

Interfacial microstructure and mechanical properties of A356/6061 bimetal fabricated by liquid-solid compound casting

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Abstract: A356/6061 bimetallic specimens were prepared by liquid-solid compound casting. The effects of various casting conditions on the interfacial microstructure and mechanical properties of the bimetallic specimens were studied. Results demonstrate that a combination of chemical zinc deposition and electroplating can create a dense protective layer on the surface of the 6061 aluminum bar, achieving complete metallurgical bonding at the bimetallic interface. The interfacial microstructure is primarily characterized by equiaxed grain formation, with eutectic silicon distributed along the grain boundaries. Notably, the thickness of the zinc plating layer does not significantly influence the microstructure of the interface transition layer. Pouring temperature is critical for establishing metallurgical bonding at the bimetallic interface, with the thickness of the transition layer increasing as the pouring temperature rises. The hardness of the bimetallic composite interface falls between the hardness values of the two constituent materials. While the thickness of the galvanized layer has a minimal effect on interfacial shear strength, there is a slight decrease in shear strength with increasing pouring temperature, with a maximum value recorded at 68 MPa.

Keywords: bimetal; compound casting; aluminum alloy; interfacial microstructure; mechanical properties

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1 Introduction

Bimetallic composites are innovative materials created through specific manufacturing processes, consisting of a combination of two distinct materials. By synergistically integrating the hardness, thermal conductivity, corrosion resistance, and shear strength properties of these constituent materials, bimetal composites exhibit exceptional physical characteristics and remarkable design versatility^[1-3]. Therefore, they are widely used in automotive, aerospace, electronics industries, etc.^[4]. The forming technologies for bimetallic composites are diverse, encompassing various methods, including rolling, brazing, dual-flow casting, and liquid-solid compound casting^[5-8]. Among them, the

liquid-solid compound casting has garnered significant attention in recent years due to their extensive material selection, high productivity, and cost-effectiveness.

A strong metallurgical bonding interface is crucial for the successful fabrication of bimetallic materials. However, achieving a seamless connection between heterogeneous metals is challenging due to the differences in the properties of the two materials and the presence of a natural oxide layer on the surface of the solid-phase material. Extensive studies have been conducted including the adjustment of casting process parameters and the implementation of anti-oxidation protection measures for the solid-phase matrix^[9-11]. Liu et al.^[12] investigated the effect of extrusion pressure on the microstructure and mechanical properties of the copper-aluminum composite interface. They reported that the thickness of the transition zone gradually decreased with increasing extrusion pressure; however, the tensile strength remained relatively unchanged. Wu et al.^[13] established a metallurgical bonding interface between Al and Fe by precisely controlling

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the melt flow rate and temperature during the die-casting process, with the primary phases of the bonding layer identified as $\text{Al}_{60}\text{Cu}_{30}\text{Fe}_{10}$ and $\text{Fe}_2\text{Al}_{15}$. Notably, aluminum alloys, when used as solid-phase substrates, are more susceptible to oxidation compared to iron and copper substrates. The melting point of the oxide layer is significantly higher than that of the aluminum itself, and this oxidation phenomenon is further exacerbated at elevated temperatures. Schwankl et al. [14] successfully formed a zinc coating on the surface of wrought aluminum alloys through zincate treatment, achieving metallurgical bonding with cast aluminum alloys. This was confirmed by mechanical testing results, demonstrating excellent metal bonding performance. Li et al. [15] conducted a comprehensive investigation on the impact of various surface coatings on the interface microstructure and properties of aluminum/magnesium bimetal castings. The results indicated that aluminum/magnesium bimetallic castings treated with plasma-sprayed nickel exhibited a significant improvement in shear strength compared to those with zinc coatings and nickel-copper composite coatings. Specifically, the shear strength increased by 69% compared to untreated bimetallic castings.

Currently, significant progress has been made in the research on liquid-solid composite bonding of Fe/Al [16], Al/steel [17], Cu/Al [5,18], and Al/Mg [19-22]. However, studies focusing on the interfacial microstructure and mechanical properties of two aluminum alloys with similar melting points are still scarce. Cast aluminum alloys are widely utilized in industrial production due to their excellent casting properties, favorable heat treatment characteristics, and superior strength-to-weight ratio along with ductility. In contrast, wrought aluminum alloys offer excellent machinability, good plating characteristics, significant corrosion resistance, and high toughness [23]. A356 aluminum alloy is a commonly used high-silicon aluminum alloy, known for its excellent fluidity. It is well-suited for gravity casting, low-pressure casting, high-pressure casting, and other casting processes, making it ideal for producing complex and structurally intricate castings. As a wrought aluminum alloy, 6061 aluminum is widely used across aerospace, automotive, marine, and construction industries due to its high strength, excellent toughness, corrosion resistance, and superior machinability. Therefore, the A356/6061 bimetallic material combines the outstanding properties of both aluminum alloys, offering the potential for a broader range of applications.

In this study, the liquid-solid compound casting process was employed to fabricate a bimetallic composite material consisting of A356 and 6061 aluminum alloys. The microstructural characteristics and mechanical properties of the interface in the bimetallic composite were investigated through microscopic characterization and mechanical property testing, while simulation software ProCast was utilized to model the compound casting process. Subsequently, the influence of casting conditions on both the microstructure and mechanical properties of the bimetallic composite samples was discussed.

2 Experiment

2.1 Materials and surface treatment

The two aluminum alloys utilized in the experiment comprised A356 aluminum ingot and 6061 aluminum bar. The chemical composition of these materials, as determined by ICP-OES analysis, is presented in Table 1.

Table 1: Chemical composition of A356 and 6061 aluminum alloys (wt.%)

Alloy	Si	Fe	Zn	Mg	Cu	Mn	Al
A356	6.50	0.10	0.35	0.25	0.25	0.35	Bal.
6061	0.60	0.45	0.25	0.94	0.23	0.15	Bal.

