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Research Article

THE EFFECTS OF WELDING PRESSURE AND REINFORCEMENT RATIO ON WELDING STRENGTH IN DIFFUSION-BONDED AlMg3/SiCp COMPOSITES

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In this study, using the diffusion welding method, welded joints were created with AlMg3/SiCp composite materials, and the mechanical strengths of these joints were examined. The AlMg3/SiCp composite specimens were cut out of plates produced directly with the semi-solid stir-squeeze casting method and contained 10% SiCp and 20% SiCp reinforcement. To examine the effects of reinforcement ratios on joint strength, specimen couples with the same and different reinforcement ratios were created. To examine the effects of different welding pressures on joint strength, by keeping the welding temperature constant at 580°C, welding was performed under 3 different pressures as 1.5 MPa, 2.5 MPa and 3.5 MPa. By determining the mechanical strengths of the welded joints that were formed by shear test, the effects of reinforcement ratios and welding pressures on joint strength were investigated. As a result of the shear tests applied on the welded specimens, in the specimens that were diffusion-welded, welding quality decreased based on increasing reinforcement ratios, but as the amount of pressure and application duration increased, joint strength increased. As the SiC ratio increased in the joint zones, diffusion became difficult, and weak joints were obtained. The microscopic structure of the joint zone was examined by using optical microscopy and scanning electron microscopy (SEM). It was seen that diffusion welding could be successfully performed in bonding SiCp-reinforced aluminium composites if the suitable welding pressure and duration are selected.

Key words*: Diffusion Welding, Aluminium, SiC, Metal Matrix Composites, Shear Test.*

1. Introduction

Metal matrix composite (MMC) materials are advanced materials that have increasing usage rates in almost all industrial fields, especially defence, automotive and aviation [1-3]. A selected metal or metal alloy matrix material may not only be strengthened with reinforcements in micro/nano dimensions and different forms, but all thermal processes and cold forming methods that can be

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applied on the metal or metal alloy selected as the main matrix material may also be performed [4]. Although MMCs continue to be used and developed in almost every sector, it is one of the main problems that need to be overcome that, in bonding applications of these materials with different metals or themselves, the superior technical properties gained in production cannot be transferred to the joint zone [5-7]. Especially in bonding applications of particle-reinforced composite materials with fusion welding, different densities of the reinforcement material and the matrix material lead to separation of the matrix material that goes into a liquid form and the reinforcement materials in various forms, failure of achieving the reinforcement distribution before the welding process and formation of segregation zones [8, 9]. Besides this, problems such as formation of unwanted reaction products due to processing temperatures higher than the melting temperature, uncontrolled solidifications that form during cooling or cracking of welding zones by excessive reduction of the ductility of the material are also frequently encountered [10-14]. In solid-state welding methods where melting does not take place, it is aimed for the materials to be bonded to preserve their structures and properties before the welding process, while the welding parameters in the diffusion bonding/welding method are temperature, pressure, duration of pressure application and atmosphere, welding zones with adequate mechanical properties may be obtained by providing the optimum values, and this method may also be used to bond MMCs according to the reports in the literature [15-23]. However, welding particle-reinforced aluminium composites is difficult and requires taking special precautions. Systematic work on this issue has been encountered in very few studies, and in this study, the weldability of MMC materials containing different reinforcement ratios was examined. Composite specimen couples with the same and different reinforcement ratios were prepared from AlMg3/SiCp composite blocks, and the prepared specimens were subjected to diffusion welding at the temperature of 580°C and under pressures of 1.5 MPa, 2.5 MPa and 3.5 MPa. To determine the effects of reinforcement ratios on joint strength, shear and microhardness tests were applied, and the microstructures of the bonded-welded joints were examined by optical microscopy and SEM.

2. Experiments

2.1. Materials

The specimen material consisted of AlMg3/SiCp composite material obtained by the semi-solid stir and squeeze casting method. This method is described in a patent held by Urkmez Taskin and Taskin [23, 24]. As the matrix material in the composite materials to be subjected to diffusion welding, the AlMg3 (EN AW 5754) aluminium alloy, which has good weldability, ductility and toughness properties and excellent corrosion resistance especially against seawater, was used. The chemical, mechanical and physical properties of AlMg3 are shown in Tables 1 and 2. As the reinforcement material, SiCp particles with grain sizes of 500 Mesh (~12 μm) were utilized. With semi-solid stirring, the reinforcement material can be homogenously stirred into the matrix alloy in the desired ratio, and during stirring, problems such as flocculation of the reinforcement, separation from the mixture or precipitation are not encountered. Additionally, as reinforcement addition takes place at a relatively lower temperature than liquid stirring methods, formation of unwanted reaction products is minimized [20, 23, 25].

