# The interfacial microstructure and mechanical behavior of Mg/Mg bimetal composites fabricated by insert molding method

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## Abstract:

As the lightest structural materials, Mg alloys exhibit outstanding advantages such as high specific strength, high specific stiffness, good damping characteristic, low shock absorption, etc. Due to these advantages, the Mg alloys can be used in aerospace, military, and other lightweight applications. Nowadays, Mg alloys are nominated as “21st green engineering materials”. However, Mg alloys are also facing many challenges for widening the industrial application such as the lower strength, the limited deformation ability, the poor corrosion resistance and so on. To overcome these disadvantages, fabricating the Mg/Mg bimetal composites by combining the advantages of different Mg alloys is a better choice. However, from the current references, it can be seen that the good interface bonding cannot be achieved for the traditional fabrication methods such as solid-solid bonding and liquid-solid bonding due to the influence of oxide layer on the surface of magnesium alloys. Recently a novel method named insert molding was proposed by the current authors, which could solve the technical problems mentioned before. In this report, the studies of Mg/Mg bimetal composites fabricated using this method in the past two years will be reviewed, aiming at understanding the interfacial bonding mechanisms and mechanical behaviors of the same/different series of magnesium alloys. Combining with the following deformation and heat treatment, the current method can provide another available choice for the fabrication of Mg/Mg bimetal composites.

**Key Words:** Magnesium alloys; bimetal composites; insert molding; interfacial bonding mechanism; interfacial mechanical behavior.

## 1. INTRODUCTION

Magnesium alloys are the lightest engineering metals offering attractive alternatives to aluminium alloys for the manufacture of many low-weight castings, notably components for transport vehicles [1-3]. However, magnesium alloys have some undesirable properties including poor wear and creep resistances, which limit extensive application of magnesium alloys in many industrial fields. Using the bimetal composites such as Mg/Al[4], Al/Al[5, 6] and Mg/Mg[7-9] may be the most effective way to meet the demands for lightweight high-performance components. However, owing to the existence of oxide films on the surface, magnesium joining shows a complex process. The lower bonding rate and smaller bonding strength lead to the limited application of the solid-state joining processes such as warm rolling and vacuum diffusion bonding. Compound casting is a process through which two metallic materials—one in solid state and the other liquid—are brought into contact with each other. In this way, a diffusion reaction zone between two materials and thus a continuous metallic transition from one metal to the other is formed. This method enables forming the shape of the product and bonding other parts with complex structures at the same time. The application of this method is still very limited in magnesium alloy because solid magnesium alloys are always naturally covered with an oxide film, which is thermodynamically stable and not easily wettable by metallic melts. The oxide is not dissolved during the process and prevents the formation of a metallic bonding. An approach of joining magnesium alloys was presented by Papis et al. who used a combination of zincate treatment and electrolytically deposited Zn layer to replace the oxide layer [9, 10]. Couples of AZ31 substrate and various magnesium alloys were successfully produced by means of a laboratory-scale compound casting process under controlled thermal conditions. Defect-free interfaces could be realized by applying a droplet of the liquid alloy onto a preheated Zn coated substrate in an Ar6.0 atmosphere with subsequent slow cooling. However, previous work performed by Rübner et al. has shown that using a combination of zincate treatment and electrolytically deposited Zn layer could be successful in laboratory-scale, but did not lead to a sound process in extensive industrialization production[6]. The very high and locally varying melt velocities sometimes completely washed away the Zn-coating. In addition, the comparatively thick Zn coating led to a strong embrittlement of the interface where intermetallic phases are formed.

Recently, the study and development of compound casting named insert moulding, based on Olivier's method[11], was focused on the realization of Al/Ti and Al/Mg bimetals. With continuously heating, the metallic melt, which comes into contact with interface, supplies enough heat to fuse the outermost regions. The wettability increases drastically, and the insert material is alloyed with the bulk melt. This method exhibits excellent industrial application prospects for the preparation of Mg/Mg bimetal composites due to low production, simple production procedure, low adverse impact by oxide and high interface bonding strength of the product. The current work is mainly aimed to investigate two different kinds of interface precipitation behaviours. Based on published reports and this study, it has been found that the metallurgical bonding interface could be classified into two types. Type I is the casting of similar series of magnesium alloys where no new phase as a secondary phase is formed in the interface during solidification. Type II is to cast different series of magnesium alloys where new phase as a secondary phase can be precipitated in the interface during solidification. The corresponding mechanical properties are also investigated for the Mg/Mg bimetal composites with two different types of interface structure in this study.

