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# Effect of Post-Weld Heat Treatment on the Solid-State Diffusion Bonding of 6061 Aluminum Alloy

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**Abstract:** The precipitation-hardenable aluminum alloy 6061 (AA 6061) is favored for aerospace components and automotive parts. However, the tenacious oxide layer on the surface greatly limits the quality and applicability of joining AA 6061. In this study, the joining method of solid-state diffusion bonding was implemented for AA 6061 plates, and the effects of post-weld heat treatment (PWHT) on the joint interface were investigated. The bonding temperatures were within the range of 500–530 °C, and the time periods varied from 30 to 240 min under a static pressure of 5 MPa in a vacuum. The diffusion bonded specimens were subjected to T4- and T6-PWHT to improve the bonding quality. The interfacial microstructure of the joints was analyzed by scanning electron microscopy, and the mechanical properties were evaluated with shear tests. The experimental results showed that the shear strength of the diffusion bonded joint could reach around 71.2 MPa, which was highly dependent on bonding temperature and holding time, and T6-PWHT further enhanced it to over 100 MPa. The effects of PWHT on the diffusion bonded AA 6061 joint were investigated, and the fractography on the sheared surfaces indicated that PWHT-T6 played an important role in enhancing joint strength, which was consistent with the measured shear strength. The sequential PWHT for AA 6061 after diffusion bonding was proven to be feasible for bonding of AA 6061 parts, and the joint strength was sufficient for industrial needs.

**Keywords:** aluminum alloy 6061; diffusion bonding; post-weld heat treatment; fractography



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## 1. Introduction

Aluminum alloys have been widely used in engineering structures in the automotive and aerospace industries due to their unique physical properties, such as low density, high specific strength, good formability, and excellent corrosion resistance. To allow the utilization of aluminum alloys in these machinery manufacturing industries, the joining method is a major concern in the provision of complex structures for a wide variety of applications. Traditionally, welding technologies such as laser beam welding (LBW) [1], tungsten inert gas welding (TIGW) [2–4], and friction stir welding (FSW) [5,6] have been adopted for a wide range of Al alloy joint structures. However, the application of welding to aluminum alloy is not favored because the process involves melting the base material, which causes residual stress from the shrinkage of solidifying material and the heat affected zone (HAZ), which eventually degrades the joint strength. Brazing is considered as an alternative to welding because of the lower brazing temperature [7–9]. The higher tolerance of the process parameter window in brazing comes with the advantage of cost-effectiveness for mass production. However, common filler metals, such as BAlSi-4 and Al-12Si alloys, exhibit high brazing temperatures (above 566 °C) that are close to or above the melting points of some aluminum alloys [10,11], leading to the risk of joint degradation. Some low-temperature filler metals and the transient liquid phase (TLP) bonding technique have been

adopted to address this issue [12,13], and bonding materials such as Cu, Ag, and Mg, which are melting point depressants that form eutectics or intermetallic compounds (IMCs) with Al alloy, have been developed to avoid the risk of melting the base material. For example, silver and copper-based filler metal [14] and Cu or Ag foils as interlayers [12,13,15,16] that form Al–Cu or Al–Ag IMCs at the interface have been utilized to provide sound interfaces. However, research showed that the failure and breakage of the joint usually initiated in the IMC phase and led to deterioration of the joint strength due to embrittlement [14,17].

Based on the difficulties encountered, solid-state diffusion bonding has become an attractive technique due to the ease and the good quality that can be achieved with similar and dissimilar materials [18–20]. The major difference between diffusion bonding and other conventional joining methods is that it allows lower bonding temperatures. Two nominal surfaces of the base material are directly bonded under external pressure for specific bonding times. This approach avoids heat effects and the formation of IMCs while maintaining satisfactory bond strength without significant deformation [21,22]. Diffusion bonding of aluminum alloys is thus greatly influenced by bonding conditions such as temperature, external pressure, suppression, holding time, and surface roughness [22,23]. Saleh [24] performed 1 h diffusion bonding of 2014 aluminum alloy with copper interlayer at 475 °C, under a pressure of 4 MPa. The best bonding tensile strength was 188.36 MPa. However, a 1.9 μm thick $Al_2Cu$ intermetallic compound was formed on the interface. The formation of brittle intermetallic at the interface may cause the toughness of the joint to decrease. The main difficulty in the diffusion bonding of aluminum alloys is their readily oxidized nature. The adherent oxidation layer on the surface continues to be a challenge for diffusion bonding of aluminum alloys because it prevents close contact of the base material and acts as a diffusion barrier, impeding atomic interdiffusion and resulting in poor metallurgical bonds [23]. Surface treatments of aluminum substrates such as wiping with acetone or immersion in dilute sodium hydroxide [25] have been proposed to remove or disrupt the continuous oxide layer so that metallic bonds can be created in localized areas; however, the pre-treatment process of the sample surface limits the applicability of this approach. Chen et al. [26] used a 1 keV argon ion beam cleaning for 120 min to remove the oxide on aluminum during the low-temperature diffusion bonding of pure aluminum. The best tensile strength of 62.3 MPa can be obtained bonded at 350 °C for 3 h under the pressure of 10 MPa. In order to overcome the problem of the oxide on aluminum, Zinong et al. [27] used a large deformation hot roll joining method to join 1060 aluminum alloy at a high temperature of 550–600 °C. The bonding strength of about 83–114 MPa was obtained.

