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Investigation on Effect of Temperature on Mechanical Properties and Microstructure of Dissimilar Ti-5Al-2.5Sn and AA2219 Alloy Joints through Diffusion Bonding Process

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Abstract

The joining of Ti-5Al-2.5Sn to AA2219 dissimilar alloys was studied through vacuum diffusion bonding (VDB). Samples were bonded at various temperatures under 15 MPa pressure for 45 minutes. The mechanical properties of the bonded lap joints were evaluated with shear and Vickers micro hardness tests, while scanning electron microscopy (SEM) was utilized to examine their microstructure. Energy-dispersive spectroscopy (EDS) and microstructural analysis revealed that the interfacial oxide layer diminished as the bonding temperature increased. The X-ray diffraction (XRD) analysis showed that $TiAl_3$was the only intermetallic compound formed at the interface. Results indicated that as bonding temperature increased, the interface micro hardness first increased and then decreased at higher temperatures. Furthermore, the shear strength of the bonded joint improved with rising temperature from 525 °C to 540 °C but decreased at 555 °C because of the development of a thick intermetallic layer.

Keywords: AA2219; Ti-5Al-2.5Sn Alloy; Diffusion bonding; Microstructure; Interface; Intermetallics; Shear strength.

1. Introduction

Joining dissimilar alloys is important, challenging, and valuable in engineering, manufacturing, and other applications as it results in remarkable tailored material properties such as weight reduction, cost optimization, performance improvement, design flexibility, and compatibility under diverse conditions [1].

Titanium/Aluminium (Ti/Al) dissimilar alloy-bonded joints are used in structural parts such as seat tracks, heat exchangers, and skin stringer joints in corrosive atmospheres, as well as in piping for propellant tanks, replacing traditional riveted structures in aircraft production. They are also utilized to link Al skins to Ti ribs, wings with Al alloy honeycomb, and cooling fins in airline cabins. Additionally, these joints are employed in experimental projects like NASA's YF-12 fighter wings and for joining Ti-6Al-4V (Ti64) tanks to AA2219 (AA2) transition tubing in the Geosynchronous Satellite Launch Vehicle (GSLV).Specifically, AA2 and Ti-5Al-2.5Sn (Ti5) alloys are employed in the production of turbo pump impellers for liquid oxygen (LOX) and liquid hydrogen (LH2), respectively, in the 20-tonne cryogenic engine (CE-20) because of their high strength-to-weight ratio, good corrosion resistance, weld ability, and fatigue resistance [2-6]. Given their properties, AA2/Ti5 bonded joints have the potential to replace Ti64 in tank joining, AA2 transition tubing, and turbo pump impellers for LH2. However, broader research and design considerations are required. So, joining of AA2 to Ti5 alloy is required in the aerospace industry to fabricate light-weight and low-cost products. However, these alloys exhibit significant differences in physical attributes such as crystal structure, melting point, and thermal conductivity [7-10].

Various solid-state methods for joining Ti/Al dissimilar alloys include roll bonding, friction stir welding, resistance spot welding, electron beam welding, laser welding, and DB. Among these, DB is considered the most appropriate method due to its lower formation of brittle intermetallic compounds (IMCs), limited chemical segregation, lesser microstructural degradation, and residual stresses, thereby offering better mechanical properties. In contrast, the high temperatures used in other welding processes often lead to

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the development of undesirable thick intermetallic compounds at the joint, which adversely affect bond strength [5, 11-15].

The DB process is an advanced method for joining dissimilar materials, involving the careful application of three key parameters: temperature, pressure, and holding time. The two surfaces are joined at a temperature between 0.5 and 0.8 of the absolute melting point of the parent metal, using slightly lower pressure to prevent extensive local interfacial deformation, with a holding time ranging from minutes to hours. However, the stable oxide films that form on Al and its alloys must be removed before the DB process to ensure high-quality bonded joints [11, 19-21]. These oxides can be avoided by using a vacuum or inert atmosphere inside the DB chamber and by cleaning the Al surface with alkaline and acidic solutions beforehand [9, 10, 16].

Numerous studies in the literature have explored joining Al and Ti alloys [6,8,10,18,21-26,32]. The DB of pure Ti and Al was successfully achieved, with the only intermetallic phase formed being $TiAl_3$ at the Ti/Al interface, which significantly influenced the mechanical characteristics of the bonded joint [18]. Ren Jiangwei et al. have described the development of brittle inter metallics such as TiAl, Ti_3Al, and $TiAl_3$ when studying Ti/Al rolled sheets joined through vacuum-assisted DB by aluminizing the Ti surface [6].It was observed that by controlling the bonding atmosphere, adjusting the alloy composition, introducing an interlayer at the joint, optimizing bonding parameters, and applying post-heat treatment, the development of these brittle intermetallic phases could be significantly reduced [6,25,26]. The strength of bonded joints between Cp-Ti and AA7075 is more influenced by DB temperature than by holding time and bonding pressure. At low temperatures, incomplete bonding occurs between surfaces due to their high yield strength and reduced flow ability, which prevents full coalescence at the interface [22].

