

Aluminum Surface Treatment for Improved Bonding of Magnesium/Aluminum Bi-Metallic Casting

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Abstract

Magnesium/aluminum bi-metallic castings offer significant mass saving opportunities in automotive structural applications. A "zincate+galvanizing" surface treatment has been developed for aluminum alloys to provide improved wetting and metallurgical bond with molten magnesium in bi-metallic casting, due to the removal of Al_2O_3 layer and the formation of with a very thin metallic zinc film on the aluminum surfaces. The bi-metallic experiments using a self-designed high-vacuum test apparatus provided valuable understanding of the interfacial phenomena of Mg (AM60)/Al (6061) bi-metallic samples. The test results show significantly improved shear strength in the bi-metallic samples with "zincate+galvanizing" surface treatment. It is recommended to adjust the pre-heating temperature and time of the aluminum substrates to control the interfacial reactions for optimum interfacial properties in the actual bi-metallic casting processes.

Introduction

Lightweight aluminum and magnesium castings offer significant mass savings compared with steel components in many automotive applications [1,2]. Hollow sections are generally more mass-effective in structural designs, and hollow castings can be made in gravity or low-pressure casting processes where sand cores are used to create very complex internal channels in the castings. A recent example is the Cadillac CTS front cradle which contains a 4-mm wall hollow aluminum casting made with a modified low pressure die casting using sand cores [3]. Short hollow sections can be made in high-pressure die casting with slides and, in limited cases, using high-strength salt cores. Another approach for introducing hollow sections in castings is "overcasting" where tubes of different materials are placed in the die cavity prior to casting the complex portions of the casting [4]. Overcasting is the key enabling technology needed for multi-materials designs where light metals (Al or Mg) can be cast around a tube of different materials. Overcasting is also used in producing lightweight power train castings, such as the BMW Mg/Al composite engine block [5]. The composite block consists of an aluminum insert surrounded by magnesium in the upper section of the cylinder liners and water-cooling jacket. The hypereutectic aluminum alloy insert avoids the use of additional liner technology and facilitates the highly loaded bolt joints for both cylinder head and crankshaft bearings. The insert also includes the water jacket, avoiding the potential problem of coolant corrosion with magnesium.

There are technical challenges in achieving strong metallurgical and mechanical bond in these bi-metallic castings due to the fact that both Mg and Al have high thermal conductivities, prone to form brittle intermetallic phases, and a large difference in thermal expansion coefficient. High Pressure Die Casting (HPDC) processes was found to be an effective process to overcast Mg and Al alloys onto steel, Al and Mg alloy substrates [5]. The "shrink-fit" between the cast layer and the substrate due to the large solidification shrinkage during overcasting results in a strong mechanical bond at the interface. However, no metallurgical bond was identified in the Mg/Al interface due to the high cooling rate of HPDC process and the fact the substrate material is generally covered by an oxide layer [5].

The object of this research was to develop a surface treatment process to remove oxide film in aluminum alloy substrates and develop a low melting-point metallic zinc coating to promote metallurgical

bond in the subsequent overcasting process. A high-vacuum tube furnace was designed and built to investigate the interfacial wetting and reactions between molten magnesium and the aluminum substrates. Cast magnesium alloy AM60 (Mg-6%Al-0.3%Mn) and wrought aluminum alloy 6061 (Al-1%Mg-0.6%Si-0.3%Cu) were selected to study the effects of surface treatment, contact temperature and time on the interfacial wetting and reactions between molten Mg and the substrates, providing important guidance in overcasting process development for such bi-metallic systems.

