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ORIGINAL ARTICLE

Solide State Diffusion Bonding of Al6061-SiC Nanocomposites

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ABSTRACT – Aluminium matrix composites are both strong and lightweight, and are limited in their applications due to the proper choice of welding process. Conventional welding that is based on fusion at the welded joint is not suitable because it leads to the formation of certain defects at the welded joint. For this reason, solid-state welding such as diffusion bonding is one of the suitable joining methods, as there will be no melting of any of the constituents. The solid-state diffusion bonding at 520° C of Al6061-SiC nanocomposites was investigated. This composite material was made by powder metallurgy, where aluminium alloy Al6061 was selected as the base metal, and SiC nanoparticles with an average size of 50 nm were added as reinforced particles. The effects of bonding time on the microstructures and mechanical properties of the welded material were investigated. The main characterisation techniques were optical microscopy, scanning electron microscopy coupled with energy dispersive spectroscopy, x-ray diffraction, and microhardness measurements. We have found that increasing the holding time up to 3 h at 520° C strengthens the weldability of the two basic composite materials and increases their hardness. X-ray diffraction analysis did not reveal any new phase during diffusion welding; it is considered one of the advantages of using the solid-state diffusion welding technique for the assembly of this kind of composite material. The welding success of this composite material widens its field of use, such as the automotive or space industry, because it is a light material with high mechanical properties.

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Bonding time

INTRODUCTION

A composite material is made up of at least two materials, which combine to give properties superior to those of the individual constituents. For many years, Al6061 alloy has been largely used in automotive, aerospace and marine applications. The aluminium alloy can be strengthened by adding other metallic or organic compounds such as SiC, SiO2, TiO2, TiC, TiB2, B4C, and ZrB2. The widespread applications of aluminium matrix composites (AMCs) are limited due to the high cost of reinforcements and the inadequate development of joining technology [1,2]. The most widely used ceramic reinforcement for AMCs is silicon carbide (SiC). The study of this type of composite material has aroused the interest of researchers. For example, Shankar et al. [3] mentioned that AMCs reinforced with SiC particles improve the yield strength. It is important to mention that research on AMC welding is divided into two categories: fusion welding and solid-state welding [4]. From the literature, several joining techniques have been investigated in an effort to determine which process can be used successfully for joiningAMCs, including fusion welding [3], soldering [5], liquid phase bonding transient (TLP) [6], and solid-state diffusion bonding [7]. The main problem with joining AMCs using classical fusion methods is the development of unwanted interfacial reactions between the matrix and the reinforcement [8]. It has also been observed that it is difficult to maintain the distribution of ceramic particles in the weld zone compared to that of the parent composite [9].

Therefore, assembly of AMCs by solid-state diffusion bonding is a suitable joining technique to avoid the formation of intermetallics. Diffusion welding or diffusion bonding is a solid-state welding (SSW) technique that is capable of joining similar and dissimilar metals [10]. This joining technique is performed by clamping the two metals to be welded together with their surfaces in abutment. After tightening under a given pressure, these two metals will undergo heat treatment at a constant temperature for several hours. The temperature must be between 50 – 70 % of the melting temperature of the metal. During this process, the interdiffusion of atoms through the interface represents the main mechanism of the process. Diffusion welding depends on some variables: time, applied pressure, bonding temperature, atmosphere, material properties, roughness and degree of contamination of surfaces in contact [11]. This technology is of essential importance when other competitive procedures cannot be used for reasons of characteristics or material characteristics.

In the literature, a limited number of research works have reported studies on Al-6061/SiC composites assembled by some welding techniques such as electron beam and laser welding [12], microwave welding [13], friction stir welding [14] and friction stir spot-welding [15]. Most of this work was based on Al-6061 / SiC composite materials reinforced with Si-C particles [12-14]. However, there is not enough study on the solid-state diffusion bonding of Al-6061 / SiC reinforced with Si-C particles or nanoparticles. Therefore, this article presents an investigation of solid-state diffusion

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bonding of Al6061-SiC nanocomposites at 520°C. The effect of diffusion bonding time (1, 2 and 3 hours) at 520 °C on the microstructures and mechanical properties of welded joints were studied.