The 6061 aluminum bar was cut into the required dimensions for the experiment, measuring $\Phi 8 \text{ mm} \times 160 \text{ mm}$. Due to oil stains and the formation of a dense Al_2O_3 oxide layer on its surface during processing, this oxide layer remains undissolved during composite process due to its higher melting point compared to liquid aluminum, thereby impeding metal bonding [24]. To address this issue, the experimental approach involved mechanical grinding, chemical zinc deposition treatment, and a combination of chemical zinc deposition followed by electroplating. Firstly, the surface of the 6061 aluminum bar was mechanically grinded in a sequential manner using #240, #800, and #2000 sandpapers to eliminate the oxide layer on its surface. Subsequently, the ground 6061 aluminum bar was immersed in an aluminum cleaning solution with a water-to-aluminum ratio of 1:9 at room temperature for a duration of 10 min to remove any residual substances on its surface. The bar was then rinsed with deionized water and dried. Subsequently, the 6061 aluminum bar undergone a 5 min immersion in zincate solution, followed by rinsing with deionized water and drying post completion of the chemical zinc deposition process. Finally, following mechanical grinding + chemical zinc deposition + electroplating zinc treatment, the electroplating zinc process was carried out. It is essential to maintain the electroplating bath temperature at approximately 35 °C, set the output voltage of the power supply to 0.5 V, ensure a current density of 50 $\text{mA} \cdot \text{cm}^{-2}$, and a time adhere to specific electroplating of 5 min, 10 min, and 15 min, respectively. Throughout this process, Zn^{2+} ions are directed to form a layer of metal accumulation.

2.2 Casting process

After cutting and sizing the A356 aluminum ingot and removing surface impurities, it was placed in a resistance melting furnace for melting. In order to prevent rapid cooling of the A356 aluminum melt during the bimetallic compounding process and to ensure sufficient interfacial reaction time, both the metal mold and the pretreated 6061 aluminum bar need to be preheated prior to pouring. The metal mold was preheated to 300 °C in this process, while the

6061 aluminum bar, which has undergone surface treatment, was preheated to 200 °C. The preheated 6061 aluminum bar was fixed in the middle of the mold cavity, which was 20 mm away from the bottom of the mold cavity. A356 aluminum liquid was poured from the mold sprue cup after refining and dross removal, and the pouring temperatures were 650 °C, 670 °C, 700 °C, 730 °C, and 750 °C, respectively. The casting process is shown in Fig. 1.

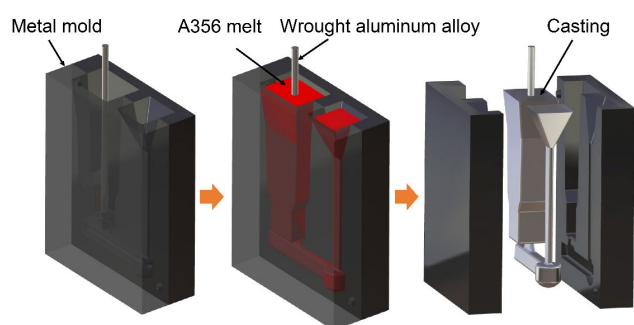


Fig. 1: Schematic illustration of the compound casting process

2.3 Microstructure characterization and mechanical property testing

The casting position shown in Fig. 2(a) was sampled using a wire cutting method, followed by sequential grinding with metallographic sandpapers of grit sizes #600, #1200, #2000, and #4000. Subsequently, the sample underwent polishing using diamond spray with granularity of 3 μm and 0.5 μm, and finally was etched for 15–20 s using a solution containing

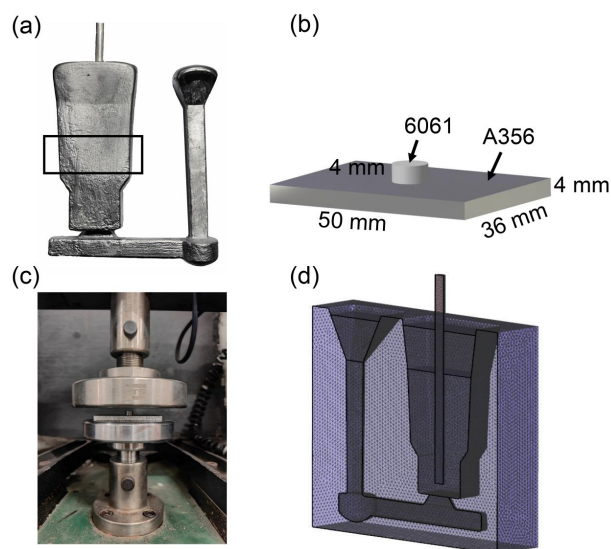


Fig. 2: Casting (a), shear specimen and size (b), shearing process (c), and mesh for simulation (d)

5% HF. The microstructure of the composite interface was analyzed using an optical microscope (OM) and a field emission scanning electron microscope (SEM) equipped with EDS. The thickness and grain size of the composite interface layer were measured using ImageJ 6.0 image analysis software. The HV-1000 A Hua Yin hardness tester was employed to assess the interface hardness of the bimetal composite sample. The shear strength of the A356/6061 composite interface was determined using a 10 kN mechanical testing machine for mechanical evaluation. The average value obtained from three samples was considered for each parameter. Figures 2(b–c) illustrate the specimen size and the procedure for the press-out experiments conducted to evaluate the shear strength of the bimetallic interface. The press-out experiments were performed using a 10 kN mechanical testing machine, and the average results from three specimens were calculated for each set of parameters.

2.4 Simulation of the compound casting process

The ProCAST software was utilized to simulate the compound casting process. By utilizing the software's built-in material database, the thermal physical properties of relevant materials such as A356 and 6061 aluminum alloys were determined. Table 2 presents the key thermal physical properties of these two alloys employed in the simulation. To enhance the simulation accuracy, a refined mesh consisting of 5,645,422 elements was employed in the simulation [Fig. 2(d)], while strategically positioned virtual sensors were utilized to record interface temperature data at critical locations throughout the entire filling and solidification process of the A356 melt and 6061 solid matrix sample.