Experimental Procedure

Materials and surface treatment

Table 1 lists the chemical composition ranges of AM60 Mg alloy and 6061 Al alloy used in this study. The main purpose of the surface treatment of the Al alloy samples was to remove the natural oxide layer from the surface and simultaneously prevent its re-formation after the treatment. The conventional zincate process refers to alkaline solutions used in a dipping (immersion) process to plate aluminum with zinc prior to electrolytic or electroless nickel plating [6]. In this study, the zincate process was modified to include a zinc-galvanizing step to replace the Al_2O_3 layer with a metallic Zn film of controllable-

Alloy	Al	Mg	Mn	Si	Cu	Ni	Fe	Ti	Cr
Mg-AM60	5.6-6.4	Bal	0.26-0.5	≤0.05	≤0.02	≤0.001	≤0.004	n/a	n/a
Al-6061	Bal	0.8-1.2	0.15	0.4-0.8	0.15-0.4	n/a	0.7	0.15	0.4-0.35

Table 1: Chemical composition ranges of the alloys studied.

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thickness (several hundred nanometers). This “zincate+galvanizing” process includes the following steps: (1) degrease; (2) alkali etching; (3) pickling; (4) zincate immersion; and (5) zinc galvanizing.

Bi-Metallic experiments

Figure 1 shows a schematic illustration for high-vacuum tube furnace test apparatus designed and built in this project for bi-metallic experiments of molten magnesium on solid aluminum substrate. This apparatus consists of four subsystems, i.e., vacuum system, gas-flow control system, driving system for liquid/solid samples, and heating system. For each experiment, the quartz tube chamber was sealed and evacuated to a vacuum level of about 5×10^{-3} Pa, using a high-powered mechanical and molecular vacuum pump, and then filled with argon gas (99.99%Ar) to a pressure of 1.2 atmosphere. A small amount of magnesium alloy (2.5 grams) was placed in a syringe-like quartz tube of 6 mm diameter, and the electric resistance furnace was heated to test temperatures of 700°C and 750°C. The molten magnesium sample was then pushed out using a graphite plunger through a narrow tip of 8 mm diameter. The magnesium droplet prepared in this way was essentially free of oxide as any possible oxide formed during melting was broken and sheared off at the syringe tip. Just before the molten magnesium was pushed, an aluminum alloy substrate (25x15x4 mm) was pushed into the hot furnace from the other side of the tube furnace and placed beneath the outlet of the syringe. After squeezing the magnesium droplet onto the aluminum substrate for a controlled time (70 sec), the bi-metallic sample was pulled into a room-temperature zone and cooled down for analysis.

Analyses and testing

The microstructure of the bi-metallic samples was examined using a MM6 optical microscope and a SIRION200 Scanning Electron Microscope (SEM) couple with energy dispersive spectroscopy (EDS). A SKY11-MH-3 hardness tester was used to measure the microhardness values of the Mg/Al interfacial regions. Figure 2 shows the schematics of shear strength testing of the bi-metallic samples, using a MTS810 mechanical testing machine. Aluminum alloy 6061 samples of 25x15x4 mm were polished and drilled with a hole of 8 mm diameter, and molten magnesium droplet then was squeezed into the hole and solidified in various process conditions. A plunger of 7.8 mm diameter was lowered to push the magnesium portion (diameter $r=8$ mm) of bi-metallic samples, to measure the load required to fracture the sample (F_{max}) and calculate the shear strength (τ_{int}) according to the following equation:

$$\tau_{int} = \frac{F_{max}}{2\pi rt}$$

Where t is the thickness of the bi-metallic sample.

Results and Discussion

Temperature control

It is important to monitor the substrate temperature vs. time at different furnace temperatures (Figure 3) during the bi-metallic experiments. Since the solidus temperature of 6061 aluminum alloy is 582°C [7], it is advisable not to overheat the substrate above this temperature to avoid any potential melting before the molten magnesium reaches the substrate surface. Therefore, according to (Figure 3), the substrate pre-heating time was controlled within 120 sec. and 80 sec, for test (furnace) temperatures of 700°C and 750°C, respectively.

Interfacial wetting and microstructure

Figure 4 compares the interfacial wetting between AM60 and 6061 substrate without and with the “zincate+galvanizing” treatment, with a furnace temperature of 750°C and substrate pre-heating temperature of 560°C. It is evident that aluminum substrate with “zincate+galvanizing” treatment (Figure 4b) shows significantly better wetting with magnesium, compared with the un-treated substrate.

