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Interfacial microstructures and mechanical properties of Mg/Al bimetal produced by a novel liquid-liquid compound casting process

Zailiang Jiang, Zitian Fan, Wenming Jiang*, Guangyu Li, Yao Wu, Feng Guan, Haixiao Jiang

State Key Lab of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, 430074, PR China

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ABSTRACT

In the present work, a novel method was proposed to produce Mg/Al bimetal using the lost foam casting (LFC) liquid-liquid compound process with a Zn interlayer, and the interfacial microstructures and mechanical properties of the Mg/Al bimetal were investigated for the first time. Obtained results reveal that a compact metallurgical interface was formed between the AZ91D magnesium alloy substrate and the A356 aluminum alloy substrate. The metallurgical interface included two reaction layers. The reaction layer adjacent to the AZ91D substrate was composed of α-Mg, $Al_5Mg_{11}Zn_4$ and MgZn phases, and the reaction layer adjacent to the A356 substrate consisted of α-Al, $Mg_{32}(Al, Zn)_{49}$ and Mg_2Si phases. The addition of the Zn interlayer not only prevented different liquid metals from directly mixing, but also restrained the formation of Mg-Al intermetallics. The microhardnesses of the reaction layers were much higher than those of the substrates, and the reaction layer close to the A356 substrate had the highest microhardness. The shear strength of the Mg/Al bimetal was about 10.91 MPa, and the fracture surface of the Mg/Al bimetal exhibited a brittle fracture nature.

1. Introduction

Currently, magnesium and aluminum alloys are widely used in automobile and aerospace industries because of their excellent properties such as low density, high strength to weight ratio and excellent castability, as indicated by Kim et al. (2017) and Jiang et al. (2016a,b,c,d). Especially, a major concern in the manufacturing of the Mg/Al bimetallic materials has been focused on the application of lightweight alloys as they can retain the excellent characteristics from the magnesium alloy and the aluminum alloy (Schubert et al., 2001).

There are a number of methods to fabricate the Mg/Al bimetal. Hajjari et al. (2012) prepared Al 413/pure Mg joint using a CO_2 sand mold compound casting process and investigated the effect of the melt/insert volume ratio on the microstructure and mechanical properties of Al 413/Mg joint, and they indicated that the thickness of the interface was greatly affected by the melt/insert volume ratio. Xu et al. (2014) proposed a zincate + galvanizing surface treatment process for aluminum alloy substrate and investigated interfacial phenomena in magnesium/aluminum bi-metallic castings produced using an over-casting process assisted with high-vacuum, and the results showed that the wetting and metallurgical bonding between the molten magnesium and aluminum substrate were significantly improved by the surface treatment process. Rao et al. (2016) used friction stir welding to join aluminum to magnesium, and studied the effect of process parameters including tool rotation rate and tool traverse speed on microstructure and mechanical properties of the Al/Mg joint, pointing out that the tool rotation rate and tool traverse speed greatly influence the weld integrity and lap-shear strength of the joint. Dai et al. (2016) reported improving weld strength of arc-assisted ultrasonic seam welded Mg/Al joint with Sn interlayer, and the maximum peak load of the joints increased 30% compared to that of the joints without Sn interlayer. Zha et al. (2017) studied high strength and ductile high solid solution Al-Mg alloy processed by a novel hard-plate rolling route, obtaining a bimodal microstructure consisting of coarse micron grains and ultrafine grains. Gali et al. (2016) evaluated the initiation of roll coating buildup during thermomechanical processing of aluminum-magnesium alloys, indicating that the work roll and work piece material composition have a great effect on the initial roll coating composition and microstructure. Amidst, the liquid-liquid compound casting process is a novel technology for preparing the Mg/Al bimetal. Two metals both in liquid state are brought into contact with each other, and the process and the cost of the production decrease due to the absence of the solid insert. During the liquid-liquid compound casting process, setting an interlayer between molten Al alloy and molten Mg alloy is the most key measure to prevent different liquid metals from directly mixing. However, the Al or Mg interlayer is not an advisable choice because there is a natural and thermodynamically stable oxide layer covered over the Al or Mg interlayer. It is hard to be dissolved during the casting process and may

* Corresponding author.
E-mail addresses: wmjiang@hust.edu.cn, jwenming@163.com (W. Jiang).

