Study on the interface of Al/Mg bimetal by static casting

Yingshui Yu, Xincheng Yu, Bo Li, Chenglong Yao
R&D Center of Fisheries Equipment and Engineering of Liaoning Province, Dalian Ocean University, Dalian 116023, China
*Corresponding author e-mail: yingshui_y@foxmail.com

Abstract. In this study, fine aluminum cladding AZ91 magnesium alloy composite ingot was prepared under static casting. The microstructure and phase constituents of the interface were investigated by optical microscopy. The result shows that the interface from the Al matrix side can be divided into three parts. A diffusion layer made up by β-Al₃Mg₂, Mg-Al intermetallic compound layer which is made up by γ-Mg₁₇Al₁₂ and a eutectic structure layer made up by α-Mg and γ-Mg₁₇Al₁₂. The element distribution is investigated by methods of electron probe microanalysis (EPMA). The component ratio of Al to Mg decreases in the whole interface. But the descent becomes very slow in the α-Mg and γ-Mg₁₇Al₁₂ eutectic structure layer. The Vickers hardness in the matrix and interface were also measured. The value of microhardness decrease with the phase changing in the whole interface from 120 HV to 275HV, but it’s still much higher than the Al matrix or AZ91 matrix as well.

1. Introduction
Magnesium and aluminum have become a favorite topic for weight-critical working environment. Magnesium alloy with a density only 1/4 of steel and similar strength of Al makes it the lightest of all constructional materials. The Mg alloy is widely used in aerospace, automobile industry and 3C products. However, one of the drawbacks of Mg alloy is the high chemical reactivity, which severely limits the use of Mg alloy[1]. The oxidation film of the Mg alloy is loosened. In that case, it cannot provide adequate protection to the matrix. The Mg alloy is not suitable for most of the corrosive environment. This drawback has become the biggest limitation on the use of the Mg alloy. In addition, the poor machining deformation ability is also one of the limitations on the application of the Mg alloy[2-5]. Al alloys owns stabile chemical property is very suitable for improving the corrosion resistance of Mg alloys. Al/Mg alloys have been extensively studied in recent years. Nevertheless, none study can completely deal with the high chemical reactivity of Mg. Al/Mg bimetal aims at using Al alloy clad on the Mg alloy have been put forward over the past years. Al/Mg bimetal not only possesses a good corrosion resistance but also improves the processing formability of the Mg alloy. A bimetal can be fabricated by using clad rolling[6], roll casting[7], hot-extruded[8], explosive welding[5]. Clad rolling was a traditional fabricating method of clad materials; it is still the most widely used method on fabricating the Al/Mg bimetal sheet. Al and Mg alloy was surface treated and cold rolled directly at room temperature[6], which suffering from macroscopic de-bonding because of the un-continuous compounds layer at the interface. By insert Al sheet between the Mg melt and roller was called the twin-roll casting (TRC) process[7], it shows us a better continuous compounds layer. Paramsothy discussed a new method to combine these two alloys with hot-extruded[4], but only a very small sample was obtained. Explosive welding is capable to join Al and Mg alloy directly, but many
preparation work was needed. No effective method has been found of clad Al and Mg alloy together. The author attempts to study from a different perspective, producing Al clad on Mg material directly by static casting. The author’s research team possesses a method to fabricate layered composite by semi-continuous casting[9]. It is hoped that information from this study may be useful for the following semi-continuous casting research.

2. Experimental

Fig. 1 shows a schematic illustration of static casting study on the Al/Mg bimetal. Casting Mg alloy (AZ91) was used as the core material, the chemical component of AZ91 alloy is listed in Table 1. Fine Al was used as the cladding layer. Al was heated to 700°C in a graphite crucible by a resistance heating furnace. The molten melt was poured into a stainless mold which was placed on a heat insulation pedestal. After pouring, the mold was moving in the direction with arrow shown in Fig. 1 to the top of the recycle pot. The liquid Al was expelled from the mold, at the same time an Al shell was left in the inner surface of the mold. The movement kept on, the mold was moved to the cooling pedestal. The movement speed and the pouring temperature of Al melt determined the temperature and the thickness of the Al shell. The Mg melt with the temperature of 670°C was poured into the Al shell. Under the effect of the cooling pedestal, the Mg solidified from the bottom upward.