Figure 5 depicts the interfacial microstructure of an AM60/6061 bi-metallic sample (furnace temperature 750°C, and substrate pre-heating temperature 560°C). The optical micrograph in Figure 5a shows a clear Mg/Al metallic boundary with no evidence of oxide in the interface. Further investigation using SEM coupled with EDS scans did show evidence of metallurgical reactions in the interfacial regions. Figure 5b, 5c exhibit some dendritic branches of α -Al in the interface. Since the substrate pre-heating temperature (560°C) is 22°C below its reported solidus temperature, it is believed that these branches formed during the interactions between molten magnesium and solid aluminum. It is apparent that the aluminum surface was partially melted by molten magnesium in the bi-metallic experiments and re-solidified

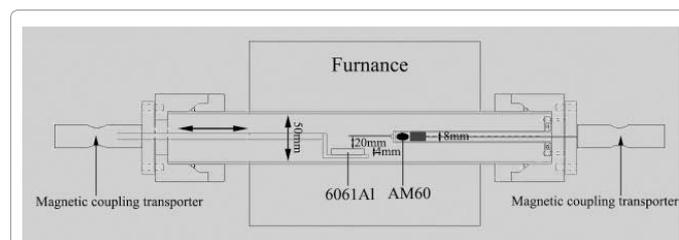


Figure 1: Schematics of high vacuum tube furnace test apparatus.

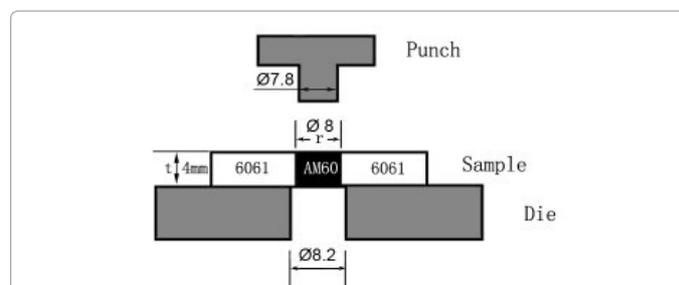


Figure 2: Shear strength test setup for bi-metallic samples (all dimensions in mm).

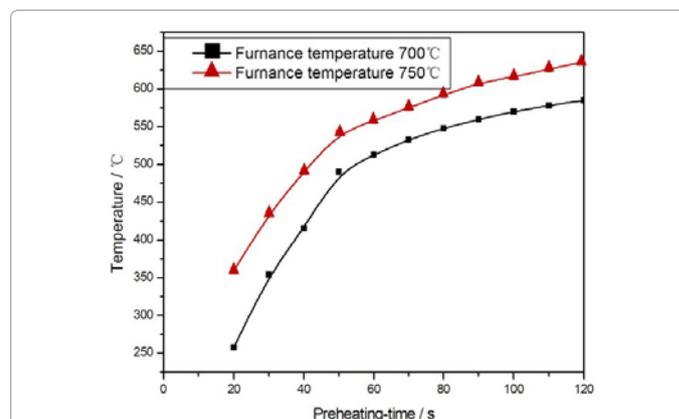
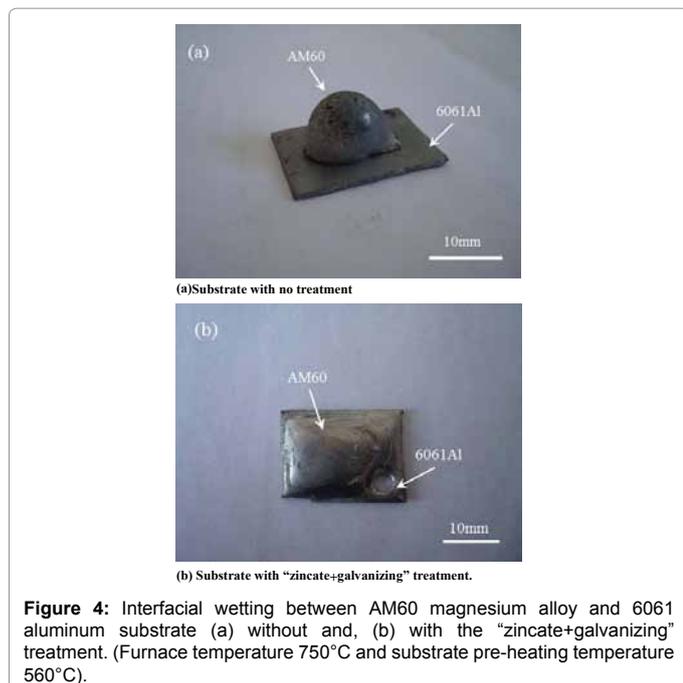