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damage the formation of the continuous metallic reaction layers between the Al alloy and the Mg alloy (Rübner et al., 2011).

It is a fantastic approach to manufacture the Mg/Al bimetal via placing a Zn interlayer between the Mg and the Al. Many researchers have made some attempts using this approach. Liu et al. (2012) used GTAW method to join Mg alloy and Al alloy with a pure Zn filler metal. They found that the formation of the Mg-Al intermetallics was prevented by the Zn element, and the Mg-Al intermetallics were replaced with an Al or Zn solid solution. Liu et al. (2008) reported that the reaction layer of Mg/Al brazed joints became thin with the thinner Zn filler-metal layers, resulting in the increase of the shear strength. Zhang et al. (2014) used a Zn interlayer to restrain the reactions between Al and Mg during the Al/Mg pre-roll-assisted A-TIG welding process. There are also some researchers to investigate Al/Zn-enriched layers on pure magnesium. Mola (2013) characterized the microstructure and hardness of the Al/Zn-enriched layer and found that the layers were composed of the $Mg_{17}(Al, Zn)_{12}$ and $Mg_5Al_2Zn_2$ ternary phases as well as the Al or Zn solid solution.

Compared with the traditional casting process, lost foam casting (LFC) is a precision, cost-effective and environment-friendly casting technology, which is suitable for producing complex precision castings (Griffiths and Ainsworth, 2016 and Jiang et al., 2013). During the LFC process, the expanded polystyrene (EPS) foam pattern is first prepared based on the shape and size of the component. Next, the EPS pattern is coated with a refractory slurry and is then placed inside a sand flask. After modeling and vibration compacting, the molten metal is poured into the EPS pattern, thereby decomposing and replacing the EPS foam pattern. Finally, a precision casting that replicates all features of the EPS foam pattern is obtained (Barone and Caulk, 2005). Currently, some researchers have used the LFC liquid-solid compound process to prepare the Mg/Al bimetal. This compound process can combine the advantages of the LFC process, such as low cost, no cores, tight tolerance, complex geometries as well as smooth surface Jiang et al. (2016a,b,c,d). Furthermore, the oxidations of the magnesium and aluminum alloys can be avoided because the gas produced from the decomposition of the foam pattern is reductive during the LFC process (Li et al., 2017). Emami et al. (2013a,b) prepared pure Al/pure Mg light metals using the LFC liquid-solid compound process and compared the interfacial microstructure and hardness of the Al/Mg light metals with the conventional sand casting. Jiang et al. (2016a, b) fabricated Al/Mg bimetallic castings using the LFC liquid-solid compound process, and investigated the interface characteristics of the Al/Mg bimetal as well as the effect of the melt-to-solid insert volume ratio on the microstructures and mechanical properties of the Al/Mg bimetal. However, no literatures reported that the Mg/Al bimetals are prepared employing the LFC liquid-liquid compound process, and only other bimetals such as HCWCI/carbon steel (Xiao et al., 2012) and A380/A2014 (Kisasoz et al., 2014) were achieved using this process. In comparison with the LFC liquid-solid compound process, the LFC liquid-liquid compound process has a much larger difficulty resulting from the mixing of different liquid metals. Additionally, the magnesium alloy and aluminum alloy during the LFC liquid-liquid compound process are easy to oxidize or combust compared to the ferrous metals, leading to the incompatible and poor bonding between the magnesium alloy and the aluminum alloy. Therefore, there still is a challenge and an unexplored field for the production of the Mg/Al bimetal using the LFC liquid-liquid compound process.