Alhazaa et al. joined Ti64 and Al7075 using a copper (Cu) foil interlayer, varying the bonding time. The Cu diffused into the Ti alloy, forming Cu_3Ti_2intermetallics and resulting in solid-state joining [8]. In a related investigation, an intermetallic layer was detected at the Ti/Al interface, along with cracks, voids, and porosity in the Al-Cu diffusion region [23]. Cu coating on Ti/Alsubstrates hindered oxidation on the Al alloy surface and improved wettability on both Al and Ti surfaces. However, joint strength decreased with increased bonding time for Cu-22%Zn, pure Sn, and Sn-Zn-based interlayers compared to Sn-Ag-based inter layers[10,24-26].

During the DB process, the process variables were optimized and their effects analyzed to achieve maximum strength, hardness, and an optimal range for interface layer thickness [21,27-32]. It was determined that bonding temperature was the most significant parameter compared to bonding pressure and holding time, and it had a considerable influence on bonding features [30-33]. However, the effect of bonding temperature on DB of Ti5/AA2 dissimilar joints remains unexplored. The study investigates the bonding characteristics of Ti5/AA2 alloy joints bonded at various temperatures while maintaining constant pressure and holding time. It aids in designing Ti5/AA2 diffusion bonds and provides better insights into how temperature influences the DB process.

2. Experimental details:

The base materials used to form a dissimilar joint in this research were AA2 Al alloy and Ti5 Ti alloy. Table 1 provides the chemical constituents of these alloys. Samples were wire-cut to dimensions of 25×20×5 mm for bonding preparation. The bonding surfaces were ground with SiC papers to a 1200-grit finish and subsequently polished with diamond paste to achieve a 1 μm finish. Both alloys were chemically treated: The Ti5 sample was soaked in a mixture of 3% hydrofluoric acid and 30% nitric acid solution, while the AA2 sample was first immersed in 6% sodium hydroxide, then in 40% nitric acid, followed by rinsing with water and air-drying to remove oxides from the bonding surfaces [8].

The hydro thrust vacuum hot press, with a load capacity of 100 tons, a maximum heating temperature of 1000°C, and a maximum vacuum of $1×10^{-6}$ mbar, was used for bonding. The bonding parameters were as follows: bonding temperature (T) ranged from 480°C to 570°C, bonding time (t) was 45 minutes, and applied pressure (P) was 15 MPa. According to the literature, bonding time can extend from minutes to hours, depending on heating temperature, applied pressure, and material properties. However, extended bonding times may cause excessive intermetallic formation and higher costs without necessarily improving bond strength. The 45-minute duration was selected after conducting trial experiments, considering all the relevant factors mentioned in previous studies [17,32]. Figure 1 illustrates the experimental parameter curve for the Ti5/AA2VDB process. The specimen was placed inside the chamber and heated to the required temperature is as shown in Figure 2. A soaking period of 10 minutes was allowed to stabilize the heat and vacuum inside the chamber before applying pressure. After bonding, the specimen was allowed to cool inside the heating chamber to room temperature before being removed.

Table 1. Chemical constituents of base alloys

Base alloy	Cu	Sn	Fe	Mg	Mn	O	C	N	H	Si	V	Zn	Zr	Al	Ti
AA2219	5.8	-	0.3	0.02	0.2	-	-	-	-	0.2	0.05	0.1	0.1	Bal	0.02
Ti-5Al-2.5Sn Alloy	-	2.5	0.5	-	-	0.2	0.08	0.05	0.0125	-	-	-	-	5	Bal

The cross-section of the bonded sample was polished and etched using a reagent composed of 5 ml of nitric acid, 3 ml of hydrochloric acid, 2 ml of hydrofluoric acid, and 90 ml of distilled water [22]. The microstructure of each Ti5/AA2 dissimilar joint was analyzed with SEM [35-39], the elemental composition at the interface was assessed by EDS, and inter metallics near the interface were identified using XRD. Shear strength of the samples was evaluated according to ASTM D1002-99 [9, 10] using a tensile testing machine (Model: MTS 30/MH), where the bonded joint was subjected to a tensile load to create shear force at the interface, determining the joint's strength [32, 34, 35]. Each condition was tested with a set of three samples. Micro hardness was measured with the HWMMT-X7 Micro Vickers hardness tester, applying a load of 1 kilogram-force (1 kgf) for 10 seconds.