EXPERIMENTAL PROCEDURES

Base Materials and Samples Preparation for Welding

Al6061-SiCp cylindrical composites were made by the powder metallurgy process with a fixed weight percentage of 10% by weight of SiC nanoparticles. Al6061 powder (63 μm) and nano SiC powder (50 nm) were supplied by Good Fellow Cambridge Limited Huntington, PE29 WR, England. The chemical composition of Al6061 and the parameters of the powder metallurgy manufacturing process are shown in Table 1 and 2, respectively.

Table 1. Chemical composition of alloy Al6061 powder (wt. %).

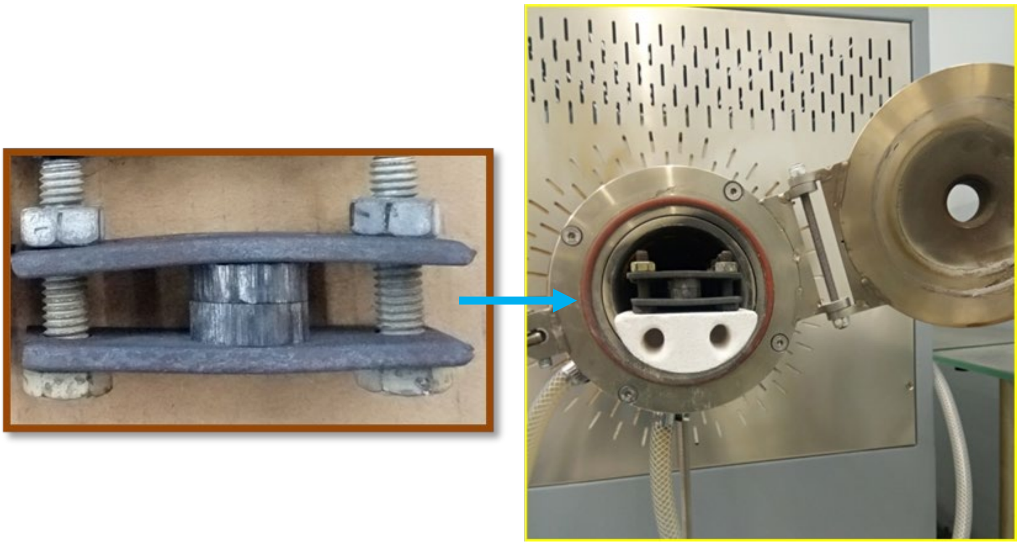
Elements	Al	Si	Fe	Cu	Mg
(wt. %)	97.5	0.6	0.5	0.4	1.0

Table 2. Parameters of synthesis by powder metallurgy of Al6061 / SiCp composites.

Powders	Al6061(63μm) and SiC (50nm)
Milling time	2 hours
Compacting pressure	10 tons
Sintering temperature	600°C
Sintering time	2 hours
Final product	Cylindrical samples (Ø=14mm)

Joining by Diffusion Bonding Process

Prior to the application of the diffusion bond technique, two cylindrical samples of Al6061-SiCp composites were polished and cleaned thoroughly by ultrasound in acetone. Then, the two samples were brought into contact, then clamped by a specific device, as in Figure1. The samples were heated to 520° C at a rate of 4 ° C / min, and held at this temperature for different bonding times (1 h, 2 h and 3 h). To avoid oxidation of the samples, the bonding was carried out in an atmosphere of argon and hydrogen. After each hold time, the sample was air cooled to room temperature. The three welded samples of Al6061-SiCp were cut perpendicular to the weld line into two parts and prepared for the different characterisation techniques.



(a) (b)

Figure 1. Diffusion bonding device. (a) clamped samples and (b) furnace.

Characterisation Methods

For microstructural observations, samples were prepared according to standard metallographic procedure and etched with HF reagent. The microstructure was observed using an optical microscope (HIROX Kh-8700) and a scanning electron microscope (HITACHI SU8020) equipped with an energy dispersive spectroscopy (EDS) detector. The X-ray diffraction (XRD) study was carried out using a Panalytic diffractometer (BRUKER D-5000) to detect any reaction product in the welded composite. The XRD was performed using the CuKα source in the range of 10° to 90°. The results were analysed using the X'pert high score plus software. The mechanical properties of the welded composite were measured using a Vickers automatic hardness tester (HM-200) at 0.05 Hv.