Figure 3: Substrate temperature vs. time at different furnace temperatures.



during cooling, forming dendritic morphology as shown in Figure 5b and 5c. The intermetallic particles shown in Figure 5b away from the Mg/Al interface were identified as $Mg_{17}Al_{12}$ per EDS analysis. The element Mg and Al mapping in Figure 5d and 5e further confirm that dendritic morphology is α -Al containing Mg solute. Therefore, it is feasible to control the interfacial reactions by adjusting the pre-heating temperature and time of the substrate in the actual bi-metallic casting processes.

Interfacial properties

Figure 6 plots the microhardness profile across the interfacial region of a Mg/Al bi-metallic sample (furnace temperature 750°C, and substrate pre-heating temperature 560°C). It is obvious that the interfacial region (about 200 mm wide) shows significantly higher hardness values, due to increased concentrations of alloying elements and $Mg_{17}Al_{12}$ intermetallic particles as shown in Figure 5.

Figure 7 compares the shear strength results of Mg/Al bi-metallic samples prepared at the furnace temperature of 750°C, with different substrate pre-heating temperatures. It shows the shear strengths of the samples with aluminum treatment are 30-90% higher than that of untreated sample. Also, the shear strength of the treated samples increased with the increasing pre-heating temperature. When the pre-heating temperature (590°C) is slightly above the temperature of the 6061 alloy, the shear strength increased significantly due to the enhanced metallurgical bond between magnesium and the substrate where more re-melting likely occurred at 582°C.

Conclusion

1. A "zincate+galvanizing" surface treatment has been developed for aluminum alloys to provide improved wetting with molten magnesium and the aluminum substrates, due to the removal of Al_2O_3 layer and the formation of with a very thin metallic Zn film on the aluminum surfaces.
2. While molten magnesium AM60 alloy does not wet un-treated aluminum alloy 6061 samples, it shows excellent wettability

with aluminum substrates after "zincate+galvanizing" surface treatment, in a high-vacuum bi-metallic test apparatus designed and built in this study.

3. The improved wetting between molten magnesium and treated aluminum substrate provides enhanced metallurgical bond and significantly higher shear strength in the Mg (AM60) /Al (6061) bi-metallic samples.