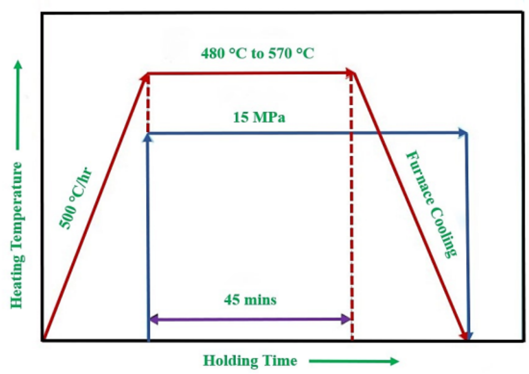

Figure 1. Experimental parameter curve forTi5/AA2using VDB process.

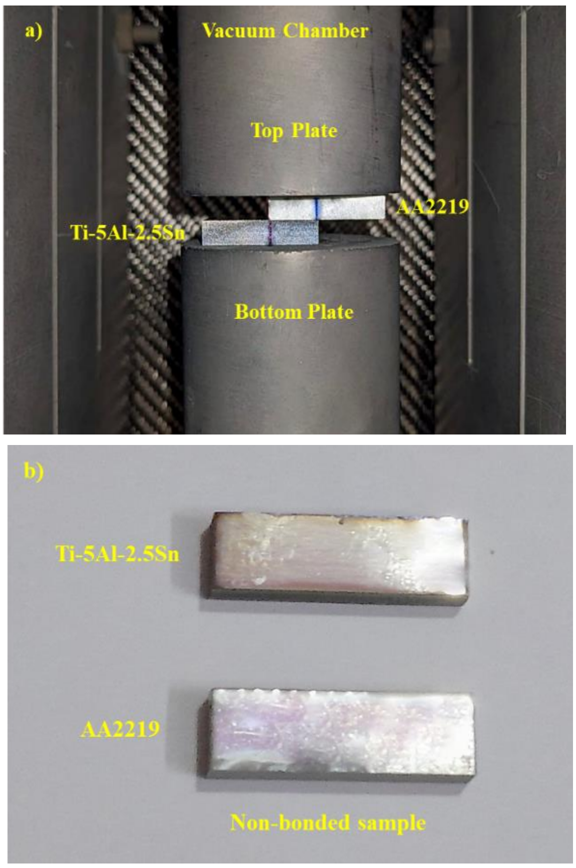

Figure2. (a) Experimental setup for Ti5/AA2bonding, and (b) a non-bonded sample made at 480 °C.

3. Results and discussion:

3.1. Microstructure at the Ti5/AA2 joint surface

The bonding temperature is the key parameter in the DB technique, as highlighted by the Arrhenius formula. Therefore, the mechanical characteristics and microstructures of the Ti5/AA2 alloy bonded at various temperatures were studied [33].

At 480 °C (see Figure 2b), the Ti5/AA2 diffusion joint failed to form because the bonding temperature and pressure were insufficient for atomic interaction at the interface. However, as the temperature increased from 525 °C thereafter to 570 °C and with an applied pressure of 15 MPa, effective bonding occurred between the mating surfaces of Ti5 and AA2 alloys when held for about 45 minutes. This contact between surface asperities and bonding time allows for sufficient atomic diffusion across the interface. Additionally, high pressure helps to control void formation and expel trapped gases and impurities from the bonding interface, leading to improved bond quality. Longer bonding times and prolonged exposure to the bonding temperature further promote atomic migration and inter diffusion between Al and Ti atoms, resulting in thicker diffusion layers and affecting the mechanical characteristics of the Ti5/AA2 joint.

The entire diffusion process between AA2 and Ti5alloy includes: (1) a macroscopic transfer of atoms between the substrates at high bonding temperatures; and (2) the formation of a new phase when Ti and Al atoms diffuse to a certain extent near the interface. The simple inter-diffusion reaction between Al and Ti atoms leads to the creation of a compound phase at the interface during high-temperature bonding.

Using SEM, the microstructure at the Ti5/AA2 diffusion-bonded joint was investigated. Figure 3 depicts the SEM micrograph of the Ti5/AA2 joint bonded at 525°C. The observation orientation was perpendicular to the axis of the diffusion-bonded joint. The dark gray region represents the Ti5 alloy, while the bright gray region represents the AA2 alloy. A narrow diffusion zone with a very thin diffusion boundary is observed at the Ti5/AA2 interface (see Figure 3a). It was also noted that the joint has some interfacial voids (see Figure 3b).