Table 1. Chemical composition of the AlMg3 alloy [23]

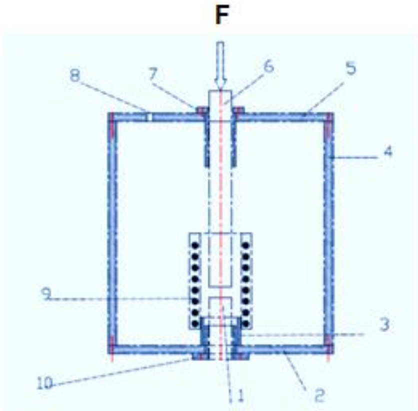
Fe	Si	Mn	Cr	Ti	Cu	Be	Mg	Zn	-
max 0.4	max 0.4	max 0.5	max 0.3	max 0.15	max 0.1	max 0.0003	2.6-3.6	max 0.2	0.1<Mn+Cr<0.6 Al-remainder

Table 2. Mechanical and physical properties of the AlMg3 alloy and composite specimens [23]

	AlMg3	AlMg3/SiCp (vol 10%)	AlMg3/SiCp (vol 20%)
Brinell hardness (HBW): (O) (H111)	45	100	148
Tensile strength (MPa) (F) (H112)	180	210	245
Proof strength (MPa) (F) (H112)	70-80	190	210
Density, g/cm^3	2.66	2.91	2.99
Young Modulus, GPa	68-72	70	76
Shear Modulus, GPa	27	-	-
Melting Temperature, °C	600-640	-	-
A-Min. elongation at fracture (%) (F) (H112)	13-14	12	10

2.2. Diffusion welding furnace and shear test apparatuses

For the diffusion welding process, the diffusion welding furnace whose picture is seen in Figure 1 was designed and produced. The picture of the apparatus that was designed for placing the specimens into the diffusion welding furnace and forming welded joints is shown in Figure 2, while the specimen dimensions are shown in Figure 3.



Part No	Part Name
1	Specimen tray
2	Lower cap
3	Resistance bearing bush
4	Body
5	Upper cap
6	Load application punch
7	Bearing bush
8	Thermocouple housing
9	Heating resistance
10	Lower bearing bush

Figure 1. Schematic drawing of Diffusion bonding apparatus [25]

Diffusion welding apparatuses were designed and produced out of steel material with the machining method. The welded specimens [28] had dimensions of 25 mm x 12 mm x 3 mm, while the shear specimens were obtained by cutting these specimens into 3 parts with dimensions of 8 mm x 12 mm x 3 mm (Figure 3). For applying the shear test, a shear apparatus was designed in compliance with the jaws of the INSTRON 1501 universal device and produced (Figure 4).

Figure 2. Diffusion bonding fixture [25]

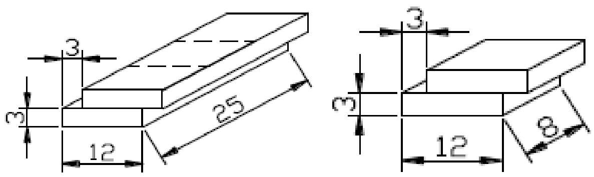


Figure 3. Dimensions of diffusion and shear test specimens [25]

Figure 4. Apparatus for the shear test and the diffusion bonded shear test specimen photo [25]

