

Research Article

Sequential Process of Diffusion Bonding and Annealing on Dissimilar Welding of Mg/Al Alloys

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Received 26 October 2020; Revised 3 January 2021; Accepted 31 January 2021; Published 11 February 2021

Academic Editor: Guoqiang Xie

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In this study, pressure supplying device based on thermal expansion and vacuum diffusion bonding method were used to weld magnesium alloy (AZ91) and aluminum alloy (6061). To enhance the microstructure and bonding properties of the welded Mg/Al alloys, the annealing process was continuously implemented on the composite specimens. Elemental analysis and structural observation/compound identification were conducted using an electron probe microanalyzer and a scanning electron microscope, respectively. For further assessment of the diffusion zone, microstructural examination was carried out using a transmission electron microscope. Furthermore, tensile strength and hardness values were also measured. The results showed that the diffusion zone widens with increasing annealing temperatures, but it changed obviously when the annealing temperature was 300°C. Intermetallic compounds in the diffusion zone were identified as Al_2Mg and $Al_{12}Mg_{17}$, the microstructure and elemental composition were uniformly distributed, and tensile strength was the largest for the specimen annealed at 250°C. A possible reason for this could be that 250°C is nearly similar to the recrystallization temperature of Mg/Al alloys. Therefore, 250°C was determined to be the most suitable annealing temperature. In addition, the thermal expansion pressure supplying process was appropriate for the diffusion bonding of Mg/Al alloys.

1. Introduction

In the wake of industry development and economy growth, energy and environmental problems are becoming more and more serious. Lightweight is an effective way to meet the requirements of energy conservation, sustainable development, and environmental protection. As lightweight materials, magnesium alloys (Mg alloys) and aluminum alloys (Al alloys) have been widely used in many fields [1–3], such as automotive, electronics, and aerospace industries [4], due to their excellent performance of high specific strength, low density, and good formability [5, 6]. In order to combine their advantages, the welding of Mg alloys to Al alloys has become more and more significant, especially for

transportation machinery manufacturing industry such as automobile manufacturing field, aviation machinery manufacturing field, and so on.

Few research studies have focused on the diffusion bonding of Mg and Al alloys by various dissimilar material joining techniques, such as fusion welding, rolling, brazing, friction stir bonding [7–9], and vacuum diffusion bonding [10–13]. However, due to the different properties of magnesium alloy and aluminum alloy, especially thermodynamic properties, it is difficult to weld them together. Besides, the intermetallic compounds (IMCs) in the interface are brittle and hard, which may seriously deteriorate the properties of the joints. Because solid-state welding can occur at lower temperatures in relative to fusion welding,

there is no mass transfer between liquid and solid phases, suggesting that the formation of IMC is reduced. Therefore, solid-state bonding technologies, such as diffusion welding, friction stir welding, and ultrasonic welding, have been widely used for controlling the formation of IMC [14, 15].

In this research, the diffusion bonding method was selected; furthermore, pressure supplying device based on thermal expansion was particularly applied. To improve the microstructure and mechanical behaviors of Mg/Al composite, annealing was carried out. In addition, microstructure and bonding properties of the diffusion layers were investigated. The pressure supplying device based on thermal expansion is considered the first time applied to the diffusion welding of Mg/Al alloys, which makes the welding process much simpler than the traditional diffusion bonding process, as no additional pressure is required during the welding process.

2. Materials and Methods

As the basic materials for this research, Mg alloy (AZ91) and Al alloy (6061) were used. The test specimen was prepared by cutting these two alloy sheets into an appropriate dimension (Figure 1). The thickness of Al alloy sheet was 1 mm. Mg alloy sheet was prerolled from 2 mm to 1 mm through a rolling mill.

Before welding, the oxide layers of raw material were ground with abrasive papers, and the polished surface was degreased using acetone. Next, the Mg alloy sheet was overlapped with the Al alloy sheet by 10 mm, and the obtained specimens were placed into a device (Figure 2). This device could just accommodate the samples, so that they were persistent along height and longitudinal direction, but no pressure was added onto the ends before being heated. Then, the device was placed in an electric furnace and heated. Based on the Mg-Al phase diagram and previous studies, the joining temperature was set as 440°C, with 60 minutes of holding time. After cooling down to room temperature, the samples were welded by the vacuum diffusion bonding method and TEPS process in the electric furnace under an argon atmosphere.

