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 perform between heterogeneous plates has always been one of the difficult issues that have long been concerned in the field of high-performance heterogeneous composite plate forming and manufacturing. This paper proposes a new method for manufacturing heterogeneous composite panels—composite panels by hard-plate rolling (HPR). In addition to adding hard plates above and below the aluminum/magnesium/aluminum (Al/Mg/Al) composite slab, the research results of the hot rolling process of the composite plate with or without the hard plates at 40%, 60%, and 80% reduction show that the hard plates can be rolled. During the manufacturing process, the shear stress in the rolling direction (RD) is partially converted into the compressive stress in the normal direction (ND), which then increases the welding pressure between the heterogeneous composite laminates, which can inhibit the occurrence of bending and edge cracks, and significantly improve the quality and shape of the board ability. At the same time, through the study of the interface structure of the composite plate, it can be known that metallurgical bonding can be achieved with a small reduction after the addition of the hard-plate, and two clear layers of Al_3Mg_2 and $\text{Al}_{17}\text{Mg}_{12}$ intermetallic compounds appear at the Al/Mg interface, and the thickness of the diffusion layer is uniform. Significantly larger than the traditional hot-rolled composite board, the thickness of the diffusion layer can reach $38\mu\text{m}$ under the condition of 60% reduction under the action of the hard-plate, the yield strength is 172.3MPa, and the elongation reaches 21.5%. In summary, the hot-rolled by hard-plate is high forming and manufacturing of performance heterogeneous composite panels provides a method.

1 Introduction

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 split die co-extrusion (PCE) process to prepare Al/Mg/Al laminates. The results show that there are no voids and cracks in the Al/Mg interface of the composite material. As the temperature increases, the thickness of the transition layer gradually increases; Yan et al. [13] prepared magnesium alloy (Mg) and aluminum alloy (Al) composite plates by explosive welding. The results showed that the "metallurgical bonding" of the explosive welding interface was achieved by local diffusion, and the diffusion layer was about 3.5 μ m, The combined interface becomes wavy; Zhang et al. [14] prepared Al/Mg/Al composites by hot rolling. The research results showed that with the increase of reduction ratio and rolling temperature, the grain size and diffusion layer width increased, and the bonding strength increased with the pressure. Lower ratio and rolling temperature increase; P.D et al. [15] processed the three-metal Al/Ti/Mg composite material by the cumulative rolling method (ARB). The research results showed that after 5 ARB cycles, the Al/Ti/Mg three-metal multilayer composite material was obtained and formed evenly distributed, the hardness gradually increases; as the number of ARB cycles increases, the elongation at break decreases.

Among them, the rolling method has been the focus of research in the forming and manufacturing of heterogeneous laminates in recent years, but the technical shortcomings exposed by traditional rolling have gradually become prominent. Therefore, improvements based on traditional techniques are imminent.

In this paper, Wang et al. [16] used a new method of corrugation + flat rolling to prepare Cu/Al composites. The research results show that the Cu/Al composites with wavy interfaces prepared by this method have good tensile properties. Zhao et al. [17] used asymmetric metal packaging to roll Al/Mg composite panels. The research results showed that the elongation rate of Al/Mg composite panels prepared by this method was 24%, and the bending performance was better than traditional rolled composite panels.

Existing research results show that applying hard-plate to rolling magnesium alloy sheet can increase the reduction of a single pass and make the sheet form a bimodal grain structure after rolling [18], which promotes the increase of elongation. For this reason, this paper uses the composite plate rolling process (HPR) with the addition of the hard-plate. After the hard-plate is added, the composite plate does not directly contact the roll, but is transmitted through the hard-plate. The contact between hard-plate and the roll will increase Part of the shear stress is transformed into compressive stress [19]. Due to the change of the stress state, the ability and quality of the composite connection of heterogeneous materials have an important influence.