Table 1. Chemical component of AZ91 alloy (at%)

|   | Al  | Zn  | Mn  | Si  | Fe  | Cu  | Ni  | Mg  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
|   | 9.4453 | 0.6616 | 0.2043 | 0.0363 | 0.0009 | 0.0047 | 0.0010 | Balance |

Figure 1. Schematic of the static casting process: 1. Crystallizer, 2. Heat insulation pedestal, 3. Cooling pedestal, 4. Recycle pot, 5. Aluminum liquid, 6. Magnesium liquid

After static casting experiment, specimen for metallographic observations were cut at the interface from the lower half of the casting ingot which is shown in Fig. 2, and observed by an optical microscope. The chemical compositions were examined by an electron probe microanalyzer (EPMA).
Vickers hardness tested by 50g loading for 5s was conducted to examine the bonding strength of the interface on Vickers hardness tester.

3. Results and discussion

3.1. Interface structure

Fig. 3 shows the optical micrographs of the as-cast ingot at the interface. The light gray part on the left is the Al shell. The Mg matrix is made up by thick branches α-Mg and discontinuous reticular α-Mg and γ-Mg\(_{17}\)Al\(_{12}\) eutectic structure on the grain boundary. It shows the Al shell interacts with the Mg core, a reaction layer with 1550 µm wide is found between them. From the Al matrix, the interface was made up by Mg-Al intermetallic compound layer which is shown in Fig. 3b as the white area of the interface and eutectic layer which is shown in Fig. 3c as the dark part of the interface. The intermetallic compound layer is divided by a jagged interface into two parts. The composition of the two parts will tested later. The width of the intermetallic compound layer is about 600 µm, the boundary of intermetallic compound extends into the eutectic layer. A large amount of broken dendrites enter into the eutectic layer.

Table 2. Element quantitative detection of the interface (at%)

| Element | Position |
|---------|----------|
|         | A        | B        | C        |
| Al      | 59.49    | 38.19    | 20.22    |
| Mg      | 40.51    | 61.81    | 79.78    |

The composition was investigated by element quantitative detection of EPMA. The detected position is shown in Fig. 3b, c. The results of the EPMA are shown in Table 2.

The EPMA results confirm that the white intermetallic compound layer can be divided into two different parts. The Al and Mg atoms percent in position A is 59.49% and 40.51% which is near the Al and Mg atoms percent of β-Al\(_3\)Mg\(_2\) phase. In the intermetallic compound layer comes next, the Al and Mg atoms percent is 38.19% and 61.84% which is close to the Al and Mg atoms percent of γ-Mg\(_{17}\)Al\(_{12}\) phase. The Al and Mg atoms percent in position C is 20.22% and 79.78% which can consider as α-Mg and γ-Mg\(_{17}\)Al\(_{12}\) eutectic structure. The results show the interface from the Al matrix side can be divided into three layers. A reaction layer made up by β-Al\(_3\)Mg\(_2\), Mg-Al intermetallic compound layer which is made up byγ-Mg\(_{17}\)Al\(_{12}\), α-Mg and γ-Mg\(_{17}\)Al\(_{12}\) eutectic structure layer.
To determine the elements distribution across the reaction layer, a quantitative chemical compositions analysis through the whole interface by EPMA was conducted. As shown in Fig 4, the ratio of Al to Mg is continuous reducing at first, a easy curve shows up before 400 µm from the Al matrix side. This is the intermetallic compound layer made up by $\beta\text{-Al}_3\text{Mg}_2$ and $\gamma\text{-Mg}_{17}\text{Al}_{12}$ next to the Al matrix. The ratio of Al/Mg content remains stable at 400 µm to 1600 µm from Al matrix side, just a slight deceases after 1200 µm from the Al matrix side. This is the $\gamma\text{-Mg}_{17}\text{Al}_{12}$ reaction zone and the $\alpha\text{-Mg}$ and $\gamma\text{-Mg}_{17}\text{Al}_{12}$ eutectic structure layer. The slight deceases of the Al/Mg content is because of the $\gamma\text{-Mg}_{17}\text{Al}_{12}$ dendrites growing into the eutectic structure, the existence of $\alpha\text{-Mg}$ decreases the Al/Mg content. The Al/Mg content reduces very quickly near the Mg matrix. The whole interface shows a clear three layers structure.