Heat treatment, on the other hand, is widely applied to aluminum alloys so as to obtain desirable mechanical properties by means of optimizing the metallurgical microstructure [28]. The strengthening processes of various kinds of binary or ternary system aluminum alloys, which primarily contain Mg, Cu, Si, and Zn [29], usually involve the formation of a supersaturated solid solution by heating the material within a certain range (solution heat treating) and subsequent quenching, followed by age hardening treatment to form intermetallic precipitates in the matrix [30]. These aluminum alloys are precipitation-strengthened due to the obstruction of the movement of dislocations during deformation by coherent clusters within the matrix.

The present paper focuses on diffusion bonding of commercial AA6061, which is precipitation-strengthened by Al–Mg–Si IMCs, and the joint is further strengthened by the post-weld heat treatment based on the temper grades of T4 and T6 [28], which were originally implemented for the purpose of strengthening the base material. The purpose of this paper is to evaluate the feasibility of diffusion bonding of AA 6061 to form large area joints for various engineering configurations, and the effects of PWHT on the diffusion bonded AA 6061 joints were investigated. The joints of AA 6061 plates were formed by solid-state diffusion bonding, and the joint strength was evaluated by shear test. Bonding parameters are suggested in this study, and the effects of PWHT with temper grades of T4 and T6 (T4- and T6-PWHT) on the mechanical properties of the joints were correlated with the morphology of the fracture surfaces after shear tests.

## 2. Experimental

The base material used in this study was rolled 6061 aluminum alloy plate with T6 heat treatment. The plate was cut into samples measuring 50 mm × 10 mm × 3 mm for diffusion bonding. The chemical composition of AA 6061 is provided in Table 1. Prior to bonding, the sample surfaces were ground flat with 1200# to 2000# silicon carbide papers and immersed in an acetone bath in an ultrasonic cleaner to eliminate surface contaminants. The polished specimens were stacked in a lap configuration with an overlap distance of approximately 5 mm. Increasing the temperature increases the diffusion rate. According to the study of Summers et al. [31], the yield strength of AA6061 is less than 10 MPa when the temperature is above 550 °C. It is necessary to have a high temperature for diffusion and without macroscopic plastic deformation of AA6061 during the diffusion bonding process. Thus, the temperatures used for diffusion bonding are between 500 and 530 °C. To form the metallurgical bonds, the stacked AA6061 specimens were diffusion bonded under a static pressure of 5 MPa and vacuum of $10^{-2}$ torr in a vacuum hot press furnace (Zhenhua Electric Heating Industry Co., Ltd., Guangdong, China). The specimens were heated at 40 °C/min to final temperature ranges of 500–530 °C and held for various time periods for identification of suitable process parameters. A schematic diagram of the dimensions of the bonded specimens is provided in Figure 1. After the bonding process, the lap-bonded samples were subjected to shear loads on the two ends of the specimen, known as a single-lap shear (SLS) test, to measure the joint strength with a tensile testing machine (Shimadzu AG-10TE.) at room temperature. Three measurements of joint shear strength were performed for each diffusion bonding condition and the average was calculated. In addition, the specimens bonded at 500 and 530 °C were post-weld heat treated with the T4 and T6 temper grades to enhance the joint strength. Note that the T4 and T6 tempering treatments were based on the dimensions of the sample (AA6061 sample plate) [28], in which the heat treatment parameters were as follows: first, solution heat treatment at 530 °C for 1 h, then removal from the furnace for water quenching at room temperature (T4), and finally artificial aging at 160 °C for 18 h (T6). The AA6061/AA6061 joints were cross-sectioned and the interfacial microstructures were observed by a field-emission scanning electron microscope scanning electron microscopy (FE-SEM, JSM-7800F) coupled to an energy-dispersive X-ray spectroscopy (EDX). The composition of the interface was analyzed with EDX. Moreover, the fractography of the fractured surfaces after shear tests was also observed by SEM and the fracture mechanisms were analyzed.

**Table 1.** Chemical composition of AA 6061 aluminum alloy (wt.%).

| Al | Mg | Si | Cu | Cr | Mn |
|---|---|---|---|---|---|
| Bal. | 1.10 | 0.61 | 0.25 | 0.12 | 0.01 |

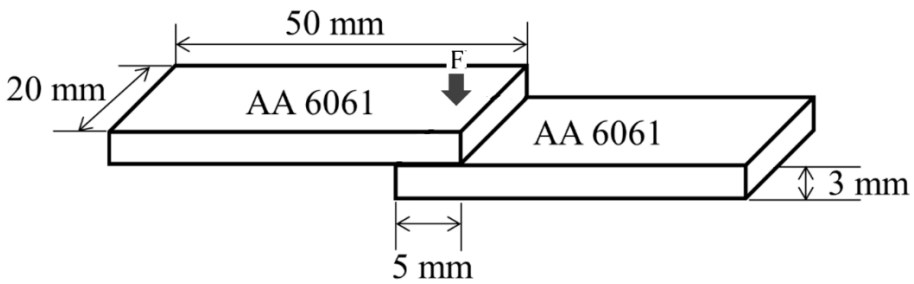


**Figure 1.** Schematic diagram of the geometry and dimensions of the diffusion bonded specimens subjected to SLS tests.

## 3. Results and Discussion

### *3.1. Interfacial Microstructure and Mechanical Properties of the Fabricated AA 6061 Joints*

Diffusion bonding is a process that involves atomic interdiffusion at the faying surface, and the weldability is highly dependent on the process temperature and time [22]. In the case of AA 6061 joints, since this process is categorized as bonding between similar metals, the interface is expected to be free of brittle IMCs. The interfacial microstructures of the fabricated AA 6061 joints after diffusion bonding at 500–530 °C for various bonding times are presented in Figures 2–5, and the relation between bonding temperature and average bonding shear strength of AA 6061 joints for corresponding bonding times is shown in Figure 6.