2 Research Plan

2.1 Process principle.

The process principle of composite plate by hard-plate rolling (HPR) is shown in Fig. 1, including rolls, hard plates and composite slabs. It can be seen from Fig. 1a) that hard-plate are added to the two outer sides of the composite slab, and the hard-plate is slightly larger than the composite slab in terms of size. Figure 1b) shows a schematic diagram of the morphological characteristics of the composite plate and the hard-plate after rolling deformation. It can be seen from the figure that the hard-plate will detach from the composite plate by itself after the rolling, which has no influence on the subsequent research of the composite plate. At the same time, the mechanical properties, SEM, and XRD test sampling locations can be known. The addition of hard-plate can change the stress state during the rolling process of the composite plate, and partially convert the shear stress into the compressive stress. On the one hand, the traditional hot-rolled composite plate will inevitably be oxidized and the temperature will be reduced during the rolling process, increase the welding pressure between which will lead to poor forming quality and useless energy consumption. In this paper, the technique of clamping the composite board between the upper and lower lining boards is adopted, taking into account the elongation of the composite board. The lining board is larger than the composite board in size, which can play the role of anti-oxidation and heat preservation.

2.2 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 boards, the size of length (a) × width (b) × height (h) is 6mm × 3mm × 1mm; the middle layer is AZ31B board, the size is 6mm × 3mm × 1.5mm; both sides are hard plates which is a stainless steel plate ASTM304 with a size of 12mm×6×1.5mm as shown in Fig. 2. Before rolling, the slab needs to be pretreated. The surface of the composite slab is scrubbed with acetone solution. The surface of the slab is polished with coarse sandpaper to remove the metal surface oxide layer to expose fresh metal, and then clean the metal surface with alcohol. In order to

prevent the hard-plate from being detached after rolling, a thin layer of water-based graphite is evenly applied to the interface between the hard-plate and the aluminum plate for lubrication, and the stacking sequence is arranged as shown in Fig. 2a), and the other side of the laminate Fixed processing at the place. Before rolling, preheating is required, the preheating temperature is 350°C, and the heat preservation is 0.5h. The rolling reductions were 40%, 60%, and 80%, respectively. The connection quality and interface structure of the hot-rolled composite plates with and without hard-plate were compared.

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	—

Figure 2b) compared with the traditional hot-rolled composite plate, the hot-rolled by hard-plate composite plate can play a role in changing the stress state and heat preservation of the composite plate. Scanning electron microscope and X-ray diffractometer were used to analyze the microstructure and interface phases of the hot-rolled Al/Mg/Al composite plate of the hard-plate. The Quanta 200F field emission scanning electron microscope was used to observe the morphology and the thickness of the diffusion layer at the aluminum-magnesium bonding interface area of the rolled plate. The scanning voltage was 20KV, and the energy dispersive spectrometer (EDS) was equipped to scan one side of the bonding interface to characterize the second the existence of phase. Test under X'Pert PRO X-ray diffractometer, tube voltage 40KV, tube current 40mA, continuous scanning of the Al/Mg/Al side bonding area, scanning range $20^{\circ}\sim 80^{\circ}$, scanning speed $0.03^{\circ}/s$.

3 Results And Discussion

3.1 Macro morphology

Figure 3 shows the hot rolling process experiment of aluminum/magnesium/aluminum composite plate with and without hard-plate with different reductions (40%, 60%, 80%) and the comparison of the morphology characteristics of the products. Figure 3b) shows the comparison of the macroscopic morphology of different deformation composite plates with and without hard-plate after rolling. It can be seen from the figure that with the increase of the reduction, the length of the composite plate after rolling shows an increasing trend. At the same time, it can be clearly seen that with the increase of the reduction, the forming ability of the composite plate during the hot rolling of the hard-plate less plate has reached the limit. When the reduction amount reaches 80%, the hot-rolled composite plate without hard-plate not only produces nonlinear distortion along the rolling direction, but also has a large number of edge cracks [20] defects. On the contrary, the composite plate after the hard-plate is rolled has a better shape and no edges. Crack defects occur. It can be seen that the hard-plate can hot-roll the composite plate and improve the deformation uniformity, and inhibit the generation of edge cracks.