## 2. Experimental procedures

AZ91/AZ31 and AZ31/WE43 bimetal composites are prepared by insert moulding method, respectively. Before the insert moulding procedure, the inserts were cut into cylindrical bars with a diameter of 40mm and height of 90mm. The surface of the insert (AZ31 or WE43) bars was mechanically polished and then treated by alkaline cleaning, acid pickling and ultrasonically degreasing with acetone. Then the pre-treated AZ91 or AZ31 pieces were melted in a steel crucible located in an electrical resistance furnace. During the melting process, a protective gas mixture containing $SF_6$ and $CO_2$ were used for preventing the formation of oxides. When the melt reaches the preset temperature, the AZ31 or WE43 bars were immersed into the melt and kept for a certain time. After that, the entire assembly (containing mold, insert and melt) protected by a protective gas, was taken out of the furnace and cooled to room temperature. To analyse the interface formation, the specimens were cut from the middle part of the samples parallel to the cylindrical insert with the size of 15 mm × 15 mm setting the interface in the middle. The specimens for microstructure observation were ground and etched. The microstructures of the specimens were examined using a Carl. ZEISS Axio Imager A2m and a ZEISS EVO-18 scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS). The elemental distributions were analyzed by JEOL JXA-8230 electron probe micro-analyzer (EPMA).The metallography specimen was shown along the bonding interface. The precipitated phases on bonding interface were checked by Rigaku D/max 2400 X-ray diffractometer with Cu Kα target and a Tecnai G2 F30 transmission electron microscope (TEM) operated at 300 kV, respectively. The interfacial shear strength was measured using a self-defined test in a universal testing machine, which was described in Ref [11]. Interfacial shear strength ($\tau$) can be calculated using the equation (1) shown in Ref [11]. The Vickers hardness was measured across the interface layer by the micro-hardness tester. The microhardness value was evaluated by averaging three mediate values of five indentation measurements. For comparison, base metals were also tested in the same condition.

## 3. Results

### 3.1 AZ31/AZ91 bimetal composites

It is clearly shown that a good metallurgical bonding between AZ31 and AZ91 alloys has been achieved and a continuous interface transition zone between AZ31 and AZ91 alloys can be observed. However, no new intermetallic compounds can be formed at the transition zone of the interface.

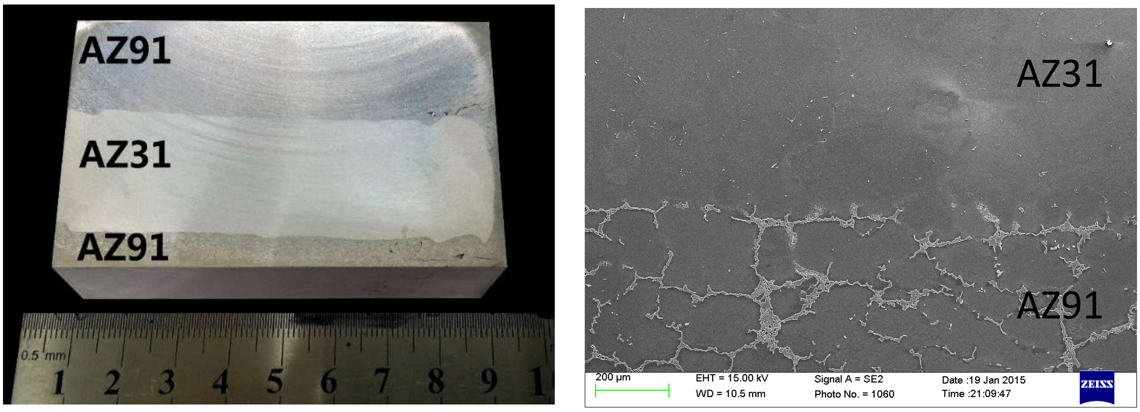


Fig.1 The appearances and SEM image of AZ31/AZ91 bimetal composites.

From the EDS results marked 1, 2 and 3 presented in Fig.2, one can conclude that β-$Al_{17}Mg_{12}$, α-Mg and Mn-rich phases (see 1, 2 and 3 in Fig.2) can be formed at the side of AZ91 alloy, which is much different from the deformed microstructures at the side of AZ31 alloy.