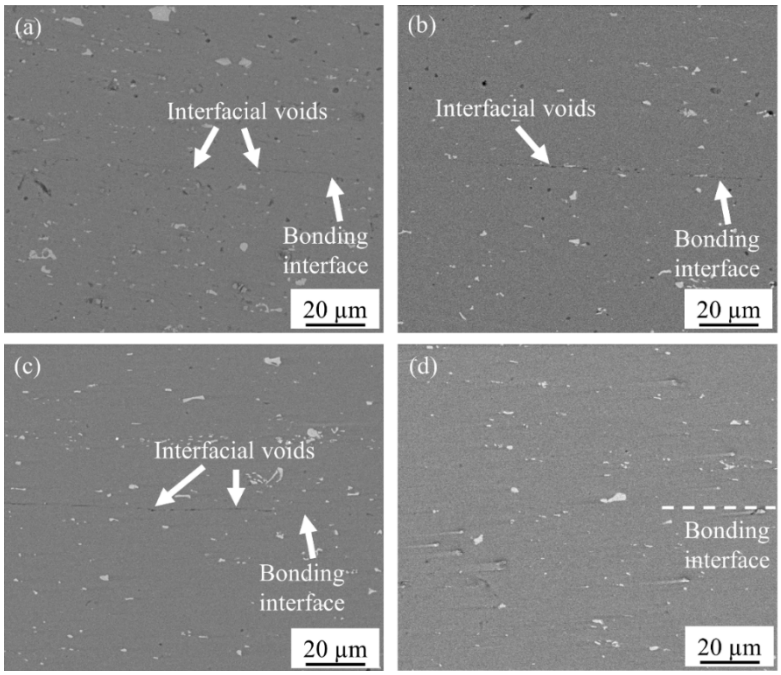


**Figure 2.** Microstructures of AA6061/AA6061 bonding interfaces after diffusion bonding at (**a**) 500 °C, (**b**) 510 °C, (**c**) 520 °C, and (**d**) 530 °C for 30 min.

As shown in Figure 2, the matrix of the AA 6061 aluminum alloy had light-colored intermetallic precipitations dispersed within it. The IMCs were rich in iron (10.13–11.87 at.%) and silicone (6.84–7.75 at.%) and also contained manganese and chromium, so they were identified as (Fe, Mn, Cr)$_3$SiAl$_{12}$ phase [32]. Figure 2 shows the joint microstructure corresponding to the bonding temperature range of 500–530 °C under a constant bonding time of 30 min. The original bonding interface for each sample condition, if clearly visible, is identified by white arrows. For crack-free interfaces, the approximate joint interface is indicated by dotted lines. Under a static bonding pressure of 5 MPa and a holding time of 30 min, the oxide film of aluminum was torn by deformation and fractured in the localized area, which provided direct metal-to-metal contact to allow atomic diffusion. As shown in Figure 2a–c, although some interfacial voids still existed at the interface of the AA6061/AA6061 joints in the samples bonded at 500–520 °C, no IMC layer formed, and the bonded areas were more than 80%. This implies that the bonding time of 30 min and temperature of 500–520 °C allowed the second stage of diffusion bonding [22]. Further increasing the bonding temperature to 530 °C with sufficient heat, as shown in Figure 2d, obviously promoted the atomic interdiffusion, as few interfacial voids or cracks were observed at the interface. The results indicated that elevating the bonding temperature increased the bonded area. In addition, prolonging the bonding time to 60, 120, and 240 min exhibited similar results; given sufficient time, diffusion led to void shrinkage and crack reduction. As shown in Figures 3–5, the joint interfaces were difficult to distinguish because of the similarity in composition of the base metal and the high-quality metallurgical bonding.

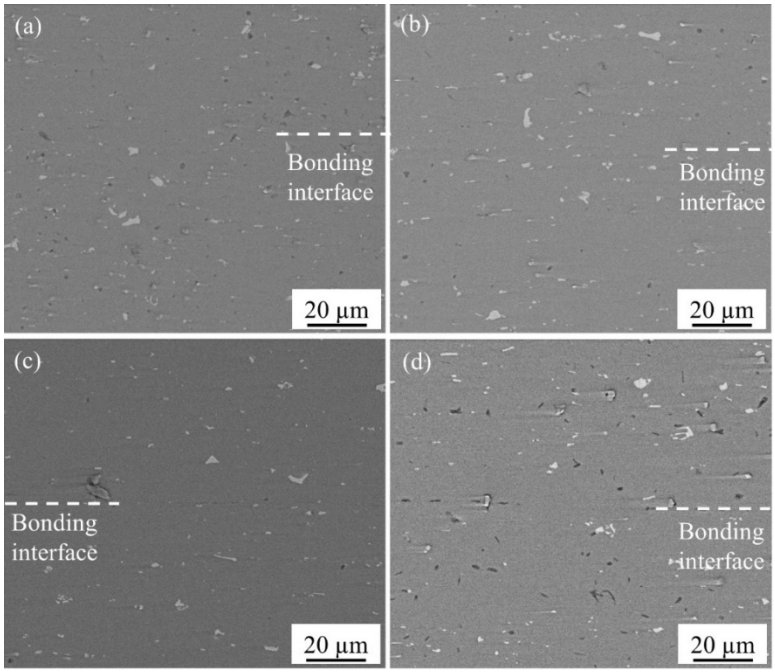


**Figure 3.** Microstructures of AA6061/AA6061 bonding interfaces after diffusion bonding at (**a**) 500 °C, (**b**) 510 °C, (**c**) 520 °C, and (**d**) 530 °C for 60 min.