Figure 3a) shows a partial enlarged view of a rolled composite plate without hard-plate with a reduction of 40%. It can be seen that the rolled composite plate without hard-plate has obvious war page at both ends of the rolled plate and separation between the layers; combined with Fig. 3b), it can be seen that on the contrary, the hard-plate rolled composite plate achieves close bonding and good quality, No interfacial gap visible to the naked eye. This is due to the small bite force when the plate enters the roll and when it leaves the roll during the rolling process, and cannot provide sufficient interface pressure, so that the composite plate cannot be tightly connected, and delamination and bending appear at the end of the composite plate. With the protection of the hard-plate, most of the tensile force in the rolling direction (RD) can be converted into the compressive stress in the transverse direction (TD), which improves the welding pressure between layers, and significantly improves the uniformity of deformation of each part of the composite board. A partial enlargement of 60% reduction with or without hard-plate is shown in Fig. 3c). On the right side is the composite plate without hard-plate after rolling. Minor edge cracks have begun to appear on both sides, and there is no edge crack defect when there is hard-plate. This is due to

the direct contact between the plate and the roll in the traditional hot rolling process of the composite plate, and the shear stress on the edge of the plate is purely shear stress, which is also the internal cause of cracking in this part [21]. When the hard-plate is applied, the rolling force is transmitted through the hard-plate, and the composite plate does not directly contact the roll. Since the size of the hard-plate is larger than the width of the composite plate in the normal direction (ND), even if the ND is slightly extended during the rolling process, the hard-plate can still play a "protective" role, thereby reducing the occurrence of edge cracks.

3.2 Interface structure

In order to further analyze the influence of the presence or absence of hard-plate on the interface structure of the hot-rolled composite plate joints. Figure 4 shows the interface structure and morphology of hot-rolled composite plates with and without hard-plate under different reduction conditions during hot rolling at 350°C. The properties of the two aluminum/magnesium bonding interfaces of the composite plate are approximately the same, so take the Al/Mg/Al side interface of the composite plate after rolling to observe the diffusion layer through SEM as shown in Fig. 4d, h), which can be seen under low magnification. The bonding interface of the Al/Mg layer of the composite plate without hard-plate hot-rolled is curved and uneven; and the interface of each layer under the action of the hard-plate is almost

linear and smooth. It can be seen that the addition of the hard-plate can improve the composite plate during the hot rolling process. Uniform deformation ability. When the reduction rate is 40%, there are microcracks and even voids at the Al-Mg interface of rolling without hard-plate, as shown in Fig. 4a), which shows that the composite plate is still in mechanical bonding at this time; Fig. 4e) the hot-rolled composite plate Al-Mg with hard-plate. The diffusion layer can be clearly observed at the interface. The gray bands $\text{Al}_{17}\text{Mg}_{12}$ appearing through element diffusion in the AZ31B layer are all marked, while in the AA1060 layer there is a dark band Al_3Mg_2 . And the interface between the layers is clear, so as to achieve metallurgical bonding [22]. The research results show that: compared with the traditional hot-rolled composite plate, the hard-plate can be the first to achieve the metallurgical bonding of the composite plate at a smaller reduction rate. Figure 4b) When the reduction is 60%, the Al-Mg interface of the hot-rolled composite plate without hard-plate begins to form an intermetallic compound layer; and Fig. 4c) can see that there is a diffusion layer at the bonding interface when the reduction is 80%, but the metal. The layers of the inter-compounds $\text{Al}_{17}\text{Mg}_{12}$ and Al_3Mg_2 are not clear. At this time, it can be seen from Fig. 3a) that the hot-rolled composite plate without hard-plate under this condition has reached the shape limit. Figure 4f, g) the addition of the hard-plate can change the stress state of the composite plate, and change the tensile stress of some rolls to compressive stress. Even if the reduction reaches 60% or 80%, the edge does not appear to be strained, which means that the increase the hard-plate can effectively improve the forming performance of the composite plate rolling.

The influence of the hard-plate on the interface structure of the hot-rolled composite plate was analyzed by EDS. Figure 5 shows the comparison of the thickness of the intermetallic compound diffusion layer under different conditions. Figure 5a) among them, shows the thickness of the intermetallic compound

diffusion layer with and without the hard-plate at a reduction of 40%. It can be seen that the addition of the hard-plate increases the diffusion layer from 2.1 μm to 23 μm , which is 9.9 times. Compared with the traditional hot-rolled composite plate, the increase in the thickness of the diffusion layer is very significant. Compared with the former, the 60% reduction in Fig. 5b) that shows that the thickness of the interface diffusion layer of the hot-rolled composite plate with or without the hard-plate has increased to varying degrees. The thickness of the interface diffusion layer reaches 38 μm under the condition of the hard-plate. Reach the maximum value; Fig. 5c) the thickness of the diffusion layer is 5.5 μm

