

Research Article

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Promoting of metallurgical bonding by ultrasonic insert process in steel–aluminum bimetallic castings

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Abstract: It is challenging to efficiently prepare bimetallic composites with excellent metallurgical bonding. Here, we present a strategy, the ultrasonic insert casting (UIC) process, to solve this problem. The ultrasound cavitation effectively destroys the oxide film and promotes diffusion in the UIC-prepared steel/aluminum bimetallic castings, resulting in a uniform reaction layer between steel and aluminum. The reaction layer contains FeAl_3 , $\text{Al}_8\text{Fe}_2\text{Si}$, and $\text{Al}_{4.5}\text{FeSi}$, and has a higher microhardness than the steel/aluminum matrix, with an average thickness of 8 μm . Moreover, the thickness of the reaction layer increases with the improvement of pouring temperature but the thicker reaction layer (approximately 12 μm) does not bring higher strength. The highest shear strength, about 70 MPa, is approximately three times higher than that without ultrasonic treatment. These results indicate a useful strategy for the low cost and high-efficiency preparation of metallurgical bonding bimetallic casting.

Keywords: ultrasonics, liquid–solid reactions, intermetallics, microstructure

1 Introduction

Through the complementing benefits of the two materials, bimetal composite materials may achieve both strong and tough capabilities, enabling them to satisfy the needs for varied material qualities in production practice. Furthermore, a well-balanced combination design can result in the lightweighting

of materials, therefore achieving the goal of energy conservation and emission reduction [1,2]. To date, solid–solid [3,4], solid–liquid [5–7], and liquid–liquid [8] composite casting technologies are used to produce bimetallic composites, and the solid–liquid composite casting technology has the benefits of wide adaptability, high efficiency, and a short process. The solid–liquid composite casting technology is the technique of pouring molten metal into the inserted metal, which is installed in the mold, generating a continuous intermetallic diffusion zone through the diffusion reaction between the solid and liquid phases, and solidifies as a component [9,10]. The traditional solid–liquid composite casting process, on the other hand, is not suitable for producing bimetallic composites such as steel/aluminum bimetallic castings because preheating the solid phase causes an oxide layer to develop on the steel surface, and prevents interface bonding [11]. To increase the wettability of dissimilar metals by avoiding oxidation, hot aluminizing [12,13], zinc coating surface modification [14], and electronickeling [15,16] are utilized. Although these technologies can achieve metallurgical bonding interfaces, there are still issues such as difficult control of the thickness of the intermetallic compound bonding layer and complicated preparation technology. As a result, preparing bimetallic composites with strong metallurgical bonding at a cheap cost and with high efficiency remains a challenge.

Unlike the protective coating approach, ultrasonic insert casting (UIC) promotes the metallurgical bonding of the interface without the need for an extra element [17]. When an ultrasonic wave propagates and interacts with diverse material, it can cause a variety of effects, including mechanical effects, thermal effects, acoustic flow effects, and cavitation effects [18–20]. The cavitation effect is frequently employed in casting to refine the grain size and improve metallurgical bonding between the reinforcing phase and molten metal by improving wettability. The effects of ultrasonic operation time and output power on the microstructure and properties of the interface bonding layer were further examined [11]. As a result,

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UIC may be more appropriate for solid–liquid composite preparation of bimetallic composites with excellent metallurgical bonding interfaces. However, there is an insufficiency in the relationship between interface microstructure and mechanical properties of bimetallic castings produced using the solid–liquid process with ultrasonic.

In this study, UIC was utilized to fabricate carbon steel and aluminum bimetal castings. The impact of ultrasonic on interface phase and microstructure formation, as well as the impact of varied pouring temperatures on the influence of interface microstructure on bimetallic bonding properties, were studied.