To enhance the mechanical properties and microstructure of the diffusion zone, the welded workpieces were subjected to annealing. Based on the Mg-Al phase diagram and past experience in annealing, the heat treatment temperatures were maintained at 200°C, 250°C, and 300°C, with 60 minutes of holding time. After heating, the samples were cooled to room temperature in an electric furnace.

To further assess their microstructural and interface properties, the annealed samples were sectioned across the diffusion zone. Subsequently, the sections were ground in a grinder and polished using the abrasive papers. Elemental analysis and structural observation/compound identification were then carried out using an electron probe microanalyzer (EPMA) and a scanning electron microscope (SEM), respectively. For transmission electron microscopy (TEM) experiment, the sample was ground to approximately 20 μm. The thickness of the sample was further reduced to approximately 0.1 μm by fine cutting with a focused ion beam

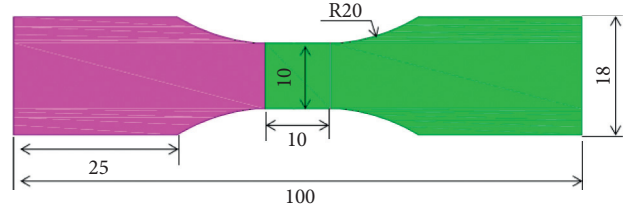


FIGURE 1: Dimension of the test specimen.

(FIB). Then, microstructure examination experiments were completed using TEM. At last, Vickers hardness testing and tensile strength measurement were carried out to evaluate the hardness and mechanical behaviors of the samples.

3. Results and Discussion

Figure 3(a) shows the microstructures of the welded Mg/Al alloy before the annealing process. Upon annealing at 200°C, 250°C, and 300°C, the microstructural changes of the joints are shown in Figures 3(b)–3(d), respectively.

The SEM micrographs demonstrated that the width of the diffusion zone increased with increasing annealing temperatures, but it changed obviously after being annealed at 300°C. This may be due to the fact that the diffusion rate of Mg/Al alloy is affected by annealing temperature. During the diffusion bonding process of AZ91 magnesium alloy and 6061 aluminum alloy, diffusion between elements Mg and Al should be taken into consideration, and it can be analyzed by Fick's law.

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}, \quad (1)$$

where C is concentration of element and D is diffusion coefficient representing the diffusion property of material and is a function of C . In general, diffusion equation can be expressed based on elemental concentration:

$$\dot{C} = \text{div} (D \text{grad} C). \quad (2)$$

If the energy of the object is represented as $e = g + T\eta + \text{tr}(\sigma\epsilon^e)$, then the first law of thermodynamics can be written as follows:

$$\rho \dot{e} - \text{tr}(\sigma \dot{\epsilon}) + \text{div} \mathbf{h} = 0. \quad (3)$$

If the Fourier law ($\mathbf{h} = k \text{grad} T$) is used, plastic work and latent heat of transformation are not considered, and terms related to elastic strain and hardening coefficient are ignored; then, (3) is expressed as follows:

$$\rho c \dot{T} - k \text{div} (\text{grad} T) = 0, \quad (4)$$

where ρ is density of material, c is specific heat, and k is thermal conductivity. When the coefficient of heat transfer and the temperature of fluid in contact with the object do not change, boundary condition is expressed by the following equation:

$$-k \text{grad} T \cdot \mathbf{n} = h(T) (T - T_\omega), \quad (5)$$

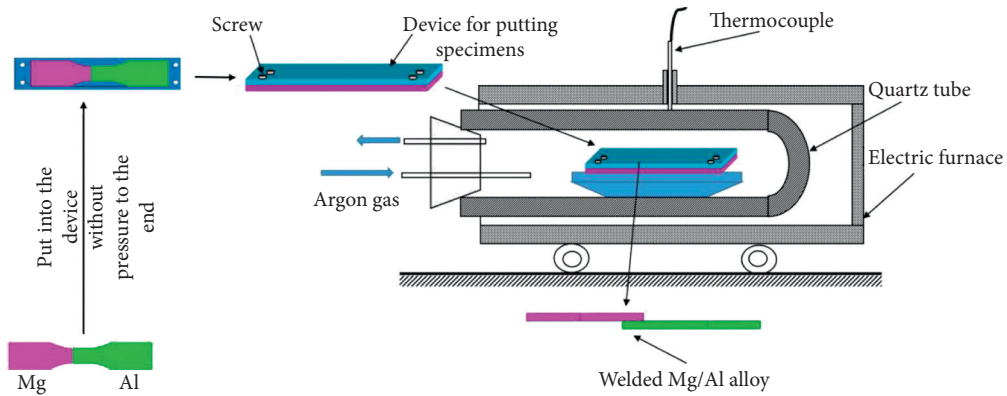


FIGURE 2: Schematic of TEPS diffusion process.

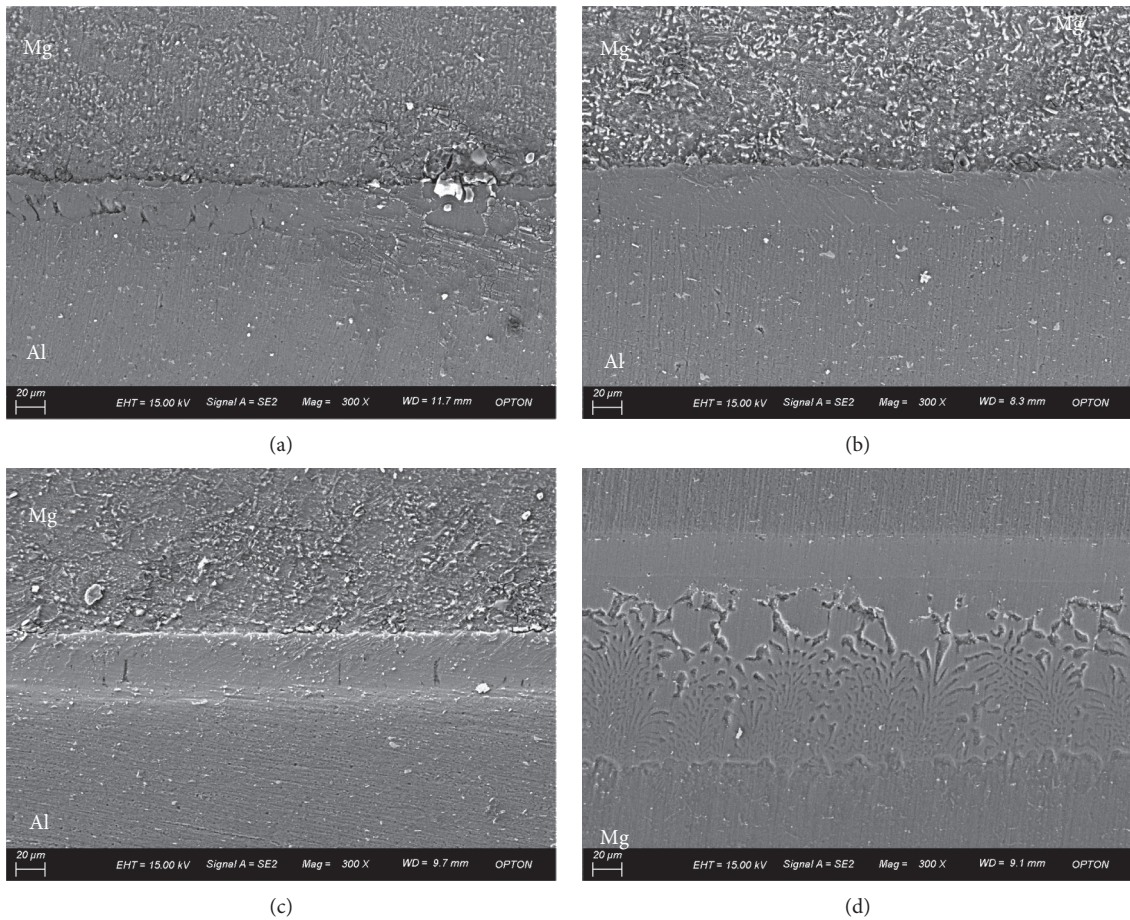


FIGURE 3: SEM micrograph of the welded specimen: (a) without annealing; (b) annealed at 200°C; (c) annealed at 250°C; (d) annealed at 300°C.

where \mathbf{n} is a vector with a direction outward from the surface of object, T_ω is the temperature of environment, and $h(T)$ is the coefficient of heat transfer between the object and environment. So when materials are determined, the temperatures of the environment will be the main factors affecting diffusion. In fact, the higher the ambient temperature is, the faster the diffusion

rate is and the wider the thickness of diffusion layers will be.