under the condition of 80% reduction, and it can be seen that the Al element content drop to 0 periodically. It also proves that the 80% reduction is too large, resulting in discontinuous distribution of the $\text{Al}_{17}\text{Mg}_{12}$ layer. Figure 5d) shows the variation of the diffusion layer thickness with different reductions under the action of the hard-plate or not. It can be seen from the figure that, compared with the rolling without hard-plate, the addition of hard-plate can increase the thickness of the diffusion layer between the composite plates. Under the three reduction conditions, the thickness of the diffusion layer increases to different degrees, up to 20.9 μm . The thickness of the diffusion layer reaches its peak at a reduction rate of 60%. Figure 5e) shows the growth rate of the diffusion layer thickness of the hot-rolled composite sheet with the same reduction amount compared with the composite sheet without the hard-plate effect. It can be seen that at a reduction rate of 40%, the thickness of the diffusion layer increases by 90.8% and reaches its peak. The 60% reduction rate is the smallest, still reaching 42.1%

3.3. XRD phase analysis

From the foregoing analysis, it can be seen that the three-layer composite board has two interface bonding layers, and since they are both Al/Mg composite interfaces, one side is taken for XRD phase analysis. Figure 6 shows the XRD pattern of the interface of the hot-rolled composite plate with and without hard-plate. Figure 6a ~ c) are the X-ray diffraction patterns of different reductions with or without the hard-plate. It can be seen that with the increase of the reduction, the number and intensity of diffraction peaks increase to different degrees, among which the diffraction peaks of Al and Mg. The quantity and intensity are the highest. The Al_3Mg_2 and $\text{Al}_{17}\text{Mg}_{12}$ intermetallic compounds also exist only in trace amounts. Figure 6a) can be seen that the number of diffraction peaks of intermetallic compounds without hard-plate is small and the intensity is low. There is no Al_3Mg_2 diffraction peak on the diffraction pattern without hard-plate reduction of 40%, and Al_3Mg_2 diffraction peaks begin to appear under the effect of hard-plate. Figure 6b, c) It can be seen that the number of diffraction peaks of Al_3Mg_2 and $\text{Al}_{17}\text{Mg}_{12}$ intermetallic compounds under the condition of 60% reduction is significantly increased, and the peak value is the highest. Especially the hot-rolled composite plate with hard-plate has the largest number of diffraction peaks. The appearance of the diffraction peak of the corresponding substance can indicate that this substance is generated at the interface of the composite plate after the rolling process, XRD observations proved the existence of the intermetallic. In the experiment, several XRD tests were performed on different positions of multiple sets of rolled plates under different process parameters, in order to more intuitively express the diffraction of intermetallic compounds Al_3Mg_2 , $\text{Al}_{17}\text{Mg}_{12}$, and Al and

Mg elements. The number of peaks and the degree of strength clarify the action mechanism of the hard-plate on the hot rolling of the composite plate. Figure 6d) After statistical analysis of a large number of XRD data of the rolled sheet under the three sets of reductions with the effect of the hard-plate, the maximum and minimum values of the diffraction peak ratio of each substance are shown in the figure. The ratio of diffraction peaks of Mg element at the interface is the largest. Although the diffraction peaks of Al_3Mg_2 and $\text{Al}_{17}\text{Mg}_{12}$ are relatively few, they still exist. (Because other elements are too small to be ignored, only the total content of Al, Mg, Al_3Mg_2 , $\text{Al}_{17}\text{Mg}_{12}$ is regarded as 100%). A preliminary conclusion can be drawn that intermetallic compounds are formed under the action of the lining board without reduction, and the various layers of the composite board achieve different degrees of metallurgical bonding.