2 Materials and methods

The ASTM 1045 carbon steel and A356 aluminum alloy raw materials were commercially bought to fabricate the steel and aluminum bimetallic castings. Rod-like carbon steel was used as an insert with an 8 mm diameter and 55 mm height. The surface of the steel insert was ground with SiC paper up to 800 grit. To eliminate oil and rust from the steel surface, the steel inserts were immersed in 10% sodium hydroxide solution and 1 mol·L⁻¹ hydrochloric acid solution for 1 min each.

The steel/aluminum bimetallic castings were prepared using the apparatus shown in Figure 1. A steel bar was inserted into the non-preheated metal mold, and the molten A356 aluminum alloy was poured into the mold cavity at 750°C; in the meantime, ultrasonic vibration was directly introduced to the steel bar during the pouring period through a needle-shaped impact bit before the horn of an ultrasound transducer. The output power of the ultrasound transducer was 1,000 W and the frequency was 20 kHz. Finally, a bimetallic casting sample was taken out of the mold after cooling down naturally. Comparative castings obtained without ultrasonic vibration were poured with the same experimental condition. In addition, bimetal castings with different pouring temperatures (720 and 780°C) were prepared under the same ultrasonic conditions.

The bonding area morphology was characterized by a PXS9-T stereomicroscope and Zeiss Axio Observer Z1m inverted optical microscope (OM). The samples were ground with 1,500 grit SiC paper, then mechanically polished using SiO₂ suspensions with a mean size of 1.5 μm. The surfaces of the OM samples were etched using a 4 wt% nitric acid alcohol solution. The detailed microstructure and chemical compositions of the interfacial layer were characterized by a JSM-6510LV scanning

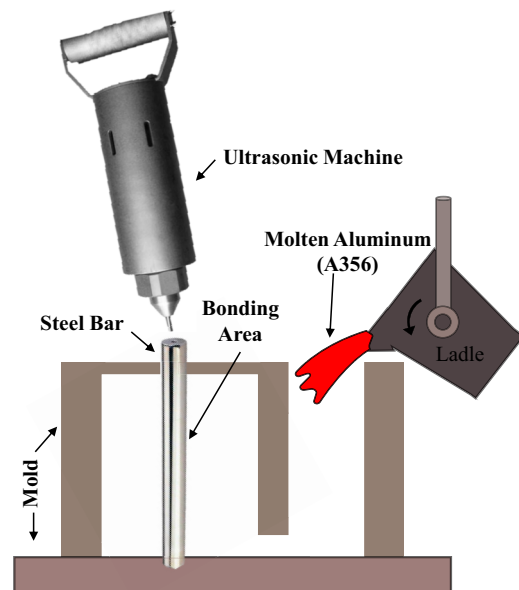


Figure 1: Fabrication process of carbon steel and A356 aluminum alloy bimetal castings with ultrasonic.

electron microscope (SEM) with an energy dispersive spectrometer (EDS).

The microhardness distributions from steel to aluminum alloy were performed using an MH-5 microhardness tester with a load of 500 g for a dwell time of 15 s. Flat, donut-shaped push-out samples with a gauge thickness of 5 mm were cut in the middle of the cylinders by electrical discharge machining and polished with 1200 grit SiC paper. The push-out samples were put into a gripper metal mold with a hole of 10 mm diameter and then the insert was pushed by a bearing steel rod with a diameter of 7 mm at a cross-head displacement rate of 0.5 mm·min⁻¹. Push-out tests were performed at room temperature using a CMT5205 universal testing machine. Figure 2 shows a schematic diagram of the push-out tests [11,21,22].