3 Results and discussion

3.1 Morphology and thickness of zinc coating on the surface of 6061 aluminum bar

The thickness and compactness of the zinc coating on the surface of 6061 aluminum bars are intricately linked to the parameters of the surface treatment process. Following 5 min of chemical zinc deposition, the zinc coating formed on the surface of the 6061 aluminum bar has a thickness ranging from 200 to 500 nm^[25]. This ultra-thin zinc layer arises due to cessation of ion exchange processes upon complete coverage by the zinc layer. The cross-sectional morphologies of zinc coating deposited on the surface of 6061 aluminum bar by chemical zinc deposition for 5 min and different electroplating zinc time are illustrated in Fig. 3. After electroplating for 5 min, 10 min, and 15 min, the resulting zinc coating thicknesses

Table 2: Main thermal properties of A356 and 6061 aluminum alloys

Alloy	Specific heat	Thermal conductivity	Liquidus temperature	Solidus temperature	Latent heat
A356	962 J·(kg·K) ⁻¹	151 W·(m·K) ⁻¹	615 °C	555 °C	388,693 J·kg ⁻¹
6061	895 J·(kg·K) ⁻¹	167 W·(m·K) ⁻¹	652 °C	585 °C	358,987 J·kg ⁻¹

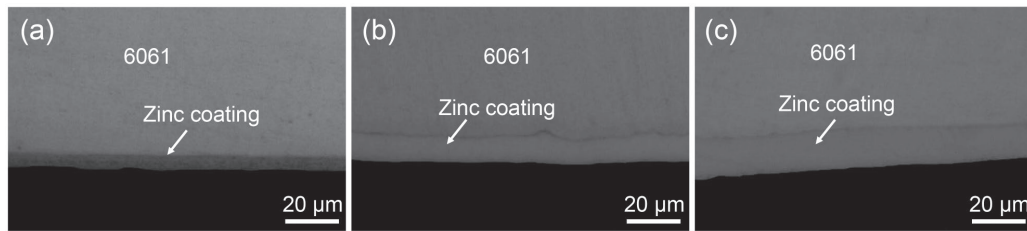


Fig. 3: Cross-sectional morphology of 6061 aluminum bar and thickness of zinc coating: (a) electroplating zinc for 5 min; (b) electroplating zinc for 10 min; (c) electroplating zinc for 15 min

are measured be 4 μm , 9 μm , and 13 μm , respectively. The efficiency of zinc electrodeposition is observed to decline as the plating duration increases. As a consequence of the plating process, Zn^{2+} is deposited and nucleated on the surface of the 6061 aluminum bar under the influence of electric current. The interface between the zinc coating and the electroplating solution forms a boundary transition layer. Initially, there is an equilibrium between solution components in this layer and those in the electroplating solution, resulting in rapid deposition of Zn^{2+} . Subsequently, as more zinc particles accumulate and grow during continued electroplating, causing an increase in coating thickness. A decrease in activation performance of anode zinc plate leads to a higher consumption rate than replenishment rate within this transition layer, consequently reducing electroplating efficiency^[26].

Figure 4 illustrates the microscopic morphology and corresponding EDS mapping results of the surface of 6061 aluminum bar following chemical zinc deposition and various durations of electroplating zinc. After 5 min of chemical zinc deposition, as shown in Fig. 4(a), the surface of the coating

exhibits significant irregularities. Corresponding EDS scanning results for Al and Zn elements are presented in Figs. 4(b–c), revealing the persistent presence of a substantial amount of Al elements on the sample surface. This observation indicates that the zinc coating formed on the surface of 6061 aluminum bar by chemical zinc deposition has the characteristics of uneven coverage and low density. After undergoing an additional 5 min electroplating zinc process, the surface of the test sample coating exhibits enhanced uniformity and compactness, as shown in Figs. 4(d–f). With an increase in plating time to 15 min, the plated surface of the specimen exhibits greater homogeneity and density, with minimal detection of Al elements.

The cross-sectional SEM image and line scanning results of Al, Zn, and O elements after 15 min of zinc electroplating are presented in Fig. 5. It is evident that the electroplated zinc layer exhibits a uniform thickness with smooth transitions for each element. Notably, no aggregation of O elements is observed at the interface, indicating the effective protection against oxidation provided by the dense electroplated zinc layer on the surface of the 6061 aluminum bar.

