 mA, and the bonding area of Al/Mg/Al side is continuously scanned. The scanning range is 20 ° to 80 ° and the scanning speed is 0.03 °/s.

### 2 Results and discussion

#### 2.1 Macromorphology

Figure 3 shows the hot rolling process experiment of Al/Mg/Al composite plate with different reduction (40%, 60%, 80%) and without hard plate and the comparison of product morphology characteristics. The comparison of macro morphology of composite plate with or without hard plate after rolling with different deformation is shown in Fig. 3b. It can be seen from the figure that with the increase of reduction, the length of clad plate increases. At the same time, it is obvious that with the increase of reduction, the forming ability of clad plate reaches the limit. When the reduction reaches 80%, the hot-rolled clad plate without hard plate not only has nonlinear

### Table 1 Chemical composition of AZ31B and AA1060 (mass %)

| Materials | 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 | –   |

Fig. 1 Schematic diagram of the principle of hard-plate rolled composite plate. a Comparison of composite slab with or without hard plate. b Schematic diagram of formed part after hard plate rolling and location of test sampling.
distortion along the rolling direction but also has a large number of edge crack [20] defects. On the contrary, the clad plate with hard plate has better shape and no edge crack defects. It can be seen that the hard plate can improve the hot rolling formability of clad plate, improve the deformation uniformity, and inhibit the generation of edge crack defects. Figure 3a shows a partial enlarged view of the rolled clad plate with 40% reduction. It can be seen that when the clad plate is rolled without hard plate, obvious warpage occurs at both ends of the rolled plate, and separation occurs between layers; according to Fig. 3b; on the contrary, the clad plate rolled with hard plate achieves close bonding and good quality, without visible interface gap. This is due to the small bite force of the plate when it enters and leaves the roll in the rolling process, which cannot provide enough interface pressure, so it is unable to realize the close connection of the composite plate, and delamination and bending appear at its end. Under the protection of hard plate, most of the tensile force in the rolling direction (RD) can be transformed into compressive stress in transverse direction (TD), and the welding pressure between layers is increased, and the deformation coordination uniformity of each part of the composite plate is also significantly improved. Figure 3c shows the local enlarged view of thickness direction with or without hard plate rolling when the reduction is 60%. On the right side is the composite plate without hard plate after rolling, which can clearly see a large number of edge cracks, and no edge cracks appear in the case of hard plate. This is due to the direct contact between the plate and the roller in the hot rolling process of the traditional clad plate. The edge of the plate is only subjected to shear stress, which is also the internal cause of cracking in this part [21]. When the hard plate is applied, the rolling force is transferred through the hard plate, and the clad plate does not directly contact with the roller. Because the size of the hard plate is larger than the width of the clad plate in the normal direction (ND), the hard plate can still play the role of “protection” in the rolling process even if it extends slightly in the normal direction (ND), so as to reduce the generation of edge crack defects.

**Fig. 2** Schematic diagram of the preparation principle of hot-rolled composite slabs. a Composite plate stacking sequence. b During the rolling process

**Fig. 3** The morphology of the rolled composite plate with and without hard-plate under different reduction conditions. a Local enlarged drawing of 40% reduction of non-hard plate hot-rolled composite plate. b The shape of hot-rolled composite plate b1, b2 and b3 under different conditions are 40%, 60%, and 80% respectively (each group is left side is hard plate rolling, and the right side is traditional hot rolling). c 60% reduction is shown with or without the thickness enlarged drawing of the hot rolled composite plate
2.2 Interface structure