3 Results and discussion

3.1 Macrostructure

Figure 3 depicts the bimetallic castings samples. The steel rod was inserted in the aluminum alloy, but the morphology at the steel–aluminum contact was different. It should be mentioned that non-ultrasonic steel/aluminum bimetallic casting has a concave-shaped morphology (Figure 3c). In contrast, aluminum alloy appears

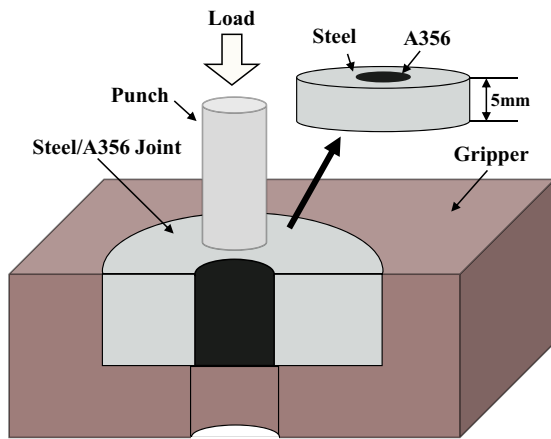


Figure 2: Schematics diagram of the push-out tests.

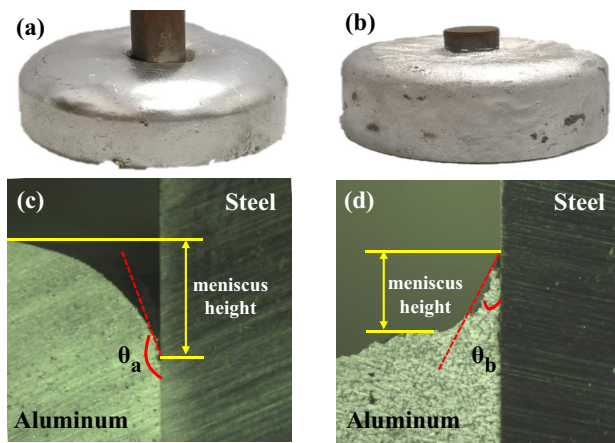


Figure 3: Macro-characteristics of the steel/aluminum bimetallic castings fabricated with and without ultrasonic treatment: (a) and (c) without ultrasonic; (b) and (d) with ultrasonic.

to climb along the steel rod at the interface of bimetallic castings with ultrasonic (Figure 3d). It is evident that ultrasonic treatment enhances the wettability of liquid aluminum on steel. When the same volume of molten aluminum was poured into the mold with and without ultrasonic under identical experimental conditions, the casting process may be regarded as a wetting balancing technique experiment in the air without the emersion process [23]. The molten aluminum alloy has a larger surface tension without ultrasonic, resulting in a concave shape, suggesting that the liquid does not wet the steel. When ultrasonic was applied to a steel rod during the pouring process, it generated a cavitation effect, which can create a powerful hydraulic pulse or high-speed cumulative jets on the steel rod surface and the liquid around it [24]. The oxide coating on the surface of solid and liquid phases was destructed by the cavitation effect [11]. As a

result, molten aluminum alloy had spread across the steel rod during the pouring process, keeping the contact wetting. Furthermore, as illustrated in Figure 3c and d, the ultrasonic significantly altered the contact angle from 159° to 28° .

3.2 Interfacial microstructures

The microstructures of the interfacial between steel and aluminum are shown in Figure 4. The carbon steel consists of pearlite (dark phase with lamellar structure) and ferrite (bright phase) on the left side, while the A356 aluminum alloy consists of α -Al (bright phase) and needle-like eutectic silicon (dark phase) on the right side. It's worth noting that bimetallic castings prepared without ultrasonic have a small gap or oxide at the interface. Usually, a steel rod with an activated surface is prone to oxidizing and forming an oxide coating, which would prevent molten aluminum from directly touching the steel rod, especially during the preheating step. In contrast, a transition layer close to A356 aluminum alloy with an average thickness of $8\text{ }\mu\text{m}$ was observed in samples without preheating, as seen in the left picture of Figure 4b, due to the ultrasonic effect caused by ultrasonic.