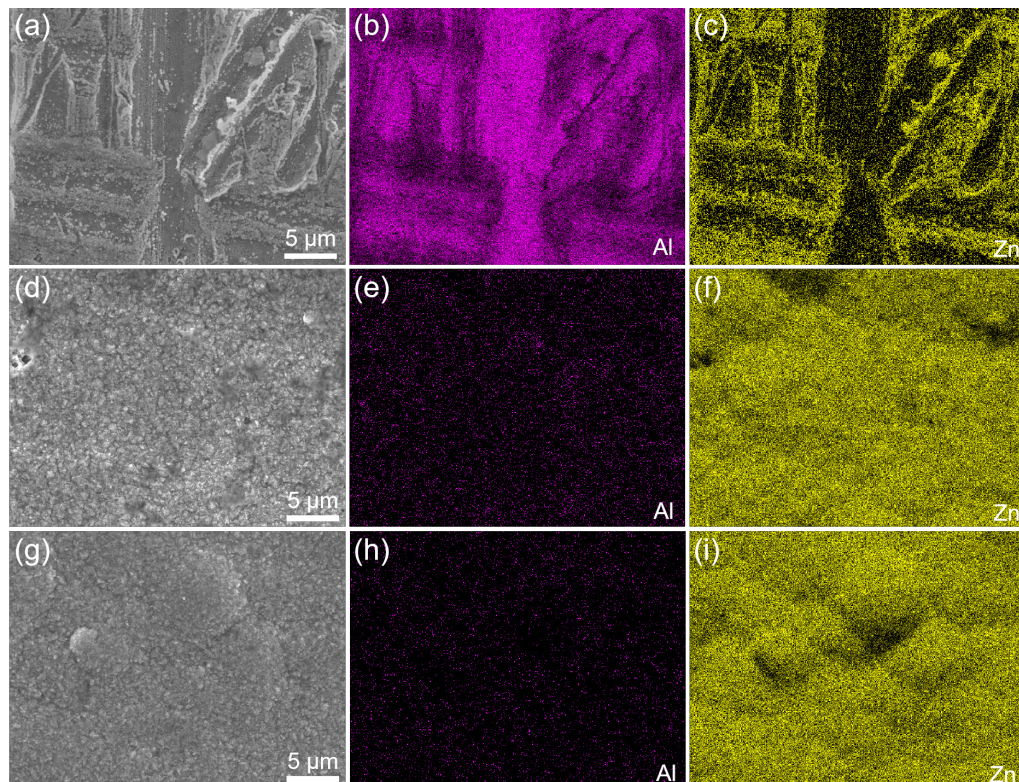


Fig. 4: Surface microscopic morphology and corresponding EDS mapping results of 6061 aluminum bar: (a–c) chemical zinc deposition for 5 min; (d–f) electroplating zinc for 5 min; (g–i) electroplating zinc for 15 min

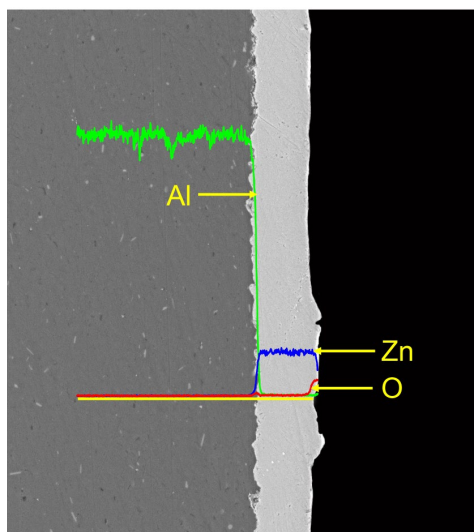


Fig. 5: SEM image and EDS line scanning results of the cross-section of 6061 aluminum bar after 15 min of zinc electroplating

3.2 Bimetallic bonding interface with different surface treatment processes for 6061 aluminum bar

The interfacial microstructure of the bimetal composite samples with different surface treatment processes for the 6061 aluminum bar at a pouring temperature of 700 °C is shown in Fig. 6. The 6061 aluminum bar exhibits a cast-rolled state, characterized by a microstructure with the absence of discernible grain boundary. The A356 microstructure primarily consists of α -Al dendrites and uniformly dispersed eutectic Si phase. As shown in Fig. 6(a), a noticeable gap exists between the mechanical grinding 6061 aluminum bar and the A356 aluminum alloy, indicating an absence of metallurgical bonding. By employing chemical zinc deposition on the 6061

aluminum bar, a limited amount of metallurgical transition layer is formed at the interface between these two metals. However, as illustrated in Fig. 6(b), a significant portion of the interface still exhibits a discernible gap. After zinc electroplating, a continuous transition layer approximately 200 μm wide forms on the side of the 6061 aluminum alloy at the A356/6061 bimetal interface. The absence of inclusions, pores, or other defects in the transition layer indicates a robust metallurgical bond has been successfully formed at the interface between the two metals [Figs. 6(c-e)]. On the A356 aluminum alloy side, a columnar grain zone grown along vertical direction of interface is observed near the interface. This phenomenon arises from the initial lower temperature (200 °C) of the 6061 aluminum bar, resulting in a high cooling rate when it comes into contact with the high-temperature A356 molten metal. Consequently, fine grains are formed initially, α -Al dendrites begin growing from the 6061 aluminum alloy side toward the A356 aluminum alloy side, which runs parallel to the heat flow, but in the opposite direction, ultimately forming a distinct vertical columnar grain zone at the interface. As the thickness of the zinc coating increases, no significant variation is observed in the thickness of the interfacial transition layer.

In the bimetallic composite fabrication process, different surface treatments are essential for achieving effective metallurgical bonding between the two metals. The oxide layer on the surface of the 6061 aluminum bar is eliminated through mechanical polishing. However, re-oxidation occurs during preheating and pouring process, thereby impeding the formation of a metallurgical transition layer. Given that the thickness of the chemically deposited zinc layer is less than 1 μm , it can be readily vaporized by high-temperature metal flow washout, thereby re-exposing the fresh aluminum substrate to atmospheric condition. Consequently, under high-temperature condition, rapid formation of an oxide film occurs, resulting