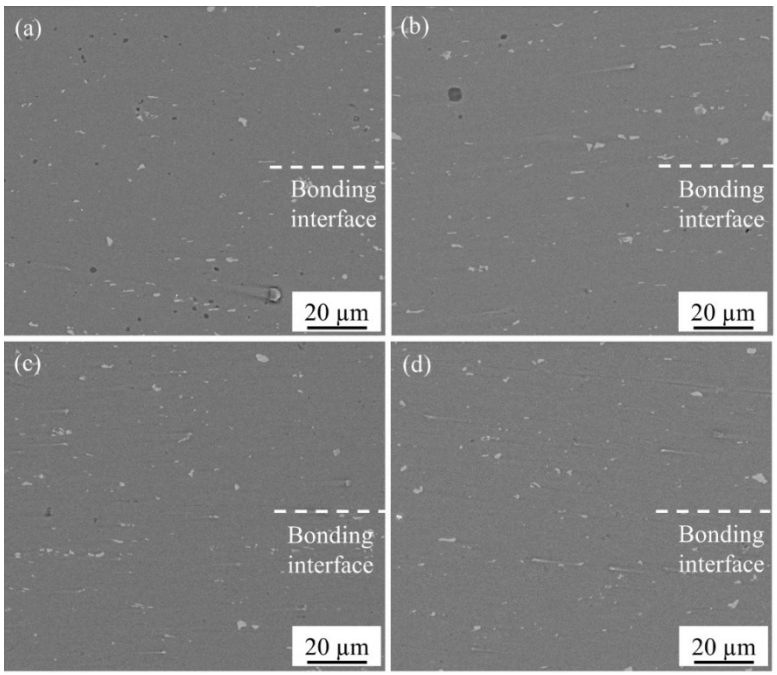


**Figure 4.** Microstructures of AA6061/AA6061 bonding interfaces after diffusion bonding at (**a**) 500 °C, (**b**) 510 °C, (**c**) 520 °C, and (**d**) 530 °C for 120 min.

The joint shear strengths measured by the SLS test are shown in Figure 6. Compared with brazing using Al–Si–Cu filler [11] or adhesive bonding [25,33], diffusion bonding of 6061 aluminum alloy has higher bonding shear strength. The joint strength with diffusion bonding was strongly dependent on two factors. One was the increasing bonding temperature, which promoted the atomic interdiffusion. With a short bonding time of 30 min and bonding temperature of 500 °C, the average joint strength could only reach around 42.7 MPa, possibly due to the cracks and voids at the interface. Further elevating

the bonding temperature to 510–530 °C while maintaining the same bonding time of 30 min enhanced the average joint strength to around 59.2–65.7 MPa, indicating that increasing the bonding temperature contributed considerably to the joint strength. Another factor that greatly affected the joint strength was the bonding time. At the bonding temperature of 500 °C, prolonging the bonding time to 60, 120, and 240 min enhanced the average joint shear strength to 61.5–70.3 MPa. However, at bonding temperatures of 510–530 °C, increasing the bonding time led to fluctuations in joint strength, in contrast to the increasing trend of bonding at 500 °C. The slight increase in average bonding shear strength at 510 °C is attributed to the higher bonding temperature due to the enhanced atomic diffusion. However, it seems that at bonding temperatures of 520–530 °C, the average joint shear strength could only reach around 60.0–66.7 MPa, despite the increased bonding time. The highest joint shear strengths were 89.15, 83.21, 79.66, and 80.33 MPa at bonding temperatures of 500, 510, 520, and 530 °C for 240 min, respectively. These results may be explained by considering the elevated bonding temperature, since it was close to the melting point of the base material. During the bonding process, grain growth is rather severe; thus, softening of the base material is likely to occur. The base materials applied in this study were identical, and no interlayer was implemented between the faying surfaces. Thus, mutual diffusion was the dominant mechanism and no IMC phase layer existed. This indicated that the results should be similar to those of the solid solution type of diffusion bonding [22], in which thermally activated mutual diffusion and softening of the base metal have a combined effect on the joint strength. The elevated bonding temperature enhanced the joint strength; however, it also led to softening of the base material and a resultant decrease in joint strength.

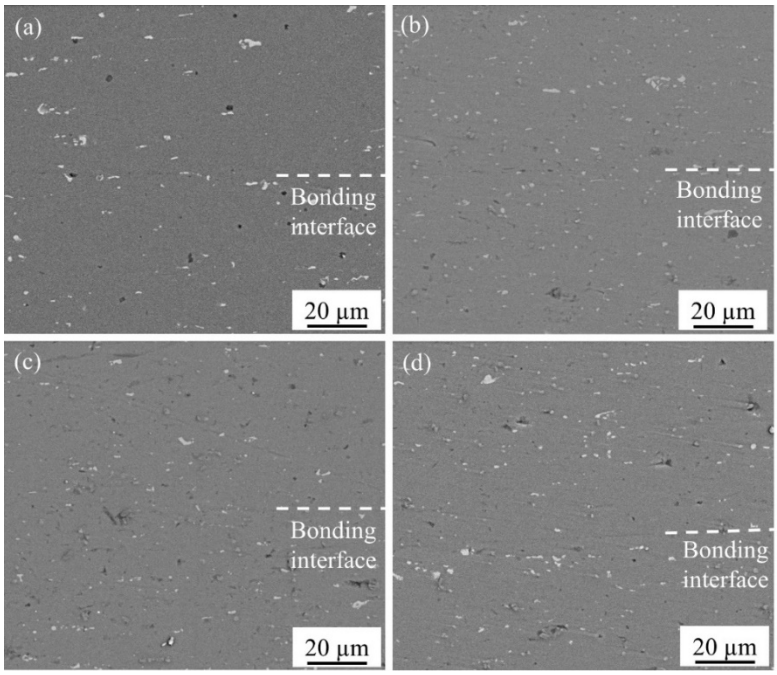


**Figure 5.** Microstructures of AA6061/AA6061 bonding interfaces after diffusion bonding at (**a**) 500 °C, (**b**) 510 °C, (**c**) 520 °C, and (**d**) 530 °C for 240 min.