As shown in Figure 4, the line scan analysis revealed that the width of the diffusion joints increased with increasing annealing temperatures. Specifically, the thicknesses of the diffusion layers changed to approximately 0.075 mm and 0.08 mm after annealing at 200°C and 250°C, and the one

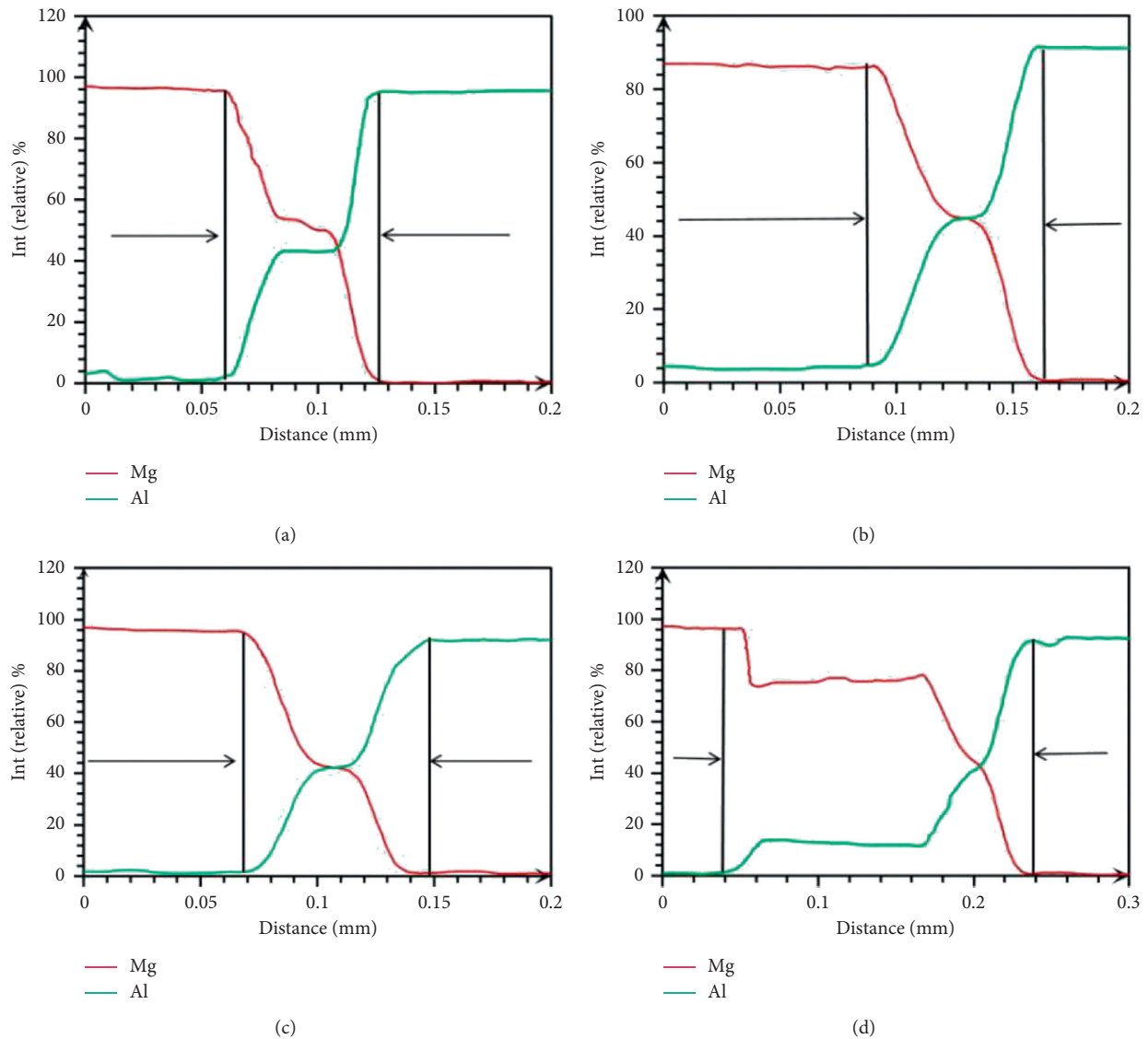


FIGURE 4: Line scan analysis for the elemental distribution of the specimens: (a) welded specimen without annealing; welded specimen annealed at (b) 200°C, (c) 250°C, and (d) 300°C.

annealed at 300°C exhibited the widest width of 0.20 mm, when compared to those without annealing. Thus, these results were consistent with those observed in SEM micrographs.

To identify the composition and crystal structure of IMC in the diffusion zone, TEM experiments were carried out, and the results are presented in Figures 5 and 6.

In Figure 5, Point A is the investigated position, which is located in the diffusion zone near Al alloy. According to the scale in Figure 5, the actual interplanar spacing was obtained by measuring the distance from points 1 and 2 to the center. From the database, the distance values of d_1 and d_2 were found to be 0.0846 and 0.1278 nm, respectively. This indicates that the crystal structure of the (4018) and (1215) planes of Al_2Mg is face-centered cubic. Referring to Figure 6, the position for investigation is marked as B, which is located in the diffusion zone near Mg alloy side. After calculating the