RESULTS AND DISCUSSION

Base Materials

The microstructure of the base composite Al6061-SiCp 10 wt.% is shown in Figure 2, revealing a homogeneous distribution of the SiC particles in the Al grains and at the grain boundaries. In addition, some micropores are observed at grain boundaries and correspond to a typical microstructure of a composite material. The XRD pattern of the sintered aluminium composites reinforced with 10wt.% SiC amount shows just two main peaks, corresponding to Al matrix and SiC particles, as in Figure 3.

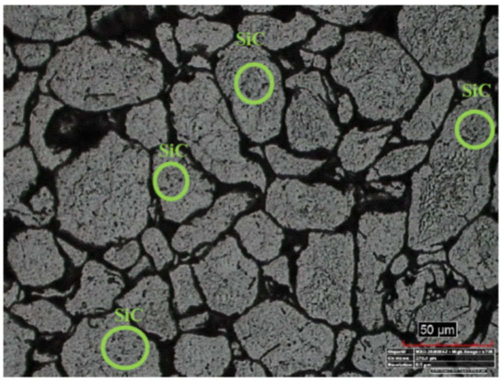


Figure 2. Typical sample of the base composite Al6061-SiCp 10 wt.%.

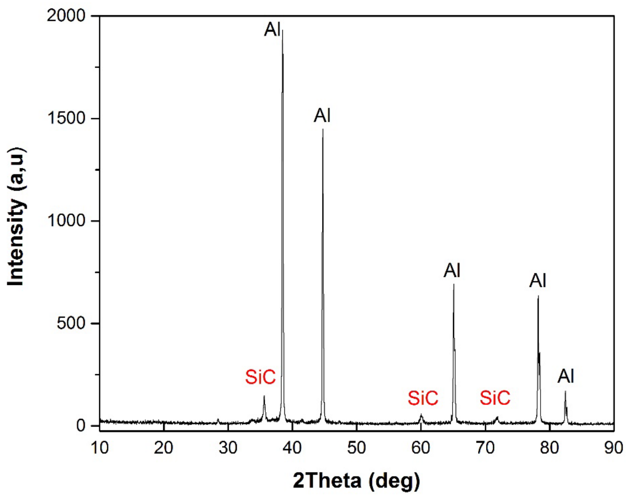
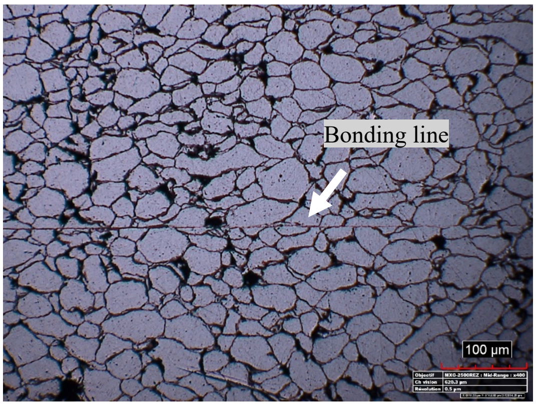


Figure 3. XRD pattern of the base composite Al6061-SiCp 10 wt. %.

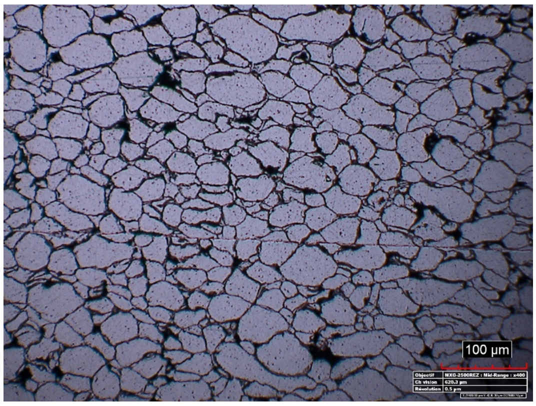
Microstructures Observation of the Welded Joint

Figure 4. shows the microstructure evolution of the welded Al6061-SiCp after the bonding diffusion process at 520°C for different holding times of 1 h, 2 h and 3 h. It is noted that no micro-defect was observed in the welded joints. It has been reported that some defects can form in the welded joint if the composite materials have been welded by traditional fusion welding methods [16]. Generally, these defects are mainly porosity and segregation of the reinforcement in the welded joint. For this reason, solid-state diffusion bonding is the appropriate technique for joining composite materials.