The SEM micrographs and EDS analysis results demonstrated that steel elements have not diffused to the molten aluminum alloy, as illustrated in Figure 4c. Furthermore, the oxygen element distributes mostly along with the interface, acting as a distinct border between steel and aluminum alloy, which is in accordance with the results of the optical metallography (as shown in Figure 4a) [11]. This indicates that the oxide on the surface of steel rods is the most significant impediment to steel dissolving and diffusion. On the other side, the presence of oxide prevents the steel from bonding to the aluminum alloy metallurgically. According to the EDS analysis results of interfacial phases, the UIC samples reveal a diffusion layer containing Fe, Al, and Si element between steel and aluminum (as shown in Figure 4d), in contrast to the interfacial microstructures in bimetallic castings fabricated without ultrasonic, in which steel and aluminum alloy were just mechanic contacts. The results suggest that preheating steel rods avoids the production of oxides, whereas ultrasonic removes surface purity and enhances wettability. In this situation, the steel and aluminum have a homogeneous distribution of intermetallic layers. The steel rod would be surrounded and heated rapidly but not enough to melt when the molten aluminum pours into the mold. According to the Fe–Al phase diagram [25], iron is soluble in solid form in aluminum at high

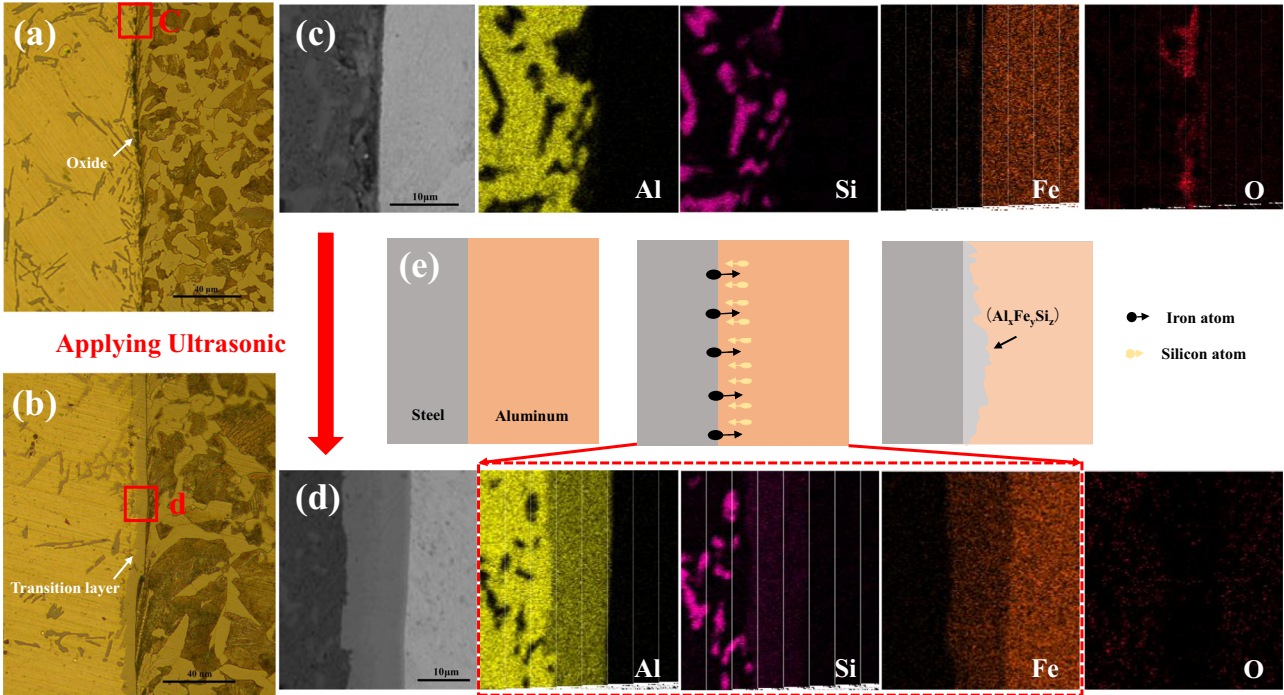


Figure 4: Detailed structure and phase of the bimetallic castings. OM images, SEM micrographs, and EDS analysis of interface micro-structure (a) and (c) without ultrasonic treatment; (b) and (d) ultrasonic treatment. Diagram (e) showing element diffusion in the formation of intermetallic compounds.