These interfacial voids in the Ti5/AA2 bonded joint could be formed due to the Kirkendall effect, as the diffusion rates of Al and Ti atoms differ. Additionally, a small quantity of oxides is trapped in the voids because of the oxides on both the Ti5 and AA2 substrates. The EDS spectrum for the interface region (Area A) of the Ti5/AA2 joint made at 525°C reveals the presence of these oxides (see Figure 4).

The DB of Ti5/AA2 joints at 540°C and 555°C is illustrated in Figure 5(a) and (b), where a thin diffusion line is observed at the boundary. As the temperature increases to 570°C, atomic diffusion effectively fills these voids, limiting oxidation under vacuum conditions (see Figure 6(a) and (b)). This is supported by the EDS analysis presented in Figure 7.

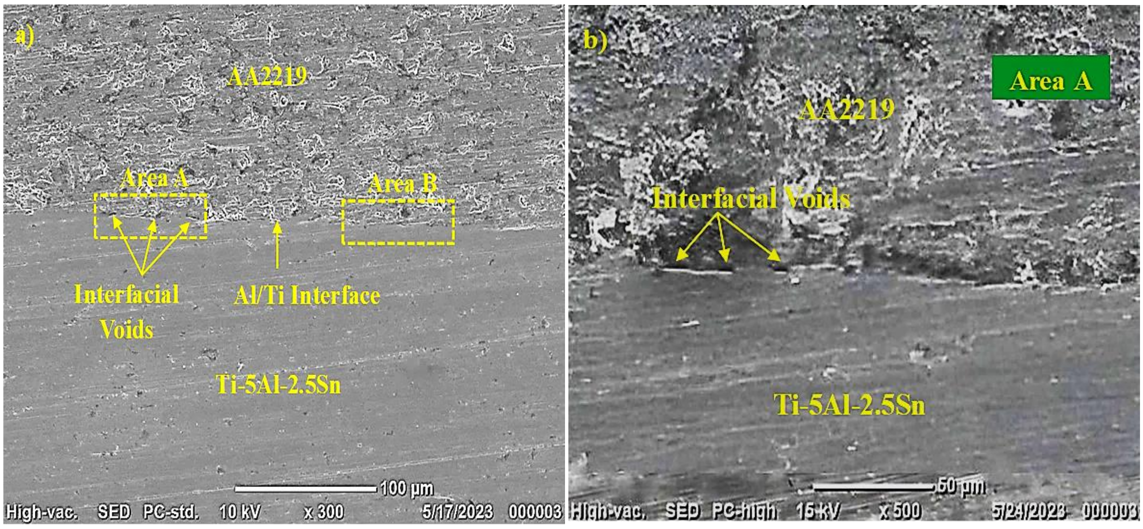

Figure 3. SEM micrograph of the Ti5/AA2 joint at (a) 525 °C, and (b) a detailed view of Area A.

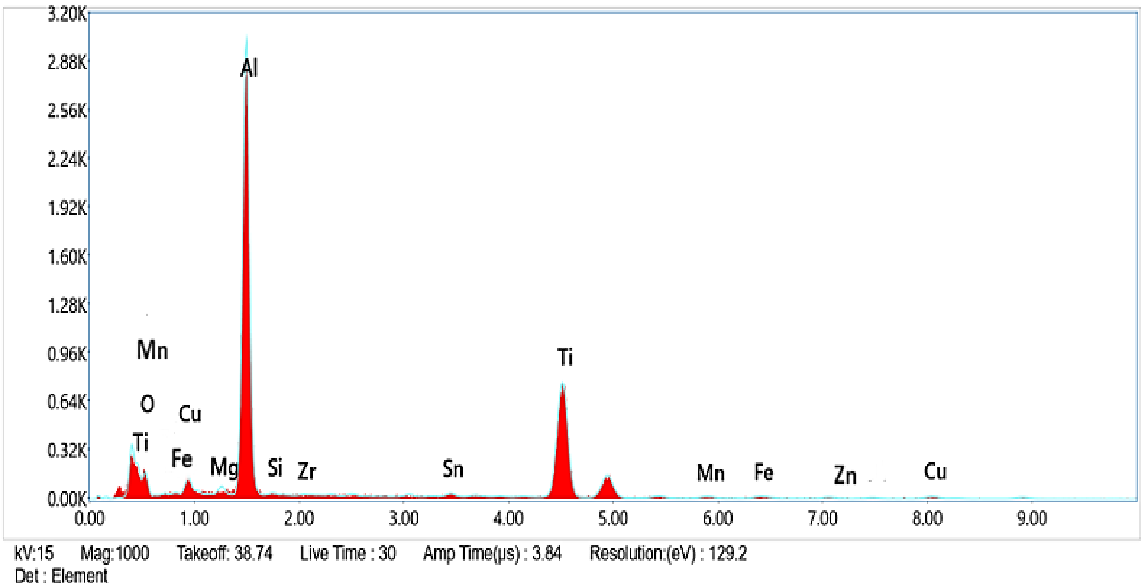

Figure 4. EDS spectrum of the interface region (Area A) of the Ti5/AA2 joint made at 525 °C.