2.3. Diffusion Welding

The diffusion welding specimens were cut out of AlMg3 composite blocks with dimensions of 25 mm x 12 mm x 3 mm using the wire erosion method. The cut specimens were placed onto each other in the welding apparatus shown in Figure 2 and joined. In the diffusion welding process, welding temperature, duration and pressure values were selected by considering studies in the literature. In the trial welding processes, welding was performed when the welding temperature was in the range of 560 - 590°C, and thus, the welding temperature was selected as 580°C. The diffusion welding process was performed under normal atmosphere and without using an intermediate layer. Two different times as 120 min and 180 min were selected as the welding durations. The welding duration started as soon as the temperature of the specimens reached 580°C. During the process, the temperature was constantly controlled. The specimens were cooled by themselves inside the furnace and under a fixed load.
The literature was taken as a basis for the pressure values to be applied in the diffusion welding process. For the diffusion welding of Al-based SiC particle-reinforcement composite materials, by conducting trials in the interval of 1-5 MPa, the lower pressure value for bonding to start was determined as 1.5 MPa, while the upper pressure value where plastic deformation started was determined as 3.5 MPa. In the same conditions, by performing welding procedures with the specified parametric values on the unreinforced matrix alloy, the reference specimens were prepared. Using three different pressure values and two different durations, 2 specimens for each case were joined by diffusion welding. The welding pressures and times used in this study are shown in Table 3 [23, 26].

Table 3. Diffusion bonding parameters used in this study

Material Combination	Temperature (°C)	Welding Pressure (MPa)	Welding Time (min)
AlMg3- AlMg3	580	1.5 2.5 3.5	120 180
AlMg3-AlMg3/SiCp, (vol 10%)			
AlMg3-AlMg3/SiCp, (vol 20%)			
AlMg3/SiCp, (vol 10%)-AlMg3/SiCp, (vol 10%)			
AlMg3/SiCp, (vol 20%)-AlMg3/SiCp, (vol 20%)			

2.4. Characterisation

Each of the welded specimens was divided into three equal parts, and a total of 6 shear test specimens with the same conditions were prepared. The surfaces of the specimens to be welded were prepared with 100, 200 and 400 mesh sandpapers, and they were left in pure alcohol before the procedure. To determine the bond strength of the diffusion welded specimens, shear and hardness tests were applied. The shear tests were performed at a progression rate of 0.5 mm/min with an INSTRON 8501 Universal test device by applying force in the compression direction. The microhardness tests were performed on the basis of the DIN EN ISO 6507-1 standard.

The welded specimens were firstly divided lengthwise into two and embedded in Bakelite. The specimens that were subjected to standard sanding and polishing procedures were finally subjected to etching. The metallographic examinations of the welded specimens were carried out by an optical microscope and by SEM.

3. Results and Discussion

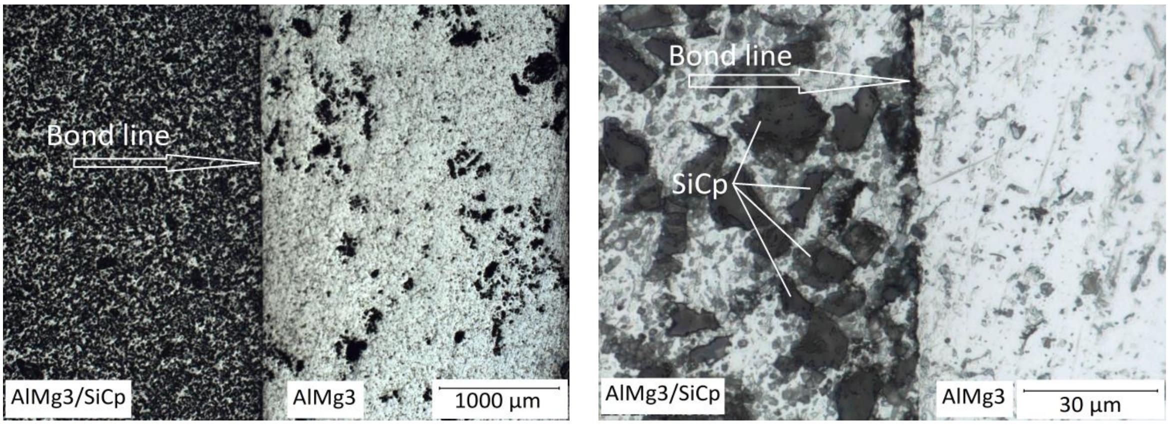
The specimens that were bonded by diffusion welding were firstly macroscopically examined, and whether or not the welding pressure caused a deformation was determined. As seen in Table 4, a preliminary study was carried out under 1.5 MPa, 2.5 MPa and 3.5 MPa of pressure and 120 min and 180 min of welding duration to determine the suitable pressure and duration. As the results obtained at the welding durations of 120 min and 180 min in the preliminary study were in parallel to each other, it was found appropriate in this study to use the welding duration of 180 min. Whether or not joint formation took place and whether or not deformation was observed are shown in Table 4 regarding the material couples' welding procedure in the preliminary study. No deformation was observed in any of the specimen couples that were welded under the pressures of 1.5 MPa and 2.5 MPa.