data shown in Figure 6, the interplanar spacing d_1 and d_2 values were determined to be 0.125 and 0.206 nm, respectively. The index of the corresponding plane of $Al_{12}Mg_{17}$ is (660) and (510), with a body-centered cubic crystal structure.

Besides, for the purpose of evaluating the mechanical behaviors of the welded specimens, the values of Vickers hardness and tensile strength were measured. During hardness measurement, a testing load of 1 kg was used, and the results are presented in Figure 7.

Notably, the hardness of Mg side was about 78 HV, which was higher compared to Al side. Moreover, the hardness of diffusion layers consisting of IMC was significantly higher than that of Mg alloy and Al alloy. The nonannealed specimens and those annealed at 200°C, 250°C, and 300°C displayed the highest hardness values of 115, 110, 101, and 104 HV, respectively. These results indicate that Mg

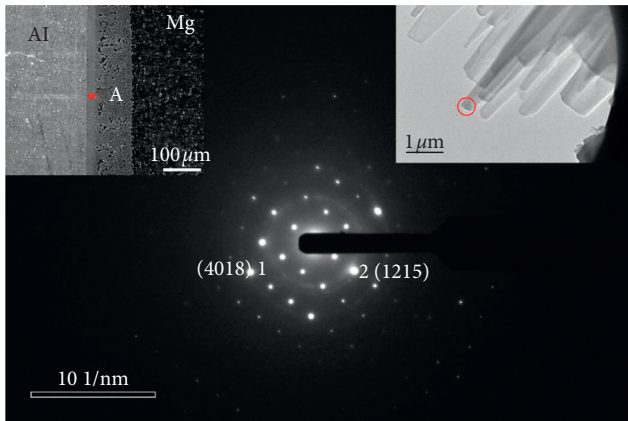


FIGURE 5: TEM image of IMC composition near Al alloy side.

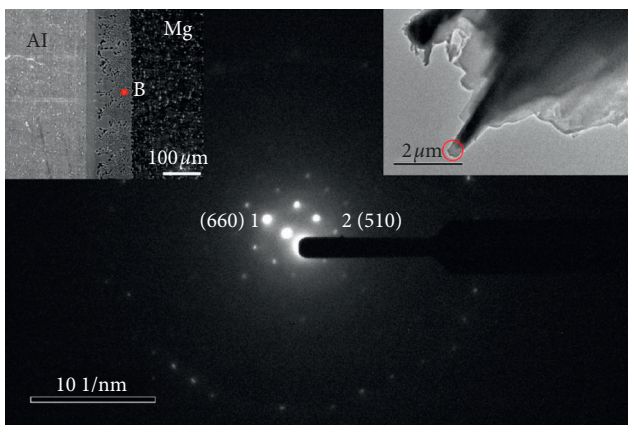


FIGURE 6: TEM image of IMC composition near Mg alloy side.