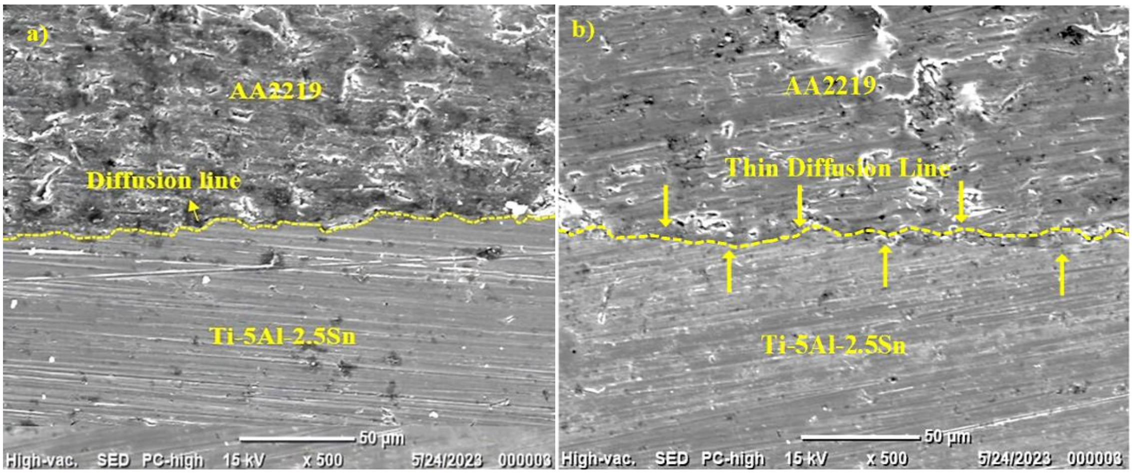

Figure 5. SEM micrograph of the Ti5/AA2 joint bonded at (a) 540 °C and (b) 555 °C.

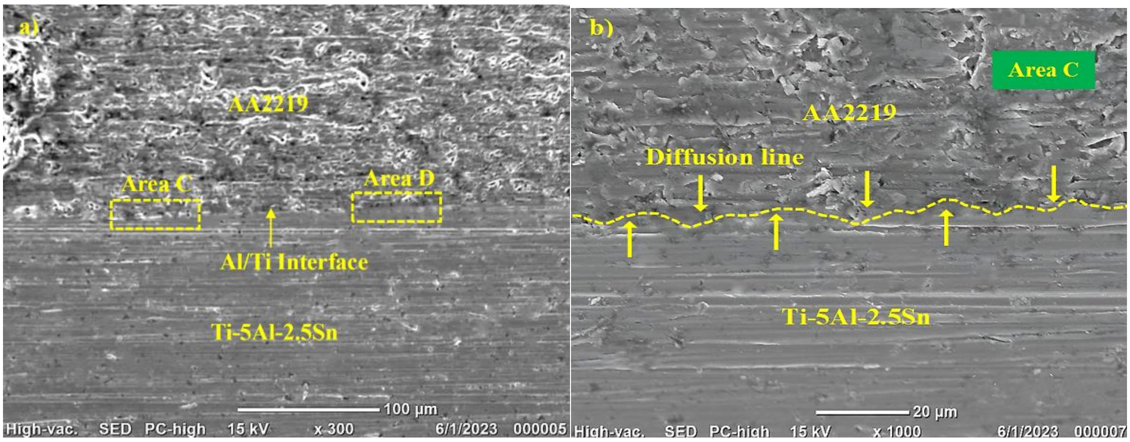

Figure 6. SEM micrograph of the Ti5/AA2 joint bonded at (a) 570 °C, showing Areas C and D, and (b) a detailed view of Area C from (a).