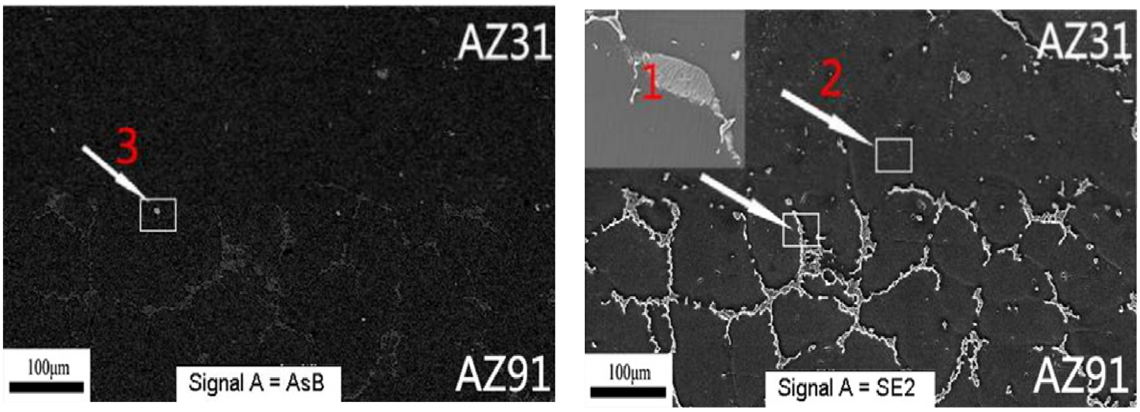


Fig.2 SEM image of the interfaces formed in specimens.

The shear strength is an important indicator to evaluate the bonding quality at the bonding interface. Fig. 3 exhibits that the current AZ31/AZ91 bimetal composites can still attain the higher shear strength value, although it is not superior to the two parent metals.

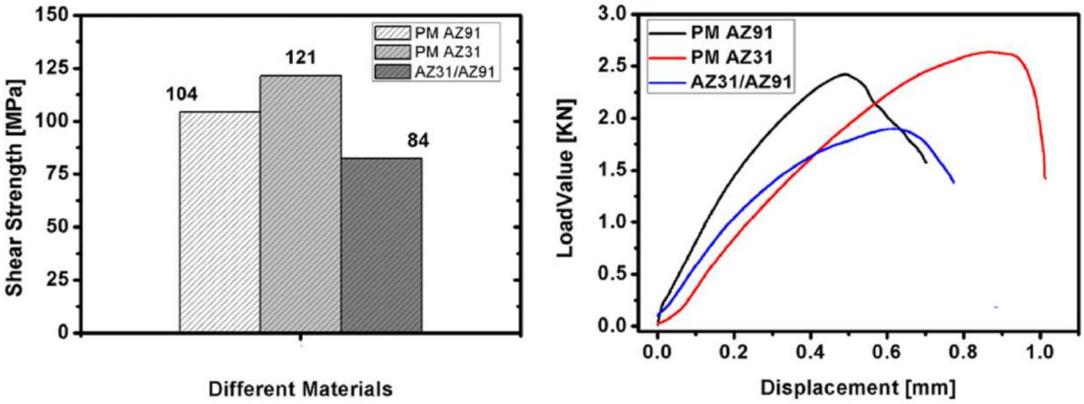
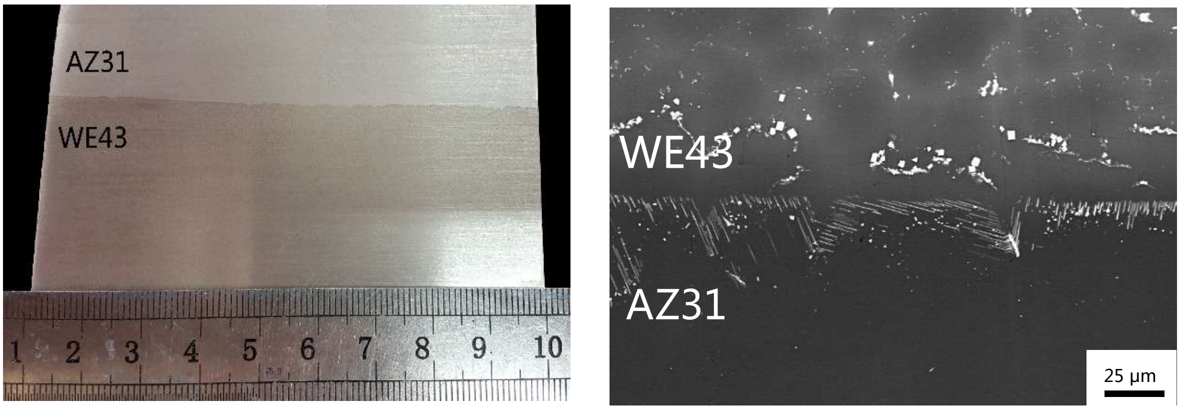