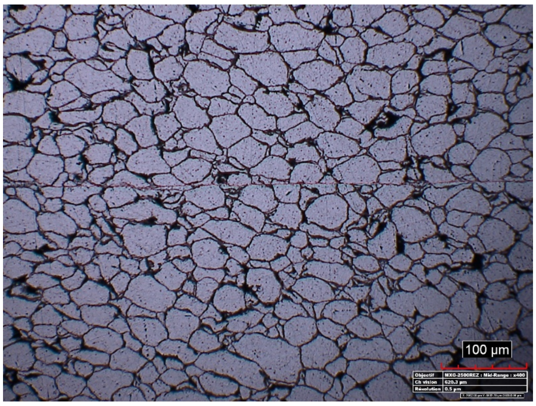
In addition to the previous observations, the increase in the holding time contributed to the weldability of the two parts of the composite material since the thin bonding line observed after 1 h of holding (shown in Figure 4(a)) gradually disappears by extending the holding time until 2 h (as in Figure 4(b)) and 3 h (as in Figure 4(c)). It has been established that a solid-state diffusion welding is carried out by the local deformation of the points of contact of the two surfaces, reduction of the pores, growth of grains through the joint, and finally, the disappearance of the interface [17]. We consider that the contact joint has undergone a hot micro deformation during the welding process at 520 °C because, at this temperature, the aluminium becomes more ductile. In addition to this phenomenon, we did not observe any significant change in grain size because the growth of Al grains would be inhibited by SiC particles during the bonding process [2].



(a) 1 h



(b) 2 h

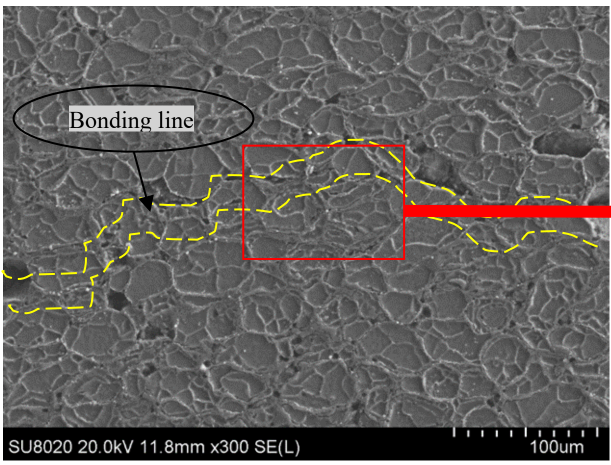


(c) 3 h

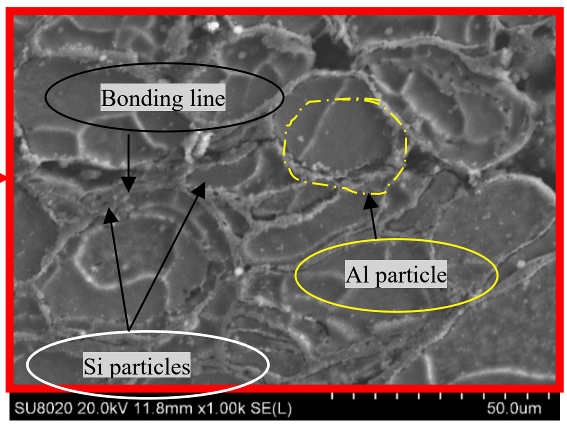
Figure 4. Optical microscopy observations of welded composite Al6061-SiCp welded at 520 °C for different holding times.

SEM Micrographs and EDS Analysis of the Joint Welded at Different Bonding Time

Figure 5 shows SEM micrographs of a selected welded sample at a bonding time of 2 hours. For more details, electron backscattered images of the same area are shown. In order to show more detail in the bonding line (mentioned between two yellow lines), a selected area of Figure 5(a), as indicated by a red rectangle, is also shown at high magnification (in Figure 5(b)). From these two figures, the grain boundaries that bind the aluminium grains together appear bright compared to the dark area. These luminous areas correspond to the atoms of silicon with atomic number Z=14. It must be remembered that the atoms of silicon have the greatest atomic number Z compared to the rest of the elements existing in the welded material (Al, Mg, O and C). As known, the element silicon in the composite material exists in the form of particles of SiC. It was also observed that some SiC particles were roughly trapped by the bond line. These observations confirm the similarity between the grain boundaries and the bond line.