3.4 Metal flow behavior

It can be seen from the foregoing analysis that the addition of the hard-plate changes the stress state of the composite plate rolling, which is bound to have an important influence on the deformation flow behavior and uniformity. In order to further study the hard-plate, the composite plate can be uniformly formed under the roll and solve the problem of edge cracks. In view of the above problems and the more vivid expression of the location of the picture taken during simulation, the upper cuboid in Fig. 7 shows two areas a and b, which correspond to the two parts taken respectively-the central part of the composite board and the edge of the single-layer aluminum plate section. Figure 7a) is a partial enlarged view of the metal flow behavior of the middle part of the hot-rolled composite plate with a hard-plate and the corresponding aluminum plate edge; Fig. 7b) is a simulation diagram of the corresponding non-lined plate. From the simulation, it can be seen that the metal flow in the middle part of the hot-rolled composite plate with the hard-plate function tends to be biased toward the normal direction; the metal flow of the composite plate without the hard-plate function is completely horizontal, which is consistent with the rolling direction. From the comparison of the partial enlarged view, the metal flow at the edge of the aluminum plate in the composite panel can be seen. In the rolling direction, we can see that the metal flow direction of the aluminum plate with the hard-plate is the lower right, while the metal flow of the aluminum plate without the hard-plate is only slightly biased to the normal direction (ND). This is because the aluminum plate is in direct contact with the hard-plate and the hard-plate is larger than the aluminum plate in the edge part, which is affected. This also proves that under the action of the hard-plate, the rolled plate is more compressed and less stretched when the edge is formed. Under the combined action of the shear stress of the roller and the compressive stress of the hard-plate, the metal flow behavior of the traditional rolled clad plate is changed into the RD unidirectional force direction under the combined action of the two forces. The two-way force causes the metal of the composite plate under the action of the hard-plate to flow into a non-horizontal direction. Therefore, the occurrence of edge cracks is reduced.

3.5 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 1b) 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 RD direction. Therefore, the tensile samples in this experiment are all taken in the RD direction. Figure 8a) is the engineering stress-strain curve of the composite plate with different reductions under the action of the hard-plate. Figure 8b) 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 172.3MPa, 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%.

4 Conclusion

1. Compared with the traditional hot rolling of composite plates, adding hard-plates can change the stress state of the Al/Mg/Al composite plate during the hot rolling process, transform the shear stress in the RD direction 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 Al_3Mg_2 and $\text{Al}_{17}\text{Mg}_{12}$ diffusion zone on the magnesium-aluminum interface. The comparison shows that the thickness of the diffusion layer of the lining 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 lining 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 Al_3Mg_2 , $\text{Al}_{17}\text{Mg}_{12}$ 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 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.

Declarations

Ethics declarations

Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

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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Competing Interests

Not applicable

Availability of data and materials

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

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Figures

Figure 1

Schematic diagram of the principle of hard-plate rolled composite plate: a) Comparison of composite slabs with or without hard-plate b) Schematic diagram of hard-plate after rolling and test sampling location map

Figure 2

Schematic diagram of the preparation principle of hot-rolled composite slabs: a) Composite plate stacking sequence b) During the rolling process

Figure 3

The morphology of the rolled composite plate with and without hard-plate under different reduction conditions: a) Partial enlarged view of the hot-rolled composite plate without hard-plate at 40% reduction b) The morphology of the hot-rolled composite plate under different conditions c) The enlarged view of the edge of the hot-rolled composite plate with and without hard-plate at 60% reduction

Figure 4

Interface morphology of hot-rolled composite plates with different reductions: a)-c) Hard-plate hot-rolled composite board e)-g) No hard-plate hot-rolled composite board d), h) Overall morphology of the composite board interface at low magnification

Figure 5

Comparison of diffusion layer thickness of hot-rolled composite plate with and without hard-plate at different reductions: a)-c) Comparison chart of 40%, 60%, 80% reduction with and without hard-plate EDS d) Comparison of the thickness of the diffusion layer e) The growth rate of the diffusion layer thickness of the hot-rolled composite plate with hard-plate

Figure 6

Comparison of diffusion layer thickness of hot-rolled composite plate with and without hard-plate at different reductions: a)-c) Comparison chart of 40%, 60%, 80% reduction with and without hard-plate EDS d) Comparison of the thickness of the diffusion layer e) The growth rate of the diffusion layer thickness of the hot-rolled composite plate with hard-plate

Figure 7

Metal flow behavior: a) Hard-plate hot-rolled composite board b) No hard-plate hot-rolled composite board

Figure 8

Mechanical performance test: a) Stress-strain curve b) Yield strength and elongation