In this paper, the LFC liquid-liquid compound process was first used to prepare the Mg/Al bimetal, and a Zn interlayer was set in the foam patterns to prevent two kinds of liquid metals from directly mixing and restrain the formation of the Mg-Al intermetallics. The objective of the present work is to propose a novel process to prepare the Mg/Al bimetal and investigate the interfacial microstructures and mechanical properties of the Mg/Al bimetal produced by the LFC liquid-liquid compound process with a Zn interlayer.

2. Experimental procedure

The base materials used in this study were respectively AZ91D magnesium alloy and A356 aluminum alloy, and their chemical compositions were Al-9.08, Zn-0.62, Mn-0.23, Mg-bal. (wt.%), and Si-6.81, Mg-0.439, Ti-0.017, Fe-0.205, Al-bal. (wt.%), respectively. Foam patterns with the dimensions of 80 mm × 35 mm × 15 mm were cut from an EPS foam board with a density of 0.02 g/cm^3 using a hot-wire foam cutter. A Zn alloy ingot (Zn-0.1%Ni) was cut by a wire electrical-discharge machining to obtain a Zn interlayer with the dimensions of 100 mm × 50 mm × 3 mm. Then, the Zn interlayer was ground by abrasive papers up to 1500 grit, followed by degreasing using the ultrasonic in ethanol. The foam pattern and Zn interlayer were bonded together using a LFC special cold adhesive, and they was then coated with a special refractory slurry and dried in a drying oven at 50°C for 2 h. Afterwards, the foam pattern was placed inside a sand flask, and then filled with the unbonded loose-sand, followed by compacting using a vibration table. Finally, the plastic film and the sprue cup were successively covered above the sand flask.

The AZ91D magnesium alloy and A356 aluminum alloy ingots were first placed inside two different stainless steel crucibles that were preheated at 300°C, and they were melted using two different electrical furnaces at 700°C. The protective gas atmosphere of the AZ91D magnesium melt was the CO_2-0.5% SF_6, and the A356 molten metal was refined using the 99.99 wt.% argon gas. When the temperatures of the AZ91D magnesium alloy and A356 aluminum alloy melts reached 700°C, the slags of the molten metals were skimmed. Next, the AZ91D alloy and A356 alloy melts were simultaneously poured into the foam patterns at 700°C after opened the vacuum pump. The vacuum pressure was 0.03 MPa in the present study. After solidification, the Mg/Al bimetal was finally obtained. The schematic illustration of the experimental equipment is illustrated in Fig. 1.

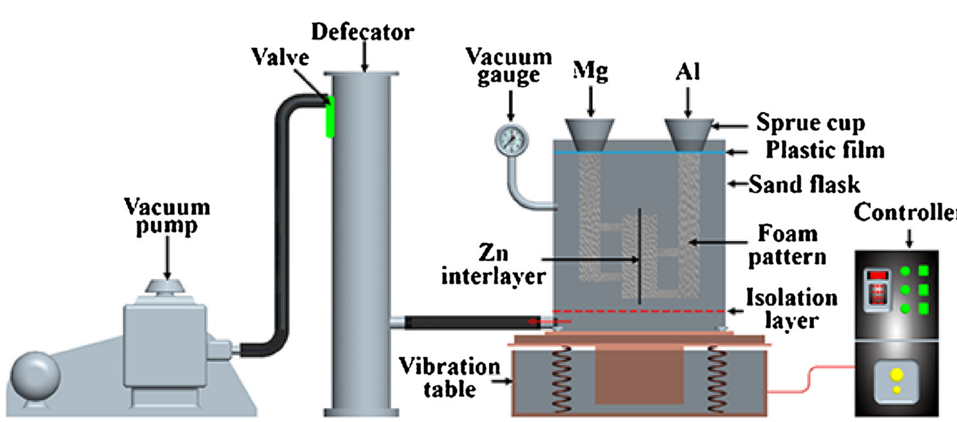

Fig. 1. Schematic illustration of the experimental equipment.