To sum up, two influencing factors, namely, elevated bonding temperature and prolonged bonding time, both contributed to the fluctuation of the bonding strength of the diffusion bonded AA6061/AA6061 joints, yielding an ultimate bonding strength of 71.2 MPa. This strength is higher than that of NaOH surface-treated adhesive bonding (21.7 MPa) [25] and gas metal arc welded AA6061 lap-bonded joints (53.3 MPa) [34], but lower than that of Ag-28Cu brazed joints (around 150–160 MPa) [14,16]. This result indicates that the joint strength obtained by the diffusion bonding method is ideal and can be expected to provide

better joint reliability because the interface is free of defects and brittle IMC phase; in fact, most of the joint fractures reported for bonding with TLP and brazing were located in the IMC phase [17].

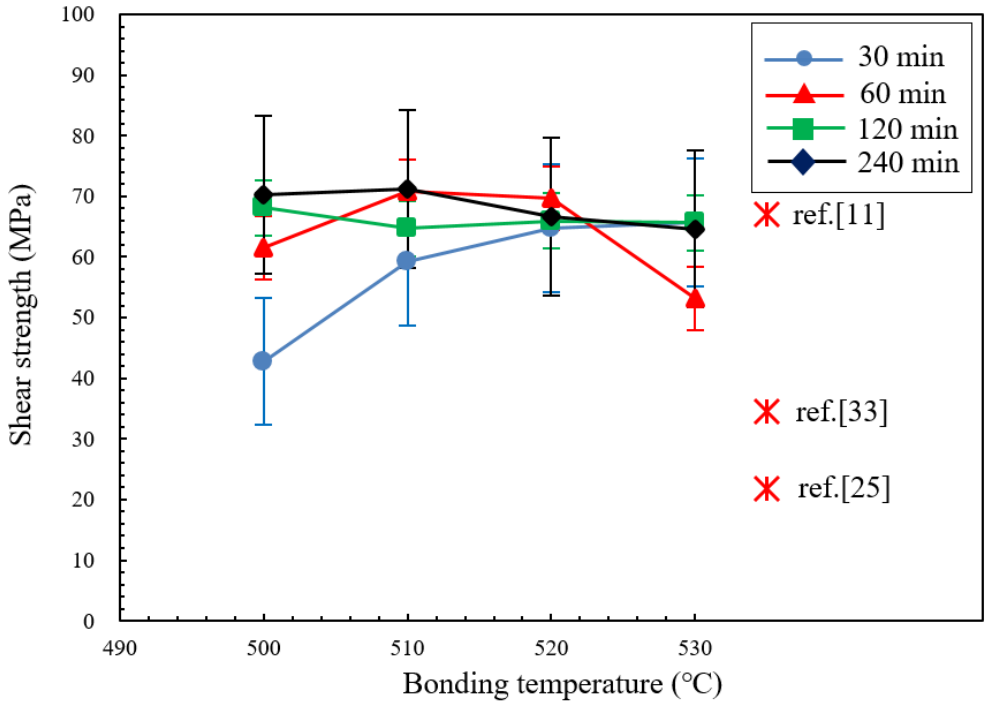


**Figure 6.** Bonding strengths of AA6061/AA6061 joints diffusion bonded at 500–530 °C for 30–240 min [11,25,33].

Furthermore, the surface morphologies of the shear-fractured samples diffusion bonded at 500–530 °C for 240 min are shown in Figure 7. The fractography of the sample bonded at 500 °C, shown in Figure 7a, featured a flat fracture surface with a mixture of voids and dimple-like fractures (black arrows) in some areas. The voids and the flat fracture surfaces indicated a fast failure region and thus a weak bond [18], but the dimple-like morphology indicated locations where local asperities yielded and strong metallic bonds were formed in the localized area [23]. Further increasing the bonding temperature revealed an increase in the number of dimpled areas distributed on the fracture surface (Figure 7b–d), and the voids were diminished. As shown in Figure 7d, the fractography of the sample bonded at 530 °C revealed a noticeable increase in the area of the elongated and equiaxed dimples (3–5 μm) on the fracture surface, implying the high plasticity of the material and strong metallurgical bonds. Based on the above results, the measured bonding strength could not provide sufficient evidence of the successful bonds in AA6061/AA6061 joints achieved by the diffusion bonding method because it was greatly affected by the high bonding temperature. However, the fractography analysis clearly suggested that increasing the bonding temperature could significantly promote the joint strength.

### *3.2. Effect of PWHT on Diffusion Bonded AA6061 Joints*

AA6061 is an age-hardenable alloy, and its mechanical properties can be improved by heat treatment. Conventionally, T6, the most widely applied temper grade, includes solution heat treatment followed by quenching and age hardening to improve the mechanical properties and weldability of AA6061 [28]. PWHT has also been utilized to improve the joint strengths of AA6061 after bonding to compensate for the thermal effects of various welding processes on the weld metal or bonding interface. Several studies have reported that T6-PWHT can also improve the joint properties of the weld metal in the TIGW process [4,34] and the interfacial structure of ultrasonic additive manufacturing by changing

the metallurgical structure [35]. However, the effect of PWHT on diffusion bonded AA6061 joints has not been reported yet.