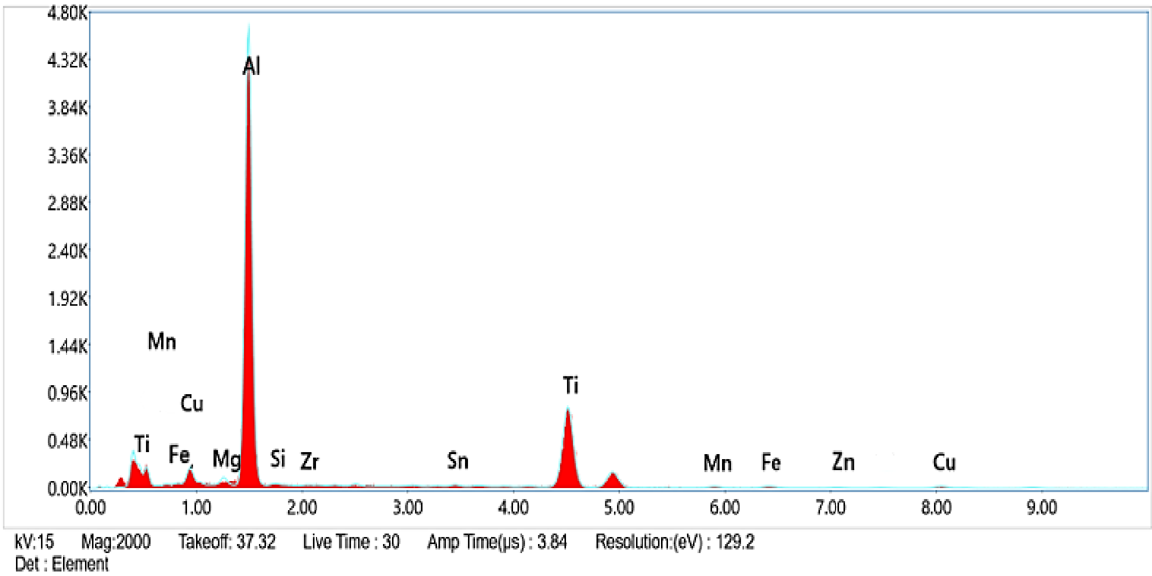

Figure 7. EDS spectrum for the interface region (Area C) of the Ti5/AA2 joint made at 570 °C.

Table 2. EDS analysis of different areas in Figures 3(a) and 6(a)

Area	Weight (wt) %										
	Al	Ti	Mg	Si	Mn	Fe	O	Zn	Cu	Zr	Sn
A	55.9	33.1	0.3	0.1	0.1	0.8	3.2	0.1	3.8	0.3	2.3
B	57.2	33.8	0.2	0.2	0.1	0.6	2.1	0.2	3.5	0.1	2.0
C	57.8	34.2	0.3	0.1	0.1	0.8	0	0.1	4.1	0.2	2.3
D	58.1	34.4	0.2	0.1	0.1	0.6	0	0.2	4.2	0.1	2.0

From the EDS analysis (Table 2), it is observed that Area A is rich in Al (55.9 wt%) and Ti (33.1 wt%) with 3.2 wt% oxygen. This results from the voids that developed at the interface during bonding at 525°C. Area B has a similar composition. However, as the temperature increases, the voids are filled with atoms, and further oxidation is not observed under vacuum conditions, as seen in Areas C and D. Homogeneity in the joint region confirms the formation of a single intermetallic phase.

3.2. XRD analysis near the Ti5/AA2 joint surface

XRD analysis was performed to investigate the intermetallic compounds formed at the transition zone of the Ti5/AA2 bonded joints. The XRD was performed using a Cu target with a current of 150 mA and a voltage of 40 kV. Figure 8 depicts the XRD pattern at the transition zone of the Ti5/AA2 dissimilar joint specimen bonded at 540 °C. Several peaks corresponding to intermetallic formation are detected, along with peaks for Al and Ti, identified as Al, Ti, and $TiAl_3$.

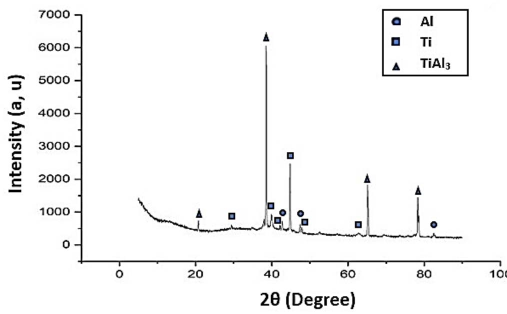

Figure 8. XRD pattern at the transition zone of the Ti5/AA2 alloy specimen bonded at 540°C.

Similarly, Figure 9 illustrates the XRD pattern at the transition zone of the Ti5/AA2 dissimilar alloy specimen bonded at 555 °C. Multiple intermetallic peaks are observed, as well as peaks for Al and Ti, again identified as Al, Ti, and $TiAl_3$.