temperatures, resulting in iron dissolving and diffusion in molten aluminum. Meanwhile, the local temperature was raised by shock waves and microjets were created by the ultrasonic explosion of cavitation bubbles [17,19]. Furthermore, silicon has a strong affinity to iron, which enhances silicon concentration near the steel surface. The reaction of

iron, aluminum, and silicon to generate intermetallic compounds is accelerated by these effects, as illustrated in the schematic diagram in Figure 4e.

More compositional analysis was taken utilizing EDS analysis at eight different locations illustrated in Figure 5, the test results were reported in Table 1 to further verify the phase composition of the diffusion layer. The intermetallic compounds identified by EDS analysis were θ -FeAl₃, τ_6 -Al_{4.5}FeSi, and τ_5 -Al₈Fe₂Si, which were consistent with previous findings [12,26–28]. Figure 5 indicates

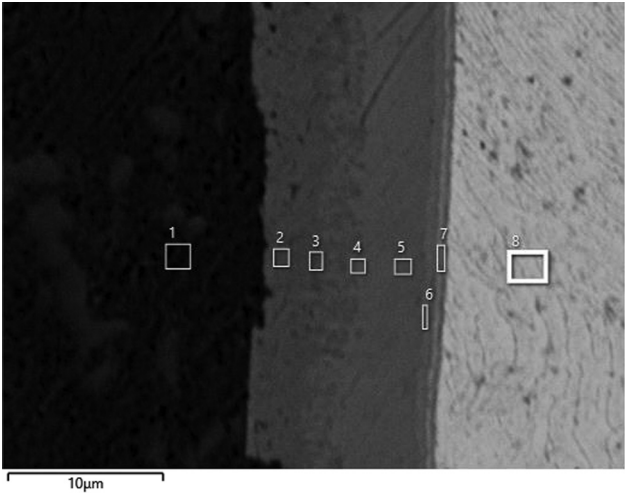


Figure 5: SEM micrograph of the interface of the steel/aluminum bimetallic castings with ultrasonic treatment taken from areas shown in Figure 4b and c.

Table 1: Results of EDS analysis corresponding to the points indicated in Figure 5

Number	Element compositions (at%)					Inference component
	Al	Si	Fe	O	C	
1	94.03	5.97	—	—	—	α -Al
2	66.47	17.62	15.91	—	—	τ_6 -Al _{4.5} FeSi
3	66.75	16.94	16.31	—	—	τ_6 -Al _{4.5} FeSi
4	68.25	12.82	18.92	—	—	τ_6 -Al _{4.5} FeSi τ_5 -Al ₈ Fe ₂ Si
5	67.55	12.00	20.45	—	—	τ_5 -Al ₈ Fe ₂ Si
6	66.98	12.20	20.82	—	—	τ_5 -Al ₈ Fe ₂ Si
7	67.28	7.63	25.09	—	—	FeAl ₃
8		1.39	65.95	3.91	28.75	Fe