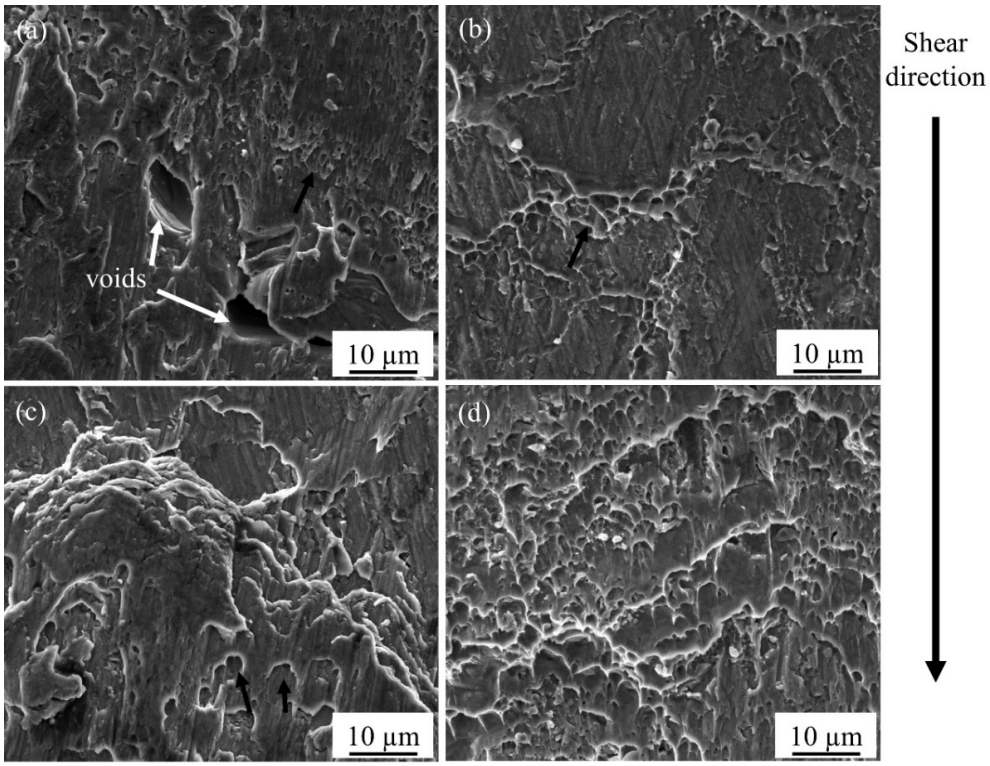


**Figure 7.** Fractography of the fracture surfaces of AA6061 joints diffusion bonded for 240 min at temperatures of (**a**) 500 °C, (**b**) 510 °C, (**c**) 520 °C, and (**d**) 530 °C.

Thus, to evaluate whether PWHT could increase the joint strength, samples bonded at extreme conditions of 500 and 530 °C for 240 min were subjected to T4- and T6-PWHT, respectively. The interfacial microstructures after the treatment are shown in Figure 8, and the corresponding bonding strengths are presented in Figure 9. Since the diffusion bonding used temperatures are close to the AA6061 solid solution temperature, it should be difficult to form second phase particle at the bonding interface. T6 heat treatment was carried out after diffusion bonding, and the precipitation strengthening phase formed in the base metal and the interface, which increased the bonding strength. As shown in Figure 8b,d, the precipitates in the matrix of the base metal were very fine, indicating possible enhancement of the tensile strength of the base metal due to precipitation hardening [36]. However, the interface of the T4-tempered AA6061 joints exhibited some cracks at the edge of the joints and into the interior of the joint, as indicated by the black arrows in Figure 8a,c. In contrast, far fewer cracks developed in the samples subjected to T6-PWHT, and the interior of the joint was free of flaws (Figure 8b,d). Note that these cracks formed after T4-PWHT and not the original diffusion bonding process. Thus, the presence of the cracks was associated with the PWHT as this stage involved heating the AA6061 joint to 530 °C and holding it at that temperature for 1 h before subsequent quenching in room-temperature water (T4). The thermal shock of quenching could have led to sudden shrinkage of the two bonded AA6061 plates, and heavy mechanical loads generated by differential expansion could have acted at the periphery of the joint, which was the stress concentration area. The bonding strengths measured by SLS test shown in Figure 9 indicated that the presence of these cracks led to a significant decrease in joint strength. On the other hand, the T6-PWHT reduced the occurrence of interfacial cracking, providing a noticeable increase (about 40–50%) in joint strength. This increase is highly related to the T6 tempering treatment, for this PWHT

led to elimination of the interfacial cracks through atomic interdiffusion during the aging process and further enhancement of the base materials due to precipitation hardening.