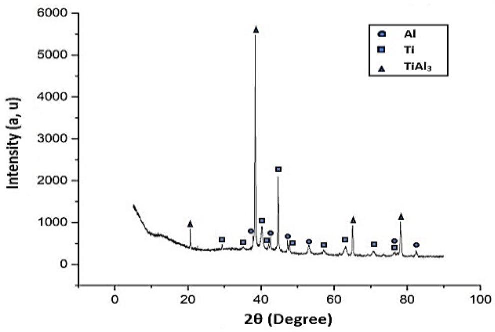

Figure 9. XRD pattern at the transition zone of theTi5/AA2 alloy specimen bonded at 555 °C.

The direct contact between Ti and Al during the solid-state DB process results in the formation of the intermetallic compound $TiAl_3$. A similar XRD pattern is observed for the Ti5/AA2 alloy specimen bonded at 570 °C.Based on the XRD results (Figs. 8 and 9), it is concluded that $TiAl_3$ is the only intermetallic compound formed at the Ti5/AA2boundary. This single intermetallic phase confirms the homogeneity near the joint region.

3.3. Mechanical properties of Ti5/AA2 bonded joints

Micro hardness was measured for the Ti5 substrate at the Ti5/AA2 interface and for the AA2 substrate normal to the interface surface using the Vickers method. The general distribution trends of micro hardness for joints bonded at various temperatures are similar. The micro hardness of the Ti5/AA2 alloy bonded joint enhances with the elevation in bonding temperature and is evenly distributed across both surfaces of the substrates, as depicted in Figure 10. This observation is consistent with findings reported in [9,40], which also demonstrated similar trends in micro hardness with increasing bonding temperatures.

For a diffusion-bonded joint made at 525 °C, the micro hardness value at the interface region was found to be 85 HV1 due to incomplete bonding at this lower temperature. This value increases to 150 HV1 at 555 °C due to the growth of inter metallics. However, at the higher temperature of 570 °C, grain coarsening leads to a reduction in micro hardness to 100 HV1.

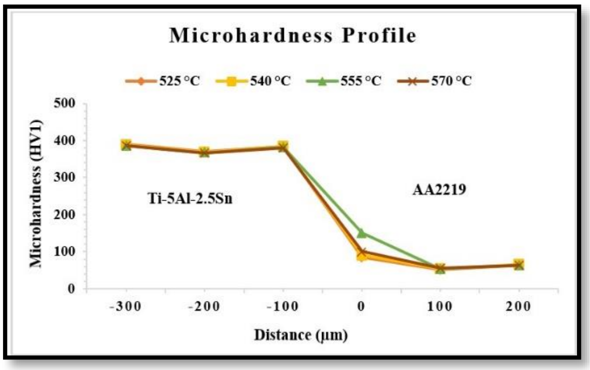

Figure 10. Micro hardness profile of Ti5/AA2 joint bonded at different temperatures.

The Ti5/AA2 bonded joints (see Figure 11(a)) were subjected to a tensile load, generating shear force at the joint to estimate the joint's strength. The shear strengths of these joints at various bonding temperatures, along with their corresponding hardness values, are presented in Table 3. Figure 11(b) presents the shear-tested samples after bonding at different temperatures.

Table 3. A summary of the micro hardness and shear strength of the Ti5/AA2joints

Properties	Bonding temperature			
	525 °C	540 °C	555 °C	570 °C
Hardness (HV1)	85	90	150	100
Strength (MPa)	25.6	49.0	44.1	33.6

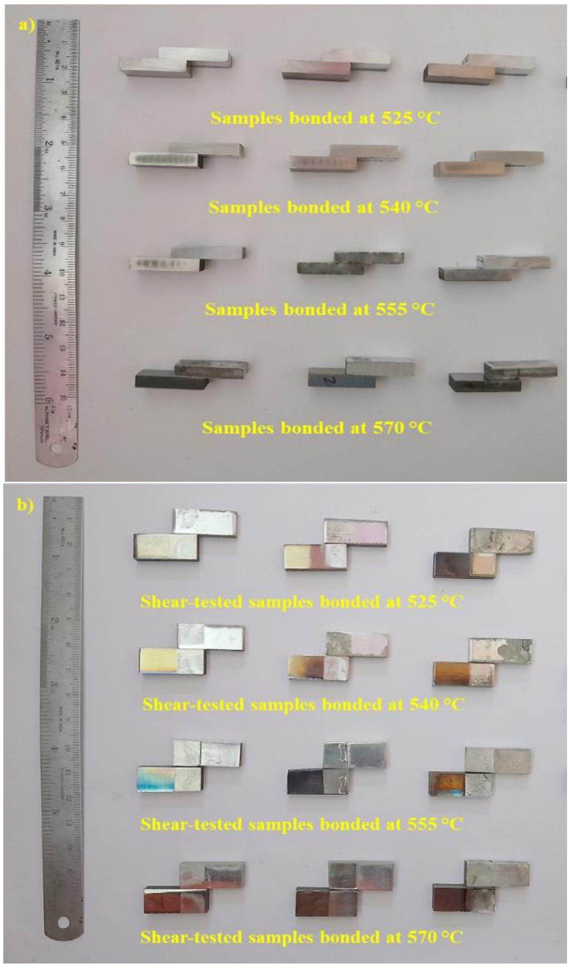

Figure 11. (a) Bonded samples made at different temperatures, and (b) shear-tested samples after bonding at different temperatures.