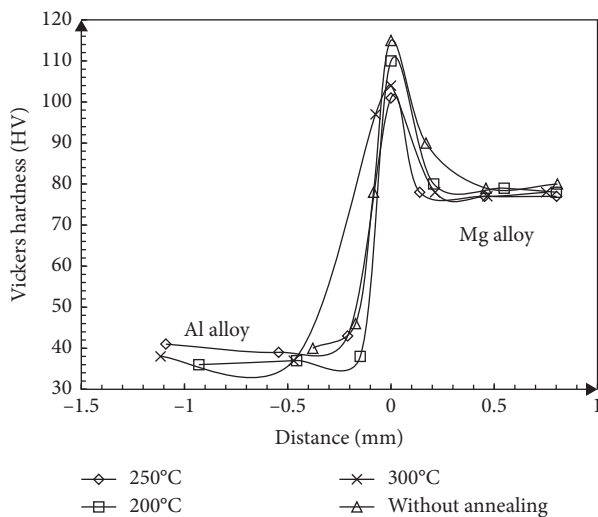


FIGURE 7: Hardness measurement results.

alloy is harder than Al alloy, particularly when annealed at 250°C, and the diffusion zone exhibits the lowest hardness.

A growing body of literature [16–18] has demonstrated that the tensile strength of bonded Mg/Al alloys ranges from 32 to 37 MPa. In this study, a tensile test was also carried out,

TABLE 1: Yield stress and tensile strength corresponding to different annealing conditions.

Conditions	Without annealing	Annealing at 200°C	Annealing at 250°C	Annealing at 300°C
Yield strength (MPa)	40	20	35.5	26
Tensile strength (MPa)	42.2	60.4	80.3	34.1

and the results of yield stress and tensile strength are presented in Table 1.

Compared to the conditions of no annealing (42.2 MPa), the tensile strength at the annealing temperatures of 200°C and 300°C was determined to be 60.4 and 34.1 MPa, respectively. When the specimen was annealed at 250°C, the tensile strength was about 80.3 MPa, which was the largest among all. However, the specimens annealed at 200°C and did not undergo annealing exhibit the yield strength of 40 MPa and 26 MPa, which are near to the corresponding tensile strength. The results indicate that the plasticity is very poor, no matter the sample was annealed at 300°C or not annealed. Contrarily, after being annealed at 250°C, the specimen exhibits the best plasticity. Combined with hardness test results, it can be depicted that annealing at 250°C can reduce the brittleness and improve the plasticity of diffusion layers. The reason is that 250°C is nearly similar to the recrystallization temperature of Mg/Al alloy. Hence, the microstructure and mechanical behaviors of Mg/Al alloy can be refined and improved, respectively, by annealing at this temperature.

4. Conclusions

In this treatise, diffusion bonding process with the usage of pressure supplying device based on thermal expansion was applied, and a series of experiments on microstructure observation and mechanical behaviors were carried out. Based on the experimental results, the following conclusions can be drawn:

- (1) The diffusion zone becomes wider with increasing annealing temperatures, especially under the condition of 300°C, in which the width changes obviously.
- (2) The composition of IMC in the diffusion zone near Al alloy side is identified to be Al_2Mg (with face-centered cubic crystal structure), while that in the diffusion layer near Mg alloy side is $Al_{12}Mg_{17}$ (with body-centered cubic crystal structure).
- (3) The annealing process results in the improvement of mechanical properties. At 250°C, the hardness value of the diffusion zone is the lowest, while the tensile strength is the highest. Thus, 250°C is considered to be the most appropriate annealing temperature.
- (4) The pressure supplying device based on thermal expansion is suitable for the diffusion bonding of Mg/Al alloys.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was partially supported by the “Magnesium Alloy Rolling Centre” in University of Science and Technology Liaoning. In addition, we would like to express our gratitude to the students Haoxin Yu and Jiayingbao Xu for their help in the experiment. This study was also supported by the Scientific Research Fund Project of Liaoning Provincial Department of Education under grant no. 2019LNQN01.

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