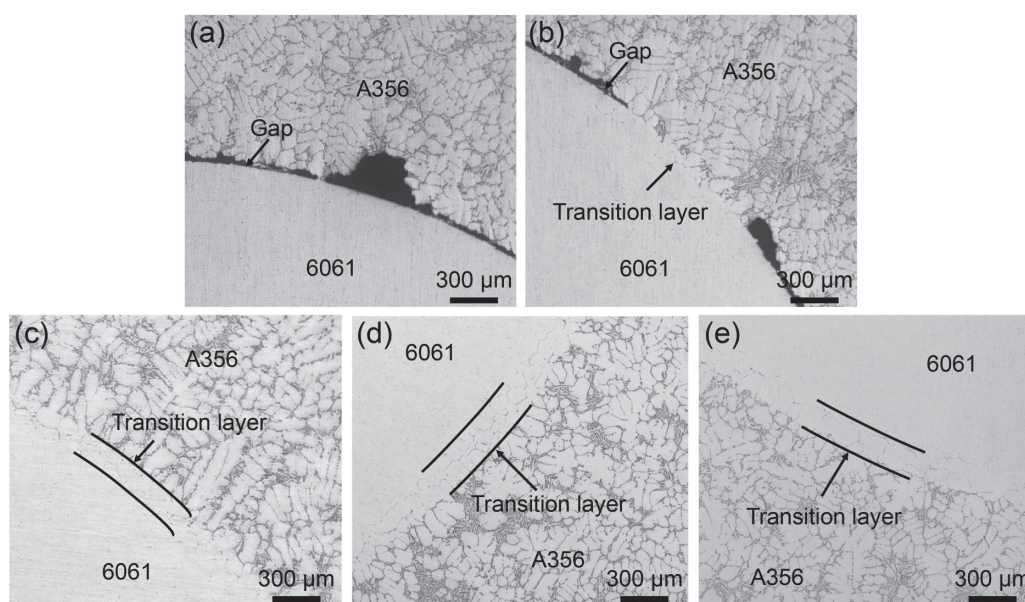


Fig. 6: Bonding interface with different surface treatment processes for 6061 aluminum bar: (a) mechanical grinding; (b) chemical zinc deposition for 5 min; (c) electroplating zinc for 5 min; (d) electroplating zinc for 10 min; (e) electroplating zinc for 15 min

in only partial achievement of metallurgical bonding at the interface. The SEM image and distribution map of the main elements, including Al, Si, Mg, and Zn, at the interface of the A356/6061 bimetal specimen, are presented in Fig. 7. The pouring temperature is set at 700 °C with a galvanizing time of 15 min. In the A356 aluminum alloy, Si serves as the primary alloying element, whereas in the 6061 alloy, the content of the main alloying element is less than 1%. Consequently, a distinct continuous interface exists between the A356/6061 bimetal system. The transition layer on the 6061 aluminum side exhibits predominantly equiaxed grain structure with grain boundaries distributed through eutectic silicon diffusion from the A356 aluminum alloy side. Furthermore, owing to zinc's low melting point (420 °C) and its high solubility in aluminum, during compound process, a uniform dissolution and diffusion of a 13 µm thick zinc layer electroplated onto both sides of the

aluminum alloy occurs without any discernible accumulation of zinc at the bonding interface.

3.3 Bimetallic bonding interface with different pouring temperatures

The interfacial microstructure of the A356/6061 bimetal composite specimens with different pouring temperatures after 10 min of electroplating zinc are presented in Fig. 8. As shown in Fig. 8(a), at a pouring temperature of 650 °C, there is a distinct gap between the two metals, however, bonding has initiated in some interface areas. This can be attributed to the rapid cooling of the melt and the limited diffusion time for elements, resulting in clustering of eutectic Si phase within the bonding region. When the pouring temperature is set at 670 °C and 700 °C, a seamless metallurgical bonding is successfully achieved between the two metals, exhibiting a bonding zone thickness of approximately

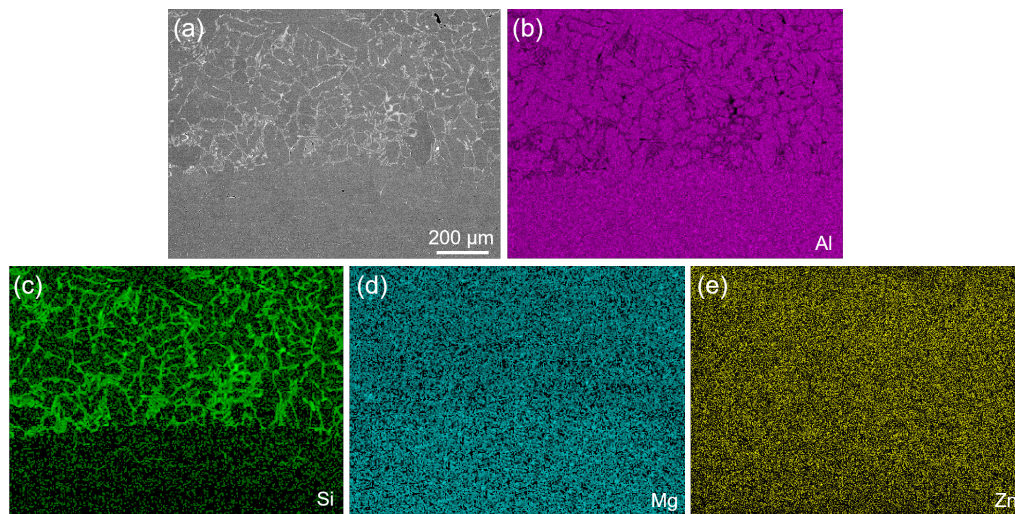


Fig. 7: SEM image (a) and corresponding element distribution (b-e) of bonding interface of the bimetallic sample with pouring temperature of 700 °C and electroplating zinc for 15 min

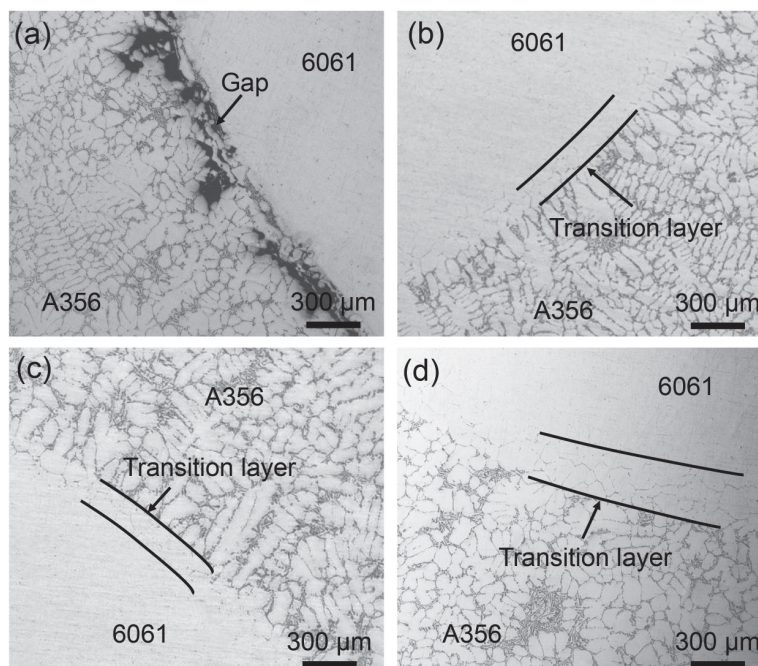


Fig. 8: Bonding interface with different pouring temperatures: (a) 650 °C; (b) 670 °C; (c) 700 °C; (d) 730 °C