In order to further analyze the influence of the presence or absence of hard plate on the interface structure of the joint of hot-rolled clad plate. The interface structure morphology of the hot-rolled clad plate with or without hard plate is shown in Fig. 4 under different reduction at 350 °C. The properties of the two Al/Mg bonding interfaces of the clad plate are similar, so the interface on one side of the clad plate after Al/Mg/Al rolling is chosen. As shown in Fig. 4d, h, the diffusion layer was observed by SEM. At low magnification, it can be seen that the interface of aluminum magnesium layer of hot-rolled clad plate without hard plate is bent and uneven, while under the action of hard plate, the interface of each layer is almost linear and even. It can be seen that adding hard plate can improve the uniform deformation ability of clad plate during hot rolling. When the reduction rate is 40%, microcracks and even voids appear at the interface between aluminum and magnesium during unlined plate rolling. As shown in Fig. 4a, it can be seen that the composite plate is still in mechanical bonding at this time. In Fig. 4e, the diffusion layer can be clearly observed at the magnesium/aluminum (Mg/Al) interface of the hot-rolled clad plate with hard plate. After element diffusion, the light gray band Al<sub>17</sub>Mg<sub>12</sub> appears in the AZ31 layer, and the dark color band Al<sub>3</sub>Mg<sub>2</sub> appears in the AA1060 layer. And the interface between layers is clear, so as to achieve metallurgical bonding [22]. The results show that compared with the traditional hot-rolled clad plate, the hardening range of diffusion layer is significantly increased. In Fig. 5b, it can be seen that, compared with the former, the thickness of interface diffusion layer of hot-rolled clad plate with or without hard plate under 60% reduction increases in varying degrees. The thickness of interface diffusion layer reaches 38 μm with hard plate, which reaches the maximum. Compared with the traditional hot-rolled clad plate, the thickness of interface diffusion layer of hot-rolled clad plate under 80% reduction increases in varying degrees. The thickness of interface diffusion layer reaches 38 μm with hard plate, which reaches the maximum. It is also proved that the 80% reduction is too large, which leads to the discontinuous distribution of Al<sub>17</sub>Mg<sub>12</sub> layer. Figure 5d shows the variation of diffusion layer thickness with and without hard plate under different conditions. Figure 5a shows the thickness comparison of intermetallic compound diffusion layer under different conditions. Figure 5a shows the thickness comparison of intermetallic compound diffusion layer under different conditions.
It can be seen from the figure that the thickness of diffusion layer between clad plates can be increased by adding hard plate compared with no hard plate rolling. Under the three reduction conditions, the diffusion layer thickness increases in varying degrees, and the maximum is 20.9 μm. At 60% reduction, the thickness of diffusion layer reaches the peak. Figure 5 e shows the growth rate of diffusion layer thickness of hot-rolled clad plate with hard plate compared with that without hard plate under the same reduction. It can be seen that the diffusion layer thickness increases by 90.8% and reaches the peak at 40% reduction. The reduction rate of 60% is the lowest, and it can still reach 42.1%.

### 2.3 XRD phase analysis

It can be seen from the above analysis that there are two interface bonding layers in the three-layer composite plate. Because they are Al/Mg composite interfaces, one side of them is taken for XRD phase analysis. Figure 6 shows the XRD pattern of the interface of the hot-rolled composite plate with or without hard plate. Figure 6 a–c show the X-ray diffraction patterns of different reduction with or without hard plate.
plate. It can be seen that with the increase of reduction, the number and intensity of diffraction peaks increase in varying degrees, and the number and intensity of diffraction peaks of aluminum and magnesium are the highest. However, Al₃Mg₂ and Al₁₇Mg₁₂ intermetallic compounds only exist in trace amount. Figure 6 a shows that the number of diffraction peaks of intermetallic compounds without hard plate is small, and the intensity is low. There is no Al₃Mg₂ diffraction peak on