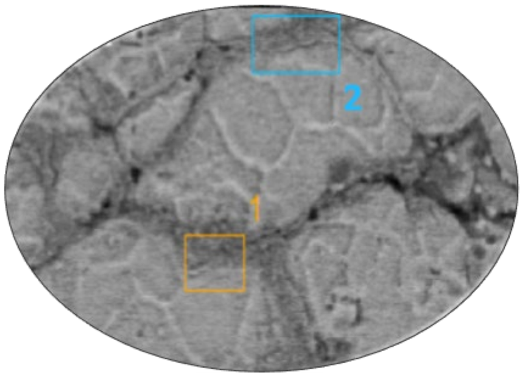
(a)



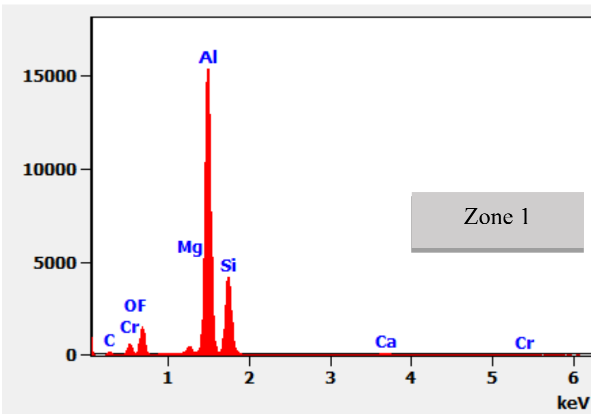
(b)

Figure 5. Backscattered electrons images of the same zone of Al6061-SiCp composites welded at 520 °C for 2 hours, with (b) is the magnification of a selected zone in (a).

To confirm with the previous observation, EDS analyses of the welded joint of the AA6061-SiCp composite were performed, as shown in Figure 6. The EDS analyses focused on two areas of the welded joint. The first zone corresponds to the bonding line; on the other hand, the second zone corresponds to a grain boundary that binds the Al particles. Based on the EDS spectra and chemical composition, the two elements Si and C exist in both zones, which confirms the high concentration of SiC in these areas. According to Kwok [18], the property of welded joints of AMCs is generally dependent on the distribution of particle reinforcements in the weld, and their uniform distribution in the weld increases the tensile strength of more than 70 to 80% of AMC parents. They considered that the aggregation or absence of particle reinforcements in the weld severely degraded the properties of the joint and subsequently caused the weld to fail. However, the presence of fluorine is due to the etching process by the HF agent. The elements Al, Si, Mg and Cu were also in the composite, which are major elements of the composite.



(a)



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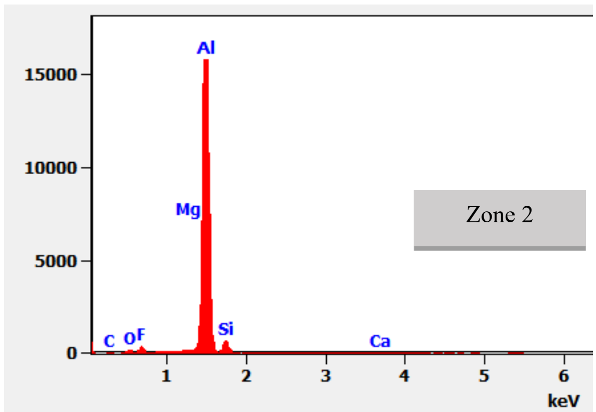

(c)

Elements	*C-K*	*O-K*	*F-K*	*Mg-K*	*Al-K*	*Si-K*	*Ca-K*	*Cr-K*
Zone (1) Wt. %	5.1	10.0	17.7	1.1	42.6	22.5	0.7	0.2
Zone (2) Wt. %	4.5	4.6	5.7	0.3	77.4	7.2	0.2	

Figure 6. (a)SEM image, (b)and (c) EDS spectra, with chemical composition on the two selected zones in the welded joint of the Al6061-SiCp composites (hold time = 2 h).

X-ray Diffraction Analysis of the Welded Al6061/SiCp AMCs

The XRD patterns of the welded Al6061-SiCp composites are shown in Figure 7. XRD analysis was conducted to identify any phase transformation, either the formation of a new phase or a metallurgical interaction between SiCp and the aluminium matrix. These assumptions did not notice by XRD because only the diffraction peaks of Al and SiC particles were revealed on the base material (in Figure 3), which did not undergo any change during the hold at 520 ^oC, as in Figure 6. Therefore, the SiC particles did not react with the aluminium matrix during diffusion welding. This result is in agreement with previous work, which had observed that silicon carbide did not react in the solid-state with the most aluminium alloy [3]. Likewise, according to some studies, no harmful phase or brittle phase has been revealed by XRD in the welded joint of aluminium composite materials [19,20].