200 μm . The distinction lies in the fact that at 670 $^{\circ}\text{C}$, the melt cools more rapidly, resulting in the formation of denser and vertically ordered columnar crystals on one side of the A356 alloy, along with a more homogeneous distribution of eutectic silicon. As the pouring temperature increases to 730 $^{\circ}\text{C}$, the remelting zone of the 6061 aluminum bar widens, resulting in an expansion of the transition layer thickness to 260 μm . Nevertheless, when the pouring temperature is further increased to 750 $^{\circ}\text{C}$, substantial deformation due to melting occurs in the 6061 aluminum bar. Consequently, the 6061 aluminum alloy loses its suitability as a high-strength preform material, rendering it unsuitable for forming bimetal composite materials.

3.4 Mechanical properties

The hardness distribution at the A356/6061 bimetal interface under different surface treatment methods for the 6061 aluminum bar is shown in Fig. 9(a). Additionally, Fig. 9(b) illustrates the interfacial hardness distribution of the A356/6061 bimetallic specimens, which are prepared by adjusting the pouring temperatures of A356 with electroplated zinc for 10 min. Based on Fig. 9(a), it is evident that the average hardness of the 6061 aluminum alloy is 54.8 HV, whereas the A356 aluminum alloy exhibits an average hardness of 69.5 HV. For the bimetallic specimens subjected to surface treatment process for the 6061 aluminum bar involving mechanical grinding and chemical

zinc deposition, a distinct gap is observed at the bimetal interface, resulting in a sudden increase in hardness from 52–59 HV to 67–72 HV within the interface region. Following the electroplating of the zinc layer, a metallurgical bonding is achieved between the two metals, with the hardness of the transition layer falling within the range of hardness values for both materials. As a result, the hardness gradually increases from 52–59 HV to 67–72 HV in the interface region. The results obtained with different pouring temperatures of A356, as shown in Fig. 9(b), exhibit similarities to those observed in Fig. 9(a). In the absence of metallurgical bonding, the hardness value undergoes a sudden change from 6061 aluminum alloy to A356 aluminum alloy; however, when metallurgical bonding is achieved at pouring temperatures of 670–730 $^{\circ}\text{C}$, the hardness in the interface region becomes intermediate between that of the two metals.

Figure 10(a) illustrates the shear strength of the A356/6061 bimetal interface subjected to different surface treatment methods for the 6061 aluminum bar at a pouring temperature of 700 $^{\circ}\text{C}$ of A356, while Fig. 10(b) depicts the shear strength of the A356/6061 bimetal interface under electroplating zinc for 10 min with different pouring temperatures. From Fig. 10(a), it is evident that there is no metallurgical bonding between the mechanical grinding 6061 aluminum bar and the A356 aluminum alloy, resulting in a shear strength approaching

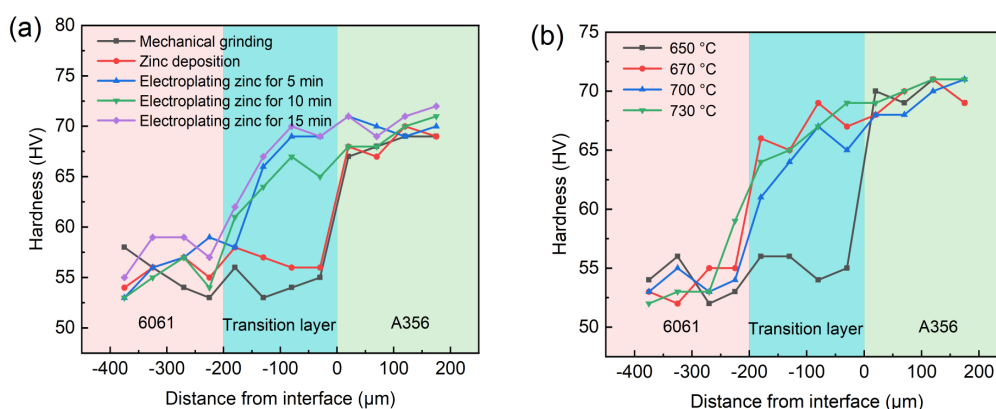


Fig. 9: Hardness distribution at the bimetal interface: (a) bimetal samples with different surface treatment processes for the 6061 aluminum bar at a pouring temperature of 700 $^{\circ}\text{C}$ of A356; (b) bimetal samples with different pouring temperatures under electroplating zinc for 10 min