Fig. 6 XRD patterns of the interface with and without hard-plate under different reductions. a–c 40%, 60%, 80% reduction with and without hard-plate XRD patterns. d With hard-plate hot-rolled composite plate interface, there are different material specific gravity maps
the diffraction pattern with 40% reduction without hard plate, but Al$_3$Mg$_2$ diffraction peak begins to appear under the action of hard plate, which indicates that the hot-rolled clad plate with hard plate can achieve metallurgical bonding at 40% reduction. In Fig. 6 b, c, it can be seen that the number of diffraction peaks of Al$_3$Mg$_2$ and Al$_{17}$Mg$_{12}$ intermetallic compounds with 60% reduction increases obviously, and the peak value is the highest. In particular, the number of diffraction peaks of hot-rolled clad plate with hard plate is the most. The appearance of the diffraction peak of the corresponding material indicates that the material is formed at the interface of the clad plate after rolling process. The existence of intermetallic compounds was proved by XRD observation. In the experiment, several XRD tests were carried out on different positions of multi groups of rolled plates under different process parameters. In order to more intuitively express the number and intensity of diffraction peaks of intermetallic compounds Al$_3$Mg$_2$, Al$_{17}$Mg$_{12}$, and Al, Mg elements, and clarify the mechanism of hard plate on hot rolling of clad plate. Figure 6 d after statistical analysis of a large number of XRD data of rolled plate under three sets of reduction with hard plate effect, there are maximum and minimum values of each material diffraction peak, as shown in the figure. The diffraction peak of Mg element at the interface is the largest, and the maximum diffraction peak of Mg element in hot-rolled clad plate with 60% reduction is 64%. Although the diffraction peaks of Al$_3$Mg$_2$ and Al$_{17}$Mg$_{12}$ are less than 1%, they still exist. The total content of Al, Mg, Al$_3$Mg$_2$, and Al$_{17}$Mg$_{12}$ is regarded as 100% because other elements are too trace and neglected. It can be concluded that intermetallic compounds are formed in every reduction under the action of hard plate, and metallurgical bonding is achieved in different degrees between layers of composite plate.

2.4 Metal flow behavior

It can be seen from the above analysis that the stress state of clad plate rolling is changed after adding hard plate, which will have an important impact on deformation flow behavior and uniformity. In order to further study the hard plate, the composite plate can be evenly formed under the roll and solve the problem of edge crack. This paper continues to explore the above problems through simulation. Therefore, the upper cuboid in Fig. 7 shows two areas a and b, which correspond to the central part of the composite plate and the edge part of the single-layer aluminum plate. Figure 7 a shows the metal flow behavior in the middle part of the hot-rolled clad plate with hard plate and the local enlarged view of the corresponding edge of the aluminum plate. Figure 7 b is the simulation diagram of the corresponding unlined plate. From the simulation, it can be seen that the metal flow in the middle part of the hot-rolled clad plate with hard plate has a tendency toward normal direction (ND). The metal flow of the composite plate without hard plate is completely horizontal, which is consistent with the rolling direction. The metal flow at the edge of the aluminum plate in the composite plate can be seen from the comparison of the partial enlarged drawing. In the rolling direction (RD), it can be seen that the metal flow direction of the aluminum plate with hard plate is in lower right, while the metal flow direction of the aluminum plate without hard plate is only slightly inclined to the normal direction (ND). This is because the aluminum plate is in direct contact with the hard plate, and the size of the hard plate at the edge is larger than that of the aluminum plate. It is also confirmed that under the action of hard plate, the rolling plate is pressed more and pulled less at the edge forming, and the metal is subjected to both the shear stress of roller and the compressive stress of hard plate. Under the combined action of the two forces, the metal flow behavior of traditional rolling clad plate is changed into RD unidirectional stress direction. The bi-directional force makes the metal flow in non-horizontal direction under the action of hard plate, so the generation of edge crack is reduced. It can also be seen from the SEM that the element diffusion between the layers of the composite plate is better when there is hard plate effect. This is closely related to the change of metal flow direction. The extrusion flow of aluminum plate and magnesium plate under the action of hard plate promotes the diffusion of elements. It can also be seen from the appearance of the products that after forming, the connection between the layers of the composite plate with hard plate is closer, and the edge crack is significantly reduced.