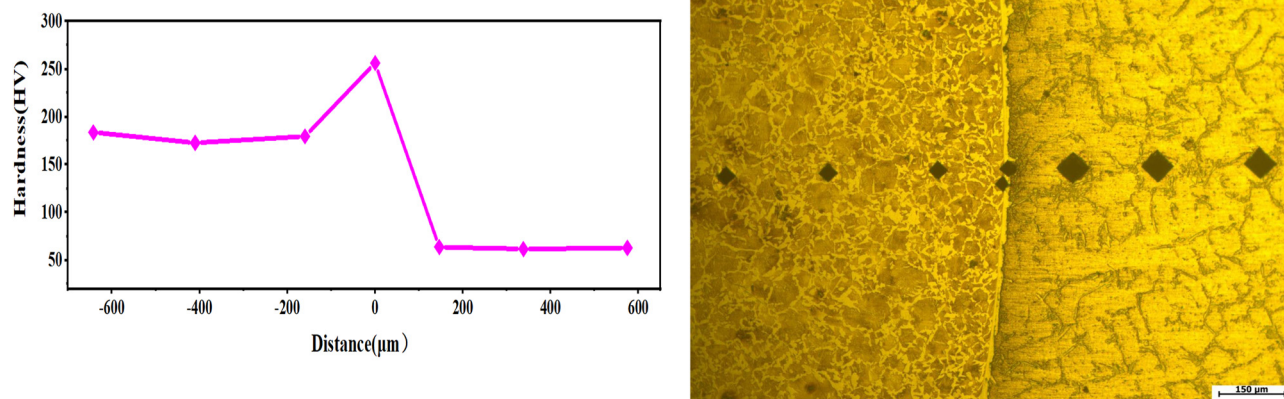


Figure 6: Microhardness distribution at the steel/aluminum bimetallic castings' interface area after ultrasonic treatment.

that τ_6 was found near the Al-rich phase, whereas FeAl_3 was found near the Fe phase. In this study, molten aluminum alloy contacted Fe first, causing the formation of iron aluminides, as the low concentration gradient of Si at the interface also led to diffusion and enrichment of Si near the interface. More complicated reactions occurred in this instance. These reactions can be expressed as follows:



where, FemAln is FeAl_3 or Fe_2Al_5 , AlxFeySiz is $\text{Al}_{4.5}\text{FeSi}$ or $\text{Al}_8\text{Fe}_2\text{Si}$. Hence, the τ_6 phase close to the Al-rich phase can be explained by the fact that molten aluminum contains more silicon. And these reactions ensure the metallurgical bonding between the carbon steel and the aluminum alloy. Also, the results suggest that ultrasonic greatly promotes diffusion during pouring as τ_6 forms mainly related to the interdiffusion process [26]. However, more research, including detailed characterization