Fig.3 Strength of the interface zone and parent metals such as AZ31 and AZ91 alloys; typical load–displacement curves obtained from the shear tests of AZ91, AZ31 and AZ31/AZ91 bimetal composites.

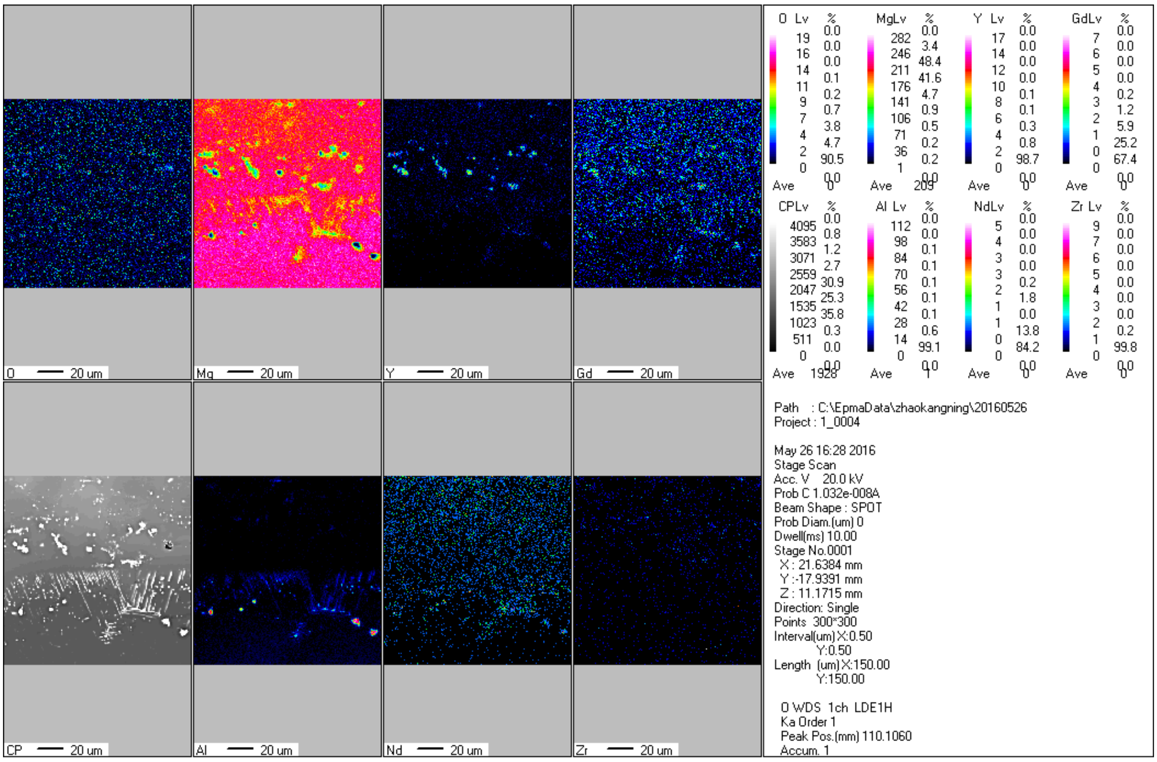
### 3.2 AZ31/WE43 bimetal composites

Fig.4 exhibits the appearances of AZ31/WE43 bimetal composites and the corresponding microstructures of the bonding interface zone. The interfacial bonding between two materials during casting is important for attaining high-performance of bimetal composites. No discernible defects such as cracks or voids at the interface are found as shown in Fig.4a, indicating that insert moulding is very efficient in fabricating bimetal composites. The interface lines on the surface along the axis of the insert are not very straight and a jagged profile can be presented, which is attributed to the difference in the melting degree of the surface. From Fig.4b, a relatively uniform transition interface with a thickness of 50-150 um consists of α-Mg grains and new intermetallic phases formed due to the contact between the WE43 alloy insert and AZ31 melt. The interface can be divided into three zones defined by the morphologies of phases as seen in Fig.4b.