Based on Figure 12, it can be inferred that as the temperature during bonding rises, the shear strength initially grows at 540 °C and then drops at 555 °C. The maximum shear strength of 49 MPa was attained at 540°C. At lower temperatures, there is insufficient energy for the diffusion of atoms, resulting in lower strength. However, as the temperature rises, inter metallics form with sufficient thickness due to faster atomic diffusion. Consequently, the thick inter metallics lead to a reduction in shear strength to 33.6 MPa at 570°C.These results are in agreement with those reported in [22, 33], which observed comparable trends in shear strength with varying bonding temperatures.

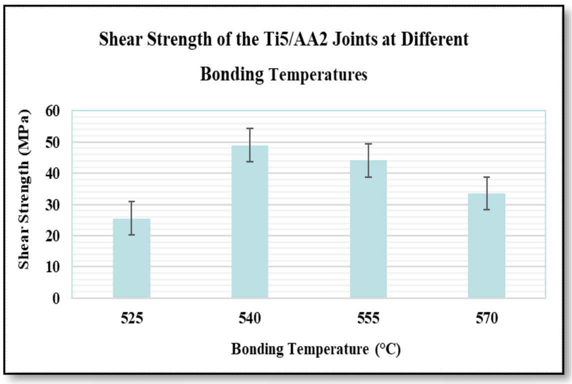

Figure 12. Shear strength distribution of the Ti5/AA2 joint at different bonding temperatures.

Bonding temperature significantly impacts the kinetics of atomic diffusion near the interface of the joint. At higher temperatures, atoms acquire sufficient thermal energy to overcome initiation energy barriers, allowing them to migrate further across the boundary to their original lattice positions, thus forming inter metallics. These results show that bonding temperature has a significant effect on intermetallic formation as well as on the micro hardness and shear strength of the Ti5/AA2 bonded joints.

The applied pressure and holding time also affect interatomic diffusion between Ti5 and AA2 alloy substrate, leading to faster bond formation and potentially higher bond strength due to increased atomic mobility from high pressure and diffusion layer formation from longer bonding times. It is observed that, with bonding temperature variation alone, both applied pressure and time deliberately influence the kinetics of atomic diffusion, despite being kept constant during the Ti5/AA2 dissimilar bonding process.

Longer bonding times for bonding AA2/Ti5 alloys result in higher production costs and higher energy consumption, indicating the trade-off between bonding time and processing efficiency. Therefore, in order to obtain the desired bond quality for bonded joints, it is imperative to optimize the bonding parameters, experimental circumstances, and material compositions.

To sum it up, Ti5/AA2 diffusion-bonded joints show promise for applications needing an appropriate combination of high strength, lightweight, and resistance to mechanical and thermal fatigue. These joints' shear strengths, which vary from 25 to 49 MPa and meet the specifications for bonding temperatures between 525 °C and 570 °C, suggest that they are suitable for challenging cryogenic and aerospace applications where AA2 and Ti5 alloys both demonstrate remarkable features and stability at very low temperatures.

4. Conclusion

This study investigates the DB of Ti5/AA2 dissimilar alloys and highlights the effects of temperature on the joint's microstructural and mechanical characteristics. The key findings are:

- Ti5/AA2 dissimilar alloys were effectively joined through a DB process at temperatures ranging from 525 °C to 570 °C, using a bonding pressure of 15 MPa and a holding time of 45 minutes.
- From XRD analysis, the only intermetallic identified is $TiAl_3$ at the Ti5/AA2 interface.
- Due to the Kirkendall effect at lower bonding temperatures, interfacial voids were observed at the Ti5/AA2 bonded joint.
- At higher temperatures, the SEM micrograph of the Ti5/AA2 interface showed a narrow diffusion line, indicating effective DB.
- The micro hardness at the Ti5/AA2 joint's interface increased with temperature during bonding due to intermetallic formation. The maximum micro hardness of 150 HV1 was achieved for the Ti5/AA2 joint bonded at 555 °C.
- As the bonding temperature increases to 555 °C, the shear strength of the Ti5/AA2 bonded joints decreases because of thick inter metallics forming at the interface. At 540 °C, the Ti5/AA2 joint achieves a shear strength of 49 MPa.

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