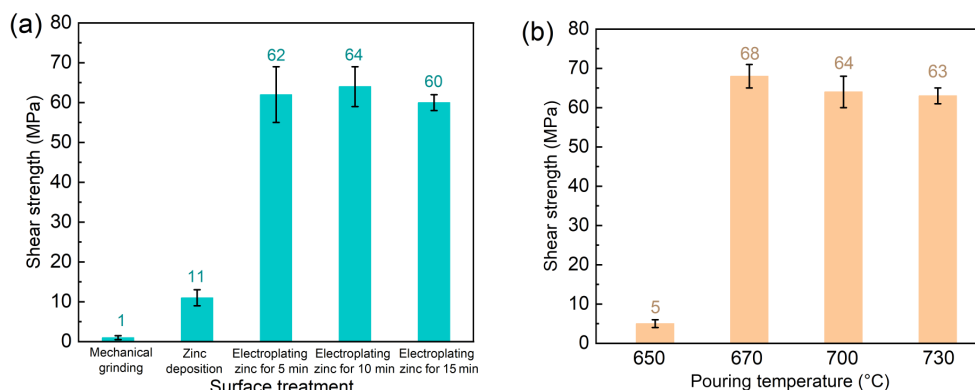


Fig. 10: Shear strength of the bimetal interface: (a) bimetal samples with different surface treatment processes for 6061 aluminum bar at a pouring temperature of 700 $^{\circ}\text{C}$; (b) bimetal samples with different pouring temperatures under electroplating zinc for 10 min

0 MPa. However, upon chemical zinc deposition, metallurgical bonding forms partially at the interface of the bimetal material, leading to an approximate shear strength of 11 MPa. Electroplating zinc for 5 min, 10 min, and 15 min further enhances the metallurgical bonding at the interface of the bimetal specimens and significantly increases its shear strength, reaching a maximum value of 64 MPa when electroplating zinc for 10 min. Notably, due to uniform diffusion of zinc coating into aluminum alloys during compound process, variations in zinc coating thickness have diminutive impact on the shear strength of the interface^[27]. When the pouring temperature is set at 650 °C, only a limited portion of the interface between the two metals exhibits metallurgical bonding, resulting in an interfacial shear strength of merely 5 MPa. With an increase in pouring temperature, complete metallurgical bonding is achieved across the entire interface, leading to a significant improvement in shear strength with a maximum value of 68 MPa at a pouring temperature of 670 °C. Notably, as the pouring temperature continues to rise, there is a slight decrease of the interfacial shear strength.

4 Discussion

Prior research has reported that two important factors influencing the metallurgical bonding between the liquid and solid phases in compound casting of dual metals are close contact between the double metals and reaching a certain temperature at the interface^[28]. Following the surface treatment process of electroplating zinc, the 6061 aluminum bar is successfully protected from oxidation and enhanced in surface wetting properties. Due to the low melting point and high solubility of zinc in aluminum alloy, the electroplated zinc layer is completely dissolved and diffused during the bimetal compound casting process, thereby facilitating intimate contact between the A356 aluminum melt and the

fresh 6061 aluminum bar substrate. Moreover, by elevating the pouring temperature, sufficient superheat is achieved in the liquid melt to ensure complete reaction between these two metals during solidification. Figure 11 presents SEM images at the bonding interface of bimetallic samples as well as Zn element distribution with different pouring temperatures (650 °C and 670 °C) under electroplating zinc for 10 min. When the pouring temperature is set at 650 °C, complete metallurgical bonding is not achieved at the interface between the two metals. A distinct aggregation of Zn element is observed, indicating incomplete dissolution and diffusion of the zinc coating. However, when the pouring temperature is increased to 670 °C, no aggregation of Zn element occurs at the interface where complete metallurgical bonding is formed. The electroplated zinc layer diffuses evenly into both sides of the aluminum alloy. This result further confirms that apart from surface treatment for solid phase substrate, pouring temperature also plays a pivotal role in the compound process of the double metals.

The bimetallic liquid-solid composite casting process was simulated using ProCAST software, and temperature change curves of the bimetallic interface were obtained at various pouring temperatures from the sampling positions (Fig. 12). When the melt temperature of A356 is lower than its dendrite coherency point temperature at which the fraction solid of the melt is about 0.2, the formation of a rigid dendritic network weakens fluid flow, thereby insufficiently affecting the metallurgical reaction between the melt and solid matrix surface^[29]. For A356 aluminum alloy, the dendrite coherency point temperature is about 580 °C. Since it is lower than the solidus temperature of 6061 aluminum alloy (585 °C), the study focuses on identifying the highest temperature at the bimetallic interface and the time exceeding the solidus temperature of 6061 aluminum alloy. The simulation outcomes are presented in Table 3.

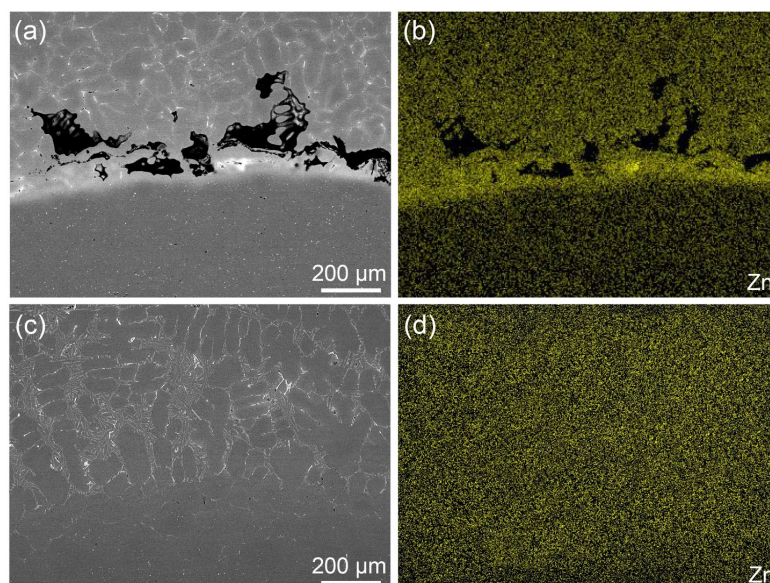


Fig. 11: SEM images of bimetallic bonding interface and Zn element distribution with different pouring temperatures under electroplating zinc for 10 min: (a, b) 650 °C; (c, d) 670 °C