![Figure 4](image)

**Figure 4.** The quantitative chemical compositions analysis through the whole interface by EPMA

The interface possesses a complex layered structure. Combining with the Al-Mg binary phase diagram which is shown in Fig. 5, the Al element and Mg element have been through a series of multiform interdiffusion, a complex layered structure was formed.

![Figure 5](image)

**Figure 5.** Al-Mg binary phase diagram

Fig. 5 shows the schematic diagram of the interface of the Al/Mg bimetal. Because the pouring temperature of AZ91 melt is 670 °C which is higher than the melting point of fine Al shell. When the high temperature AZ91 melt pours into the Al shell, the AZ91 melt remelts the surface of the Al shell. A large amount of Al elements and Mg elements exist in the molten pool. At the same time, a large amount of Al elements released into the AZ91 melt form a big mutual diffusion concentration difference at the molten pool. Under the cooling action of the shell and the cooling pedestal, the Mg alloy solidified from the shell to the core very fast. The molten pool solidified in a very short time, left a great concentration gradient of Al and Mg element. The Mg element solidified on the Al shell with the Al element released from the shell forms rich Al intermetallic $\gamma\text{-Mg}_{17}\text{Al}_{12}$. The formation of the intermetallic compound $\gamma\text{-Mg}_{17}\text{Al}_{12}$ confirms the existence of the molten pool. Only the melt of the Al
shell can provides such amount of Al elements to react with the Mg element. The liquid phase diffusion of Al element and Mg element has not finished with such big solidification speed, left a big concentration gradient of these two elements. A large amount of Al element was left in the liquid Mg melt. Under the cooling effect of the Al shell and the cooling pedestal, the Mg melt solidified from the shell to the core. The dendrites with clear direction to the core confirmed this. The \( \gamma\text{-Mg}_{17}\text{Al}_{12} \) dendrites enter into the eutectic structure. The solid phase diffusion and solute redistribution took place after the molten pool solidified. The schematic diagram of the interface of the Al/Mg bimetal is shown in Fig. 6.

![Figure 6. The schematic diagram of the interface of the Al/Mg bimetal](image)

The composition of the layer next to the Al matrix is \( \beta\text{-Al}_3\text{Mg}_2 \) which is formed by the solid phase diffusion and solid-state phase transformation of Al and Mg elements after the remelt area solidified. With the growing of the \( \gamma\text{-Mg}_{17}\text{Al}_{12} \) dendrite in AZ91 melt, the Al element content decreases very quickly approaching to the eutectic composition point and eutectic composition changing took place. \( L \rightarrow \alpha\text{-Mg} + \gamma\text{-Mg}_{17}\text{Al}_{12} \). Left the \( \alpha\text{-Mg} + \gamma\text{-Mg}_{17}\text{Al}_{12} \) eutectic structure. When the Al used up, the solidification structure is AZ91 alloy structure.

3.2. Vickers hardness

![Figure 7. Vickers hardness of the interface and the matrix from fine Al matrix side](image)

Vickers hardness of the interface and the matrix from fine Al matrix side is shown in Fig 7. The microhardness near the Al matrix shows a peak value of about 275 HV then decreases with the distance from the Al side, reducing continuously to the Mg matrix. Overall, the microhardness at the
interface is much higher than that of the Al matrix. These high hardness values are attributable to the formation of intermetallic compounds at the interface. The microhardness values changing are mainly due to the phase changing in the interface.

4. Conclusion
Al/Mg bimetal was produced by this Static study. The obtained results are summarized as follows:

(1). The top surface of Al shell was remelted by liquid Mg, which causes the vigorous reaction of Al and Mg.

(2). The interface from the Al matrix can be divided into three parts. A reaction layer made up by β-Al3Mg2, Mg-Al intermetallic compound layer which is made up by γ-Mg17Al12, γ-Mg17Al12 and eutectic structure layer. Using methods of continuous-cast for Mg/Al bimetal is not impossible, but tough cast conditions are needed.

(3). The formation mechanism of the bimetal interface is the remelt of the Al shell provides a big amount of Al element to react with the Mg element in the AZ91 melt. And the quick solidification of the molten pool left the large concentration gradient is the diffusion driving force.

(4). The value of microhardness decrease with the phase changing in the whole interface from 120 HV to 275 HV, but it’s much higher than the Al matrix and AZ91 matrix as well.

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