Table 4. Diffusion bond and deformation formation according to the applied pressure and time

Material couple	Temperature (°C)	Pressure (MPa)	Time (dk)	Deformation	Bonding
AlMg3 - Al Mg3	580	1.5	120	-	-
			180	No	+
		2.5	120	No	-
			180	No	+
		3.5	120	Yes	+
			180	Yes	+
Al Mg3 - AlMg3/SiCp (10%)	580	1.5	120	No	-
			180	No	-
		2.5	120	No	-
			180	No	+
		3.5	120	Partially	+
			180	Partially	+
AlMg3 - AlMg3/SiCp (20%)	580	1.5	120	No	-
			180	No	-
		2.5	120	No	-
			180	No	+
		3.5	120	Partially	+
			180	Partially	+
AlMg3/SiCp (10%) - AlMg3/SiCp (10%)	580	1.5	120	No	-
			180	No	-
		2.5	120	No	-
			180	No	+
		3.5	120	No	+
			180	Yes	+
AlMg3/SiCp (20%) - AlMg3/SiCp (20%)	580	1.5	120	No	-
			180	No	-
		2.5	120	No	-
			180	No	+
		3.5	120	No	+
			180	No	+

Deformation took place in the non-reinforced specimen couples and on the non-reinforced side in cases of welding with 10% and 20% SiCp-reinforced composites under the pressure of 3.5 MPa. No deformation was observed on the reinforced sides. Under the same pressure, deformation did not occur after the welding process of 20% SiCp and 10% SiCp-reinforced composites. No deformation was observed in the 20-20% AlMg3/SiCp specimen couple under 2.5 MPa. There was negligible deformation in the 10-10% AlMg3/SiCp specimen couple under 3.5 MPa. The pressure value of 3.5 MPa was determined as the upper boundary of pressure in the diffusion welding process of 10% SiCp-reinforced specimens. There was no deformation in the 20-20% AlMg3/SiCp specimens under 3.5 MPa.

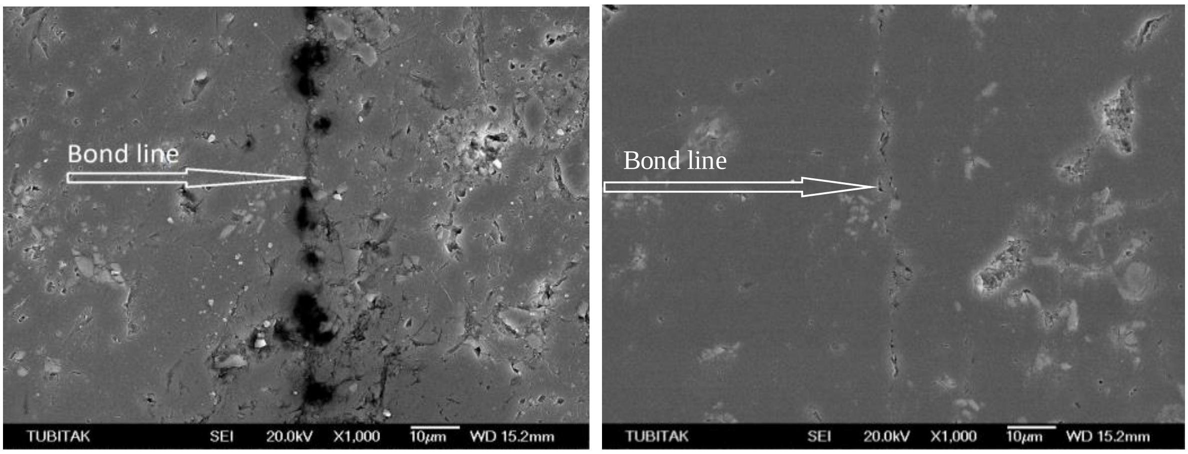
The welded joints were examined under an optical microscope and by SEM. Figure 5 shows that