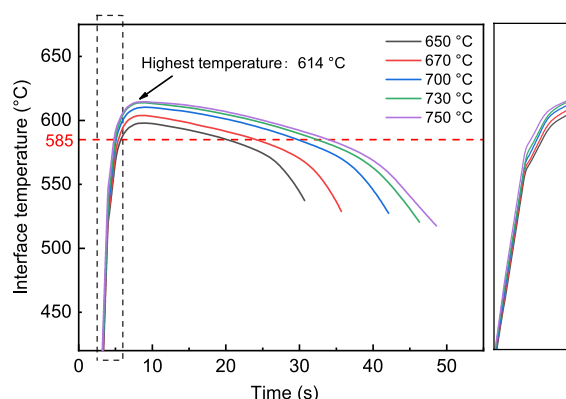


Fig. 12: Temperature variation curves of the bimetallic interface with different pouring temperatures

Table 3: Highest temperature at bimetallic interface and time exceeding solidus temperature of 6061 aluminum alloy

Pouring temperature	Time above 585 °C	Highest temperature
650 °C	13.8 s	596 °C
670 °C	19.3 s	602 °C
700 °C	23.2 s	608 °C
730 °C	28.5 s	612 °C
750 °C	30.2 s	614 °C

When the pouring temperature is 650 °C, the bimetallic interface exhibits a maximum temperature of 596 °C, which surpasses the solidus temperature of the 6061 aluminum alloy for a duration of 13.8 s. Under this specified condition, an exceedingly thin micro-melted zone is formed on the surface of the 6061 aluminum bar. Subsequently, during solidification of the A356 melt, shrinkage formation leads to tensile force at the interface. Due to partial bonding and a narrow transition layer, gaps and pores are generated at the bimetallic interface under the influence of tensile force caused by solidification shrinkage. At a pouring temperature of 750 °C, the maximum temperature at the bimetallic interface reaches 614 °C, exceeding the solidus temperature of the 6061 aluminum alloy by 30.2 s. The elevated pouring temperature leads to increased heat release during solidification of A356 melt, resulting in localized deformation of the 6061 aluminum alloy matrix and subsequently impacting the bonding quality of the composite material. To achieve the optimal bonding at the interface of bimetallic, the key lies in controlling the pouring temperature of the casting aluminum alloy within an appropriate range. This ensures that the temperature at the bimetallic interface remains above the solidus temperature of the solid-phase aluminum alloy for a sufficiently long period, thereby facilitating a full liquid-solid reaction between the two metals.

The metallurgical bonding process between A356 and 6061 alloys during liquid-solid compound casting is illustrated in Fig. 13. Upon pouring the high-temperature A356 aluminum liquid into the mold, the zinc coating on the surface of the 6061 aluminum bar dissolves and diffuses into both aluminum

alloys due to the influence of the elevated melt temperature. As a result, when fresh 6061 aluminum alloy matrix closely contacts with the A356 melt, a micro-melted region forms, blending with the A356 melt to establish a foundation for metal bonding formation. Due to the concentration gradient, Si atoms in the molten A356 aluminum alloy absorb sufficient thermal energy and diffuse, resulting in the formation of a transition layer characterized by predominantly equiaxed grains. Simultaneously, nuclei are formed within the A356 aluminum alloy based on this transition layer and grains grow perpendicularly to the interface with respect to heat flow direction, giving rise to columnar grains^[30]. With increased undercooling and interface distance, some of these columnar grain tips exhibit branching growth patterns, ultimately developing into dendrites that seamlessly connect two metal interfaces.

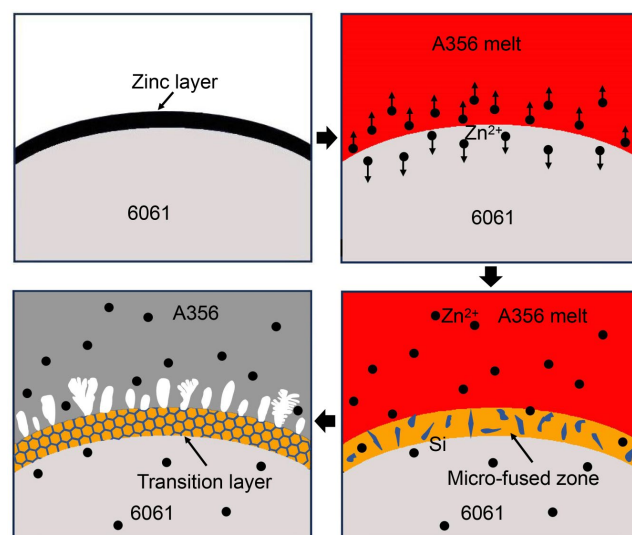


Fig. 13: Bonding mechanism of the liquid-solid composite A356/6061 bimetallic interface

5 Conclusions

(1) After mechanical grinding and chemical zinc deposition pretreatment, the electroplating of zinc results in the formation of a dense zinc coating on the surface of 6061 aluminum bar, with the thickness of the electroplated layer being directly proportional to the duration of electroplating.

(2) With the subsequent process of chemical zinc deposition followed by electroplating treatment, a continuous transition layer is formed at the A356/6061 bimetal interface when the pouring temperature reaches 670 °C. The transition layer primarily consists of equiaxed grain structure with silicon present at the grain boundaries. No accumulation of Zn element is detected at the bimetallic interface. When the pouring temperature increases from 670 to 730 °C, the width of the interface transition layer exhibits an increment from 200 μm to 260 μm.

(3) When a metallurgical bonding is formed at the A356/6061 bimetallic interface, no discernible trend in microhardness is observed within the interface region as the

thickness of the zinc coating and the pouring temperature increase. The hardness of the interface transition layer lies between the hardness values of the two alloys. Variations in the thickness of the zinc coating do not significantly affect the shear strength of the bimetallic interface. However, an increase in pouring temperature slightly reduces the shear strength of the bimetallic interface, with a maximum shear strength of 68 MPa reached at 670 °C.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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