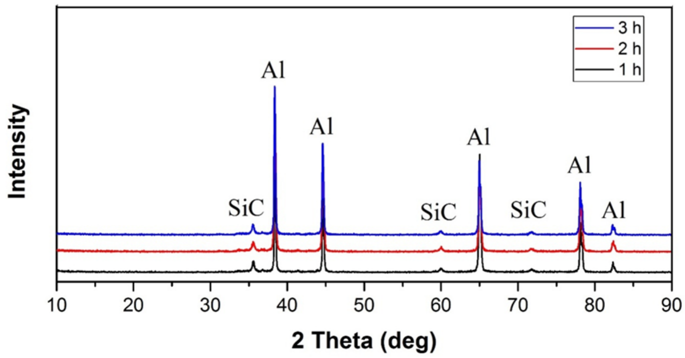

Figure 7. The XRD patterns of Al6061-SiCp composites welded at 520 °Cfor 1 hour, 2 hours and 3 hours.

Microhardness of the Welded Joint

The mechanical property of the welded composite material was evaluated with Vickers microhardness measurements along the welded joint and also for the three holding times at 520 °C, as in Figure 8. First of all, the three hardness curves have a similar shape, and it is difficult to see a noticeable difference between the different areas of the welded joint. However, it is clear that the hardness of the welded joint increases with increasing bonding time. The increase in hardness is due both to the increase in weldability of the two parts and to the effect of SiCnanoparticles on the hardening process during the holding time at 520 °C. In addition, it was found that the carbide particles of silicon act as obstacles to the movement of dislocations [21,22].

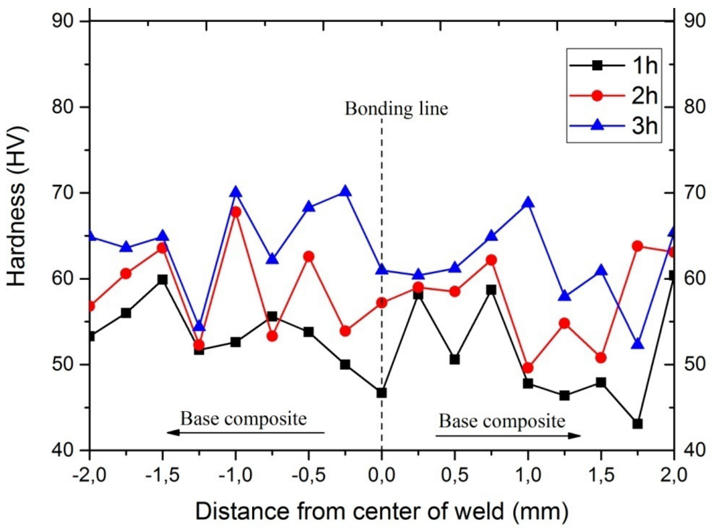

Figure 8. Microhardness profiles on the cross-section of the Al6061-SiCp composites welded at 520 °C for 1 hour, 2 hours, and 3 hours.

CONCLUSION

In the present study, the Al6061-SiC nanocomposite was successfully welded by solid-state diffusion bonding. Microstructural observations, x-ray diffraction, and hardness measurements were used as characterisation techniques. The results obtained can be summarised as follows:

i. The macro and microstructures of the welded joints did not reveal any macro or micro defects such as porosity, which testifies to the success of the joining process.
ii. The bond line disappears with the increase of the holding time up 3 hours during the diffusion process at 520 ºC, which also confirms the weldability of the composite material by this technique.
iii. According to the SEM and EDS analysis, the SiC particles were more localised at the joints between the aluminium particles and in the bond line.
iv. From optical observations, there was no variation in grain size during the diffusion process at 520 ºC.
v. XRD analysis confirmed the presence of Al and SiC, without any phase transformation during the diffusion process at 520 ° C.
vi. The hardness of the welded composite increased with increasing holding time at 520 ºC. Therefore, this diffusion bonding temperature contributed to the improvement of the mechanical properties of the composite.

From these results, the solid-state diffusion welding technique is a suitable welding technique for joining composite materials.

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