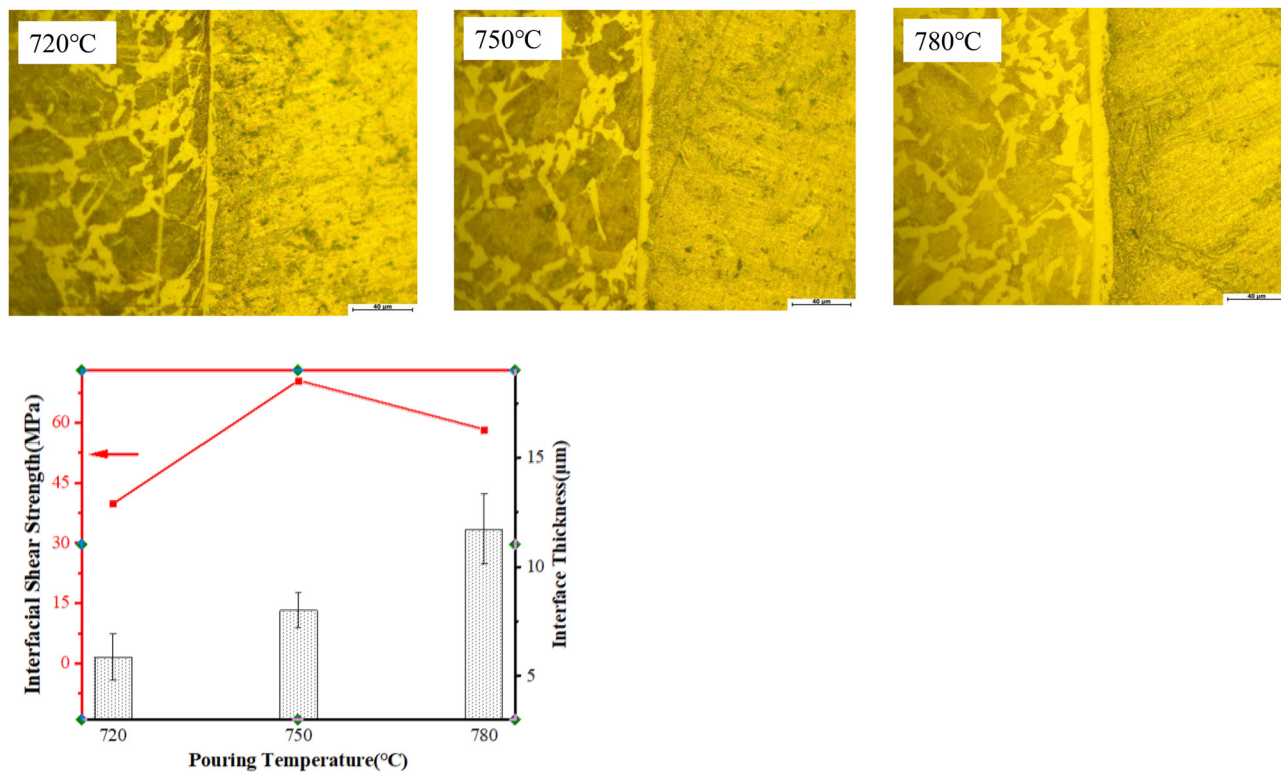


Figure 7: The relationship between the thickness of the bonding layer and the interfacial shear strength at different pouring temperatures.

testing, is required to identify whether intermetallic compounds are formed as a result of dissolution during casting or interdiffusion during solidification.

3.3 Mechanical properties

The microhardness tests were carried out along a line from steel to aluminum, as shown in Figure 6. Steel has an average hardness of 192HV, whereas aluminum alloy has a hardness of 64HV, according to the results. The hardest layer between steel and aluminum is the bonding layer, which has a hardness of roughly 260HV. Intermetallic compounds always have a high hardness as a result of this ref. [29]. Microhardness, on the other hand, maybe used to distinguish various phases in samples but not to measure the interfacial layer's bonding strength. As a consequence, a push-out test was carried out to determine the steel rod and aluminum matrix shear strength.

The formation mechanism of the interfacial layer, according to EDS analysis, reveals that diffusion of the iron element influenced the creation of intermetallic compounds, and the development of intermetallic compounds is dependent on diffusion temperature and time. Typically, the casting process of samples takes tens of seconds from pouring to cooling down naturally. As a result, there is insufficient time for iron diffusion to take place. Increasing the pouring temperature, on the other hand, can speed up the diffusion duration and rate. Several samples were made in this condition by altering the pouring temperature while using the same ultrasonic parameters to test if a thicker bonding layer was better for bonding strength.

The results reveal that, unlike the thickness of the interfacial layer (the X-axis on the right), the shear strength of samples increases first and subsequently declines as the pouring temperature increases (see Figure 7). To put it another way, a thicker bonding layer with an average thickness of 12 μm reduces bonding strength to 58 MPa rather than increasing it. The thickness of the bonding layer should be managed because of the hard and brittle features of intermetallic compounds. As reported in prior works suggests that the thickness of the intermetallic phases layer below 10 μm is suitable for technical applications [30].

4 Conclusions

- (1) The UIC technique assures bimetallic castings with metallurgical bonding by removing the oxide coating

on the steel surface and improving the wettability of molten aluminum on steel solid.

- (2) The diffusion of Fe and Si is enhanced by ultrasonic waves. Between steel and aluminum, a transition reaction layer is formed with an average thickness of 8 μm , mostly consisting of FeAl_3 , $\text{Al}_8\text{Fe}_2\text{Si}$, and $\text{Al}_{4.5}\text{FeSi}$, and it has the maximum microhardness.
- (3) As the pouring temperature rises, the bonding layer grows thicker, however, due to the intermetallic compound's hard and brittle characteristics, shear strength decreases as the bonding layer increases to 12 μm .

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Data availability statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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