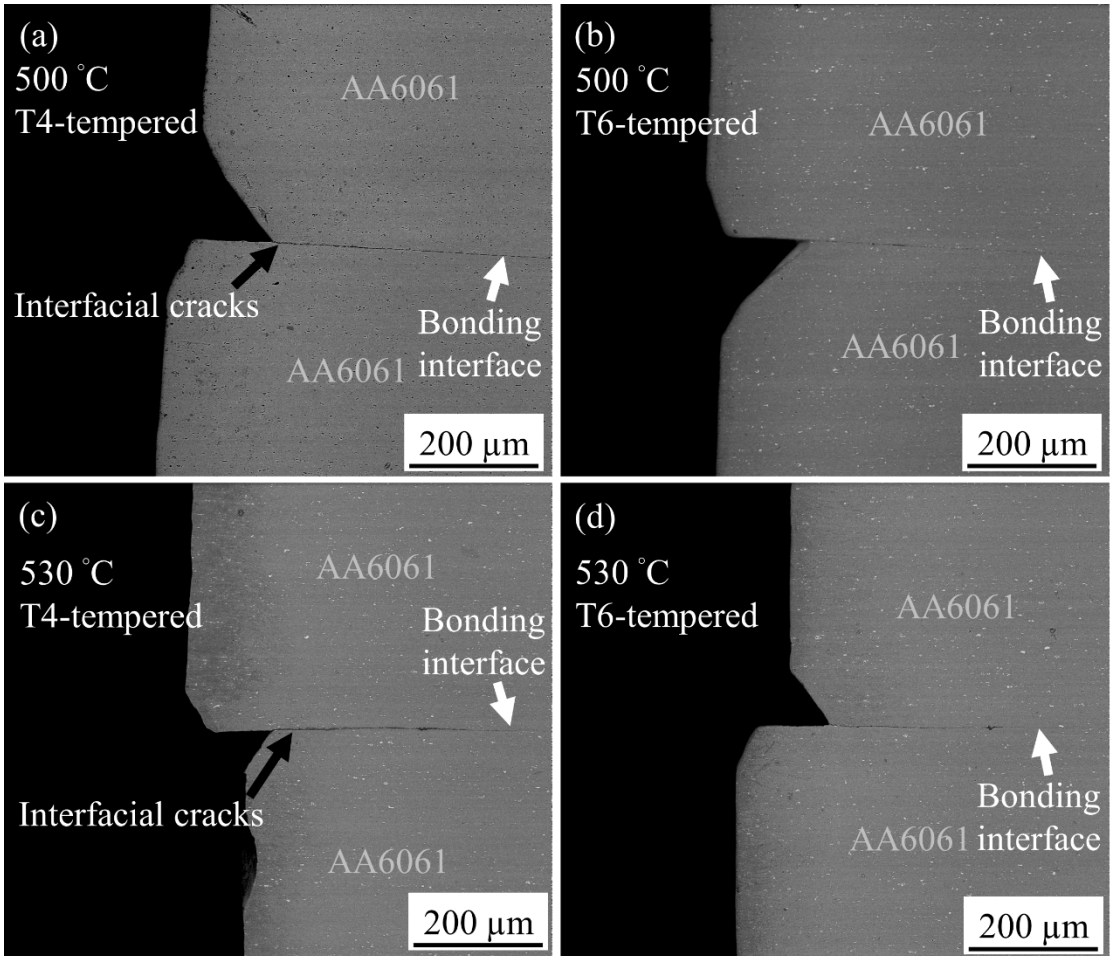


**Figure 8.** Microstructure of AA6061/AA6061 bonding interface after diffusion bonding at (**a**) 500 °C with T4-PWHT (**b**) 500 °C with T6-PWHT, (**c**) 530 °C with T4-PWHT, and (**d**) 530 °C with T6-PWHT.

Furthermore, the fractography after SLS tests of the AA6061 joints bonded at 500 and 530 °C and tempered with T4- and T6-PWHT are shown in Figure 10. The fracture surfaces of the T4-tempered AA6061 joints greatly resembled those of the samples diffusion bonded at 500 °C for 240 min. The fractography exhibited flat surfaces mainly composed of shear marks (white arrow) with some small dimples (black arrow). This indicated that, during the SLS test, the T4-tempered joints experienced fast fracture and weak metallurgical bonds, indicating low bonding strength. On the other hand, the fractography of the T6-tempered joints in Figure 10b,d showed elongated and finer dimples (1–2 µm) than those of AA6061 joints not tempered with T6-PWHT (Figure 7d). As compared with the non-PWHT samples, the fine dimples were related mainly to the smaller grain size and finer precipitations in the bonded region [37] as the artificial aging temperature (160 °C) of T6-PWHT was relatively lower than that of the diffusion bonding temperature of 500–530 °C. This type of fracture is indicative of plastic deformation and good bonding in the localized area, which is consistent with the increased bonding strength after T6-PWHT. These findings support the above claim that T6-PWHT successfully enhanced the joint strength of diffusion bonded AA6061 samples.