(a) (b)

Fig.4 Appearances of AZ31/WE43 bimetal composites and microstructures of the bonding interface zone of AZ31/WE43 bimetal composites.



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 Y :-17.9391 mm
 Z : 11.1715 mm
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             Y:150.00

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Fig.5 EPMA area concentration maps of element Y, Al, Nd and Gd for the sample.

EPMA area profiles micrographs of the interface region along with the corresponding concentration maps of element Y, Al, Nd and Gd for the sample are presented in Fig. 5. For bimetal composites between dissimilar metals, there usually appear one or several interfacial diffusion layers distributed along the interface, which consist of intermetallic compounds formed from major elements diffusing from both mating halves, and have a contrast difference from its neighborhood. In the present study, obviously interfacial diffusion layer is found and, there still exist some new phases on the bonding interface zone, which are different from the phases in constituent matrix in morphology or distribution.

The three zones of the transition zone can be identified for different microstructure morphologies. Starting from WE43, the first zone is the diffusion zone where quadrate-like phases congregated together at the boundary. The next is a precipitation free zone (PFZ) where few second phases can be found. The third part of the transition zone is the diffusion zone into the cast matrix, which is composed of the lamellar-like morphology and particulate shape phases which are sporadically distributed throughout lamellar-like phase zones adjacent to cast AZ31 matrix.

It can be seen the microstructure of WE43 magnesium alloy shows typical resolidified structure consisting of dendritic α-Mg phase and uniformly dispersed eutectic RE-rich particles. The distribution of Al elements was identical with the RE elements, mostly forming Al-RE compounds in the matrix, which constitute together the lamellar-like phases and quadrate-like phases close to AZ31. The further EDX microanalysis results (not shown) indicated that the ratio of Al/RE is close to 2.1±0.3. That is, the lamellar phase can be Al2RE phase. Similarly, from the EDX analysis the quadrate-like phase can be also confirmed to be Y-rich phase. Moreover, for other particulate shape phases which are sporadically distributed throughout lamellar-like phase zones adjacent to cast AZ31 matrix, the ratio of Al/Zr is closed to 3, which can be identified to be Al3Zr phase.

Fig.6 exhibits the shear strength values and the corresponding load–displacement curves for the samples and parent metals such as AZ31 and WE43. It can also be seen that the current AZ31/WE43 bimetal composites can still attain the higher shear strength value which is approximately 85% of the UTS of extruded WE43 alloys and the shear strength is superior to the AZ31 parent metals.

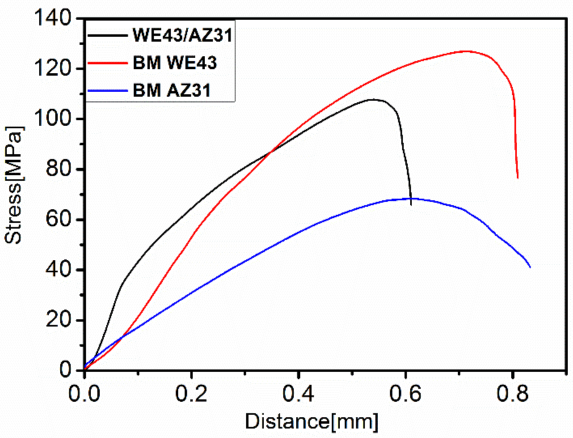

Fig.6 The interface true stress-distance curves of WE43/AZ31. Here the curves of WE43 and AZ31 parent metals are also given for comparison.

## 4. CONCLUSIONS

In this study, AZ31/AZ91 and WE43/AZ31 bimetal composites have been prepared by insert moulding method. Based on the experimental results, the conclusions can be summarized as follows:

(1) High-quality Mg/Mg bimetal composites with good metallurgical bonding have been successfully prepared and no oxides can be observed at the interface;
(2) For the same series of Mg alloys, only elemental diffusion can control the interface bonding and no intermetallic compounds can be formed. However, for the different series of Mg alloys, obviously some intermetallic compound phases can be noticed during the interfacial bonding;
(3) The Mg/Mg bimetal composites fabricated by insert moulding method can exhibit the higher interfacial bonding strength.

## ACKNOWLEDGEMENTS

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