2.5 Mechanical properties

Since the hard-plate changes the stress state and deformation behavior of the composite plate during hot rolling, the effect of the hard-plate plate has a related influence on the mechanical properties of the composite plate. Figure 1 b shows the sampling method for mechanical performance testing. Through the foregoing analysis, it can be seen that the hard plate has a significant effect on the composite plate in the rolling direction (RD). Therefore, the tensile samples in this experiment are all taken in the rolling direction (RD). Figure 8 a is the engineering stress-strain curve of the composite plate with different reductions under the action of the hard plate. Figure 8 b shows the comparison of the yield strength and elongation of the three sets of hot-rolled composite plates with reduction ratios under the action of the hard plate. It can be seen that with the increase of the reduction, the strength value and elongation first increase and then decrease. The yield strength and tensile strength of the composite plate are higher at 60% reduction, and the yield strength reaches the
maximum. The value is 172.3 MPa, and its elongation is also the largest, reaching 21.5%. It can be seen that the comprehensive mechanical properties of the hard-plate hot-rolled composite plate are the best when the reduction is 60%.

In order to further characterize the mechanical properties of the composite plate, the fracture surface of the composite plate with or without hard plate was analyzed by SEM. Figure 9a shows the scanning morphology after tensile fracture of the hot-rolled composite plate without hard plate. It can be seen from the figure that without the protection of lining plate, the composite plate will break after tension. The fracture gap at the interface between Al and Mg layers is too large, which indicates that the joint strength of traditional hot-rolled clad plate is not high. Figure 9b shows the scanning morphology of hot-rolled clad plate with hard plate after tensile fracture. It can be seen from Fig. 9b that the interface gap of hot-rolled clad plate after fracture has been greatly improved compared with traditional hot rolling. Compared with the two pictures, the fracture of hard plate is tearing magnesium plate and aluminum plate respectively. However, the fracture of hot-rolled clad plate starts from the bonding interface of aluminum magnesium plate to the fracture of the whole clad plate without the...
protection of hard plate. Therefore, due to the effect of hard plate, the interface of each layer of hot-rolled clad plate is more firmly connected.

3 Conclusion

1. Compared with the traditional hot rolling of composite plates, adding hard plates can change the stress state of the aluminum/magnesium/aluminum (Al/Mg/Al) composite plate during the hot rolling process, transform the shear stress in the rolling direction (RD) into the compressive stress in the normal direction (ND), and weld together. The increase in pressure improves the strength of the connection between the Al/Mg/Al layers, and the obtained Al/Mg/Al composite plate is relatively flat and has no curling. Even if the reduction reaches 80%, there is no edge cracking defect. Significantly improve the forming ability and quality of composite panels.

2. The research results show that hot rolling of the hard-plate can increase the thickness of the diffusion layer of the composite plate, forming a two-layer structure Al3Mg2 and Al17Mg12 diffusion zone on the Mg-Al interface. The comparison shows that the thickness of the diffusion layer of the hard hot-rolled composite plate is greater than that of the traditional hot-rolled under the same conditions. Among them, the thickness of the diffusion layer of the hard hot-rolled Al/Mg/Al composite plate reaches the maximum when the reduction amount is 60%. Under this condition, the mechanical properties of the composite plate are also better.

3. The XRD test results show that the hot-rolled Al/Mg/Al composite plate of the hard-plate can form Al3Mg2, Al17Mg12 intermetallic compounds with a small reduction, so that the metallurgical bonding between the composite plates can be realized. Metallurgical bonding can be achieved by hot rolling of the hard-plate under the condition of a small reduction. This method provides scientific guidance and technical reserves for the research on the forming and manufacturing of heterogeneous composite plates.

Author contribution Composite plate connection is currently a hot research direction in the field of plastic processing. The hot-rolled composite by hard-plate proposed in this paper provides a new idea for the connection of composite plates.

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Data availability The data obtained in the framework of this study are available to the journal upon request.

Declarations

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Consent to participate Not applicable

Consent for publication Not applicable

Competing interests Not applicable

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