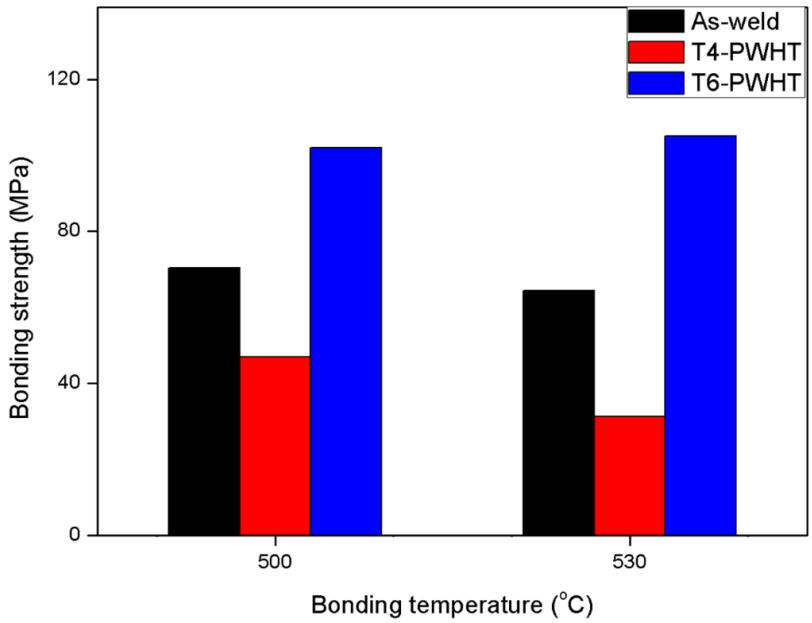


**Figure 9.** Bonding strengths of AA6061 joints diffusion bonded at 500–530 °C for 30–240 min after T4- and T6-PWHT.

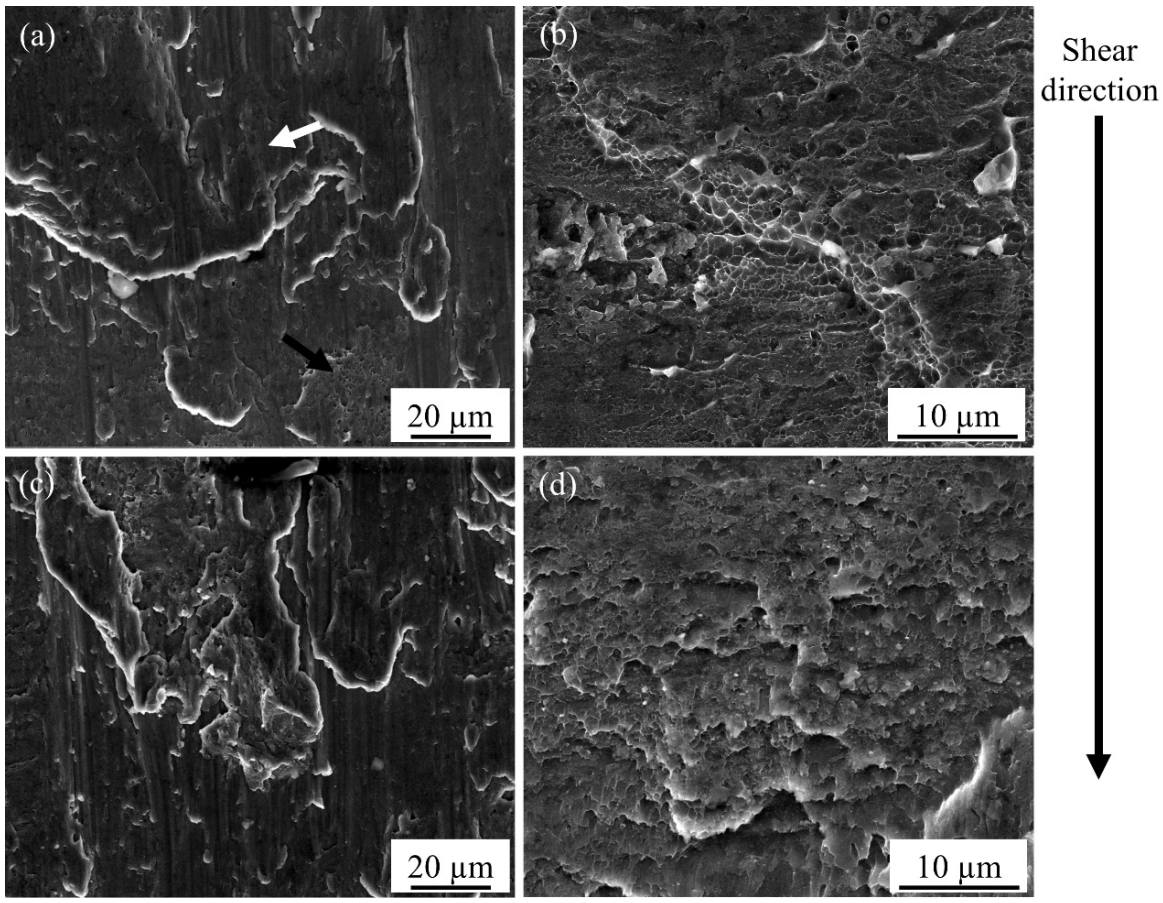


**Figure 10.** Fractography of AA6061 joints diffusion bonded at temperatures of (**a**) 500 °C with T4-PWHT, (**b**) 500 °C with T6-PWHT, (**c**) 530 °C with T4-PWHT, and (**d**) 530 °C with T6-PWHT.

In summary, our study shows that diffusion bonding of AA6061 for large area joint applications is feasible, and the joint strength can be further enhanced with T6-PWHT. Such a method should be important in bonding AA6061 structural components for two reasons: it is cost effective due to the simple manufacturing process, and the joint strength is sufficient for industrial needs.

## 4. Conclusions

This paper has presented the feasibility of solid-state diffusion bonding of AA 6061 joints and the effects of PWHT on the mechanical properties and fracture mechanisms of the bonded AA 6061 specimens. The morphological analysis and the evolution tendency of the corresponding joint strengths on the samples diffusion bonded under various bonding conditions revealed that the two dominant factors were bonding temperature and holding time, in close similarity to the solid solution type of diffusion bonding in metals. The average bonding shear strength could reach 71.2 MPa at 510 °C for 240 min, which is comparable to the strengths achieved by brazing or TLP bonding. The highest joint shear strengths were 89.15 MPa at bonding temperature of 500 °C for 240 min. After T6 heat treatment, the average bonding shear strengths of the AA6061 joint bonded at 500 and 530 °C for 240 min increased from 70.31 to 101.04 MPa and 64.41 to 105.11 MPa, respectively. The SEM fractographs revealed morphological differences in the fracture surfaces of strong and weak joints, in which elongated dimples were indications of excellent bonding. Furthermore, PWHT of the diffusion bonded AA 6061 specimens enhanced the joint strengths by around 40–50%. This result can be mainly attributed to T6-PWHT as the favorable interdiffusion condition provided by the artificial aging of T6 could eliminate the cracks that resulted from the previous quenching process (T4), and the lower aging temperature also led to a smaller grain size and finer precipitates within the AA 6061 material, as confirmed by fractography analysis.

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