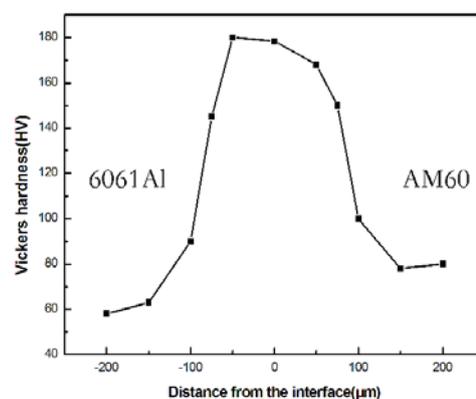
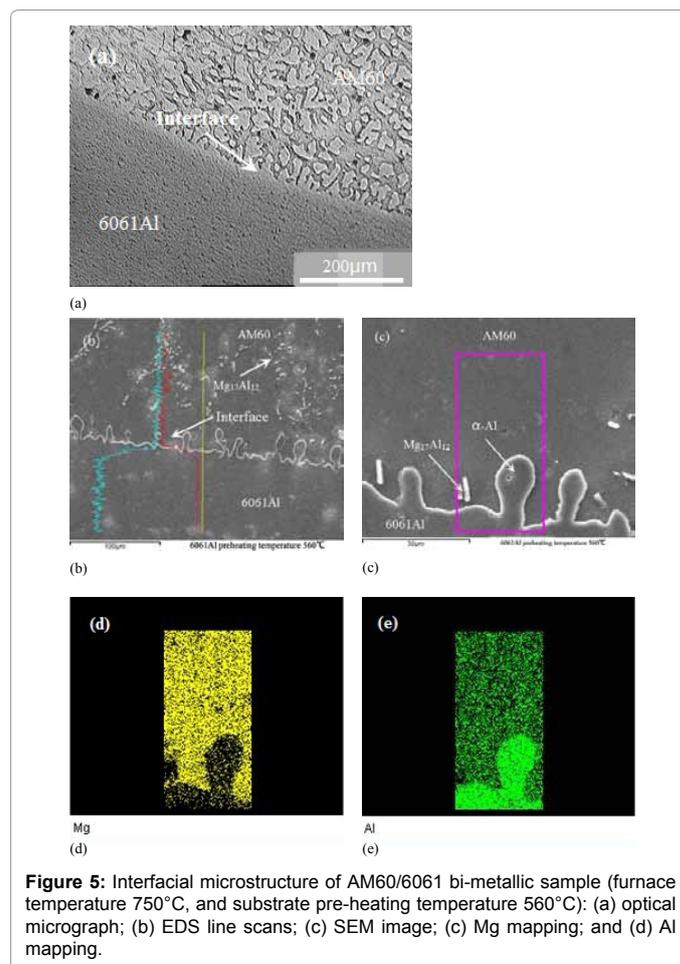


Figure 6: Microhardness measurements across an AM60/6061 interfacial region (furnace temperature 750°C, and substrate pre-heating temperature 560°C).

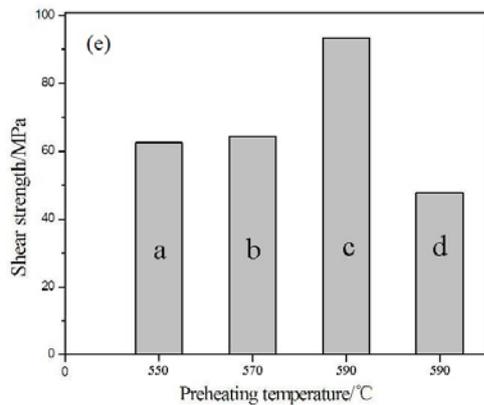


Figure 7: Interfacial shear strength of Mg/Al bi-metallic samples (furnace temperature of 750°C) of different substrate pre-heating temperatures: (a) 550°C/treated; (b) 570°C/treated; (c) 590°C/treated; (d) 590°C/untreated and (e) peak strength comparison.

- The Mg/Al interfacial reactions and metallurgical bond are related to the temperature and time of such interactions. It is, therefore, feasible to control the interfacial reactions by adjusting the pre-heating temperature and time of the substrate in the actual bi-metallic casting processes.

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References

- Taub AI, Krajewski PE, Luo AA, Owens JN (2007) The evolution of technology for materials processing over the last 50 years: The automotive example. *JOM* 59: 48-57.
- Luo AA (2002) Magnesium: Current and potential automotive applications. *JOM* 54: 42-48.
- Alan A. Luo and A.K. Sachdev (2007) Development of light metals automotive structural subsystems proceedings of the 3rd International Conference on Light Metals Technology 2007, 223-228.
- Luo AA, Sachdev AK (2011) Process development and characterization of overcasting systems", in proceedings 115th Metalcasting Congress. American Foundry Society 11-81.
- Hoeschl M, Wagener W, Wolf J (2006) BMW's Magnesium-Aluminium composite crankcase, state-of-the-art light metal casting and manufacturing. SAE Technical Paper 2006-01-0069.
- Porter FC (1991) Zinc handbook. CRC Press, UK.
- Alcoa (2012) Understanding extruded aluminum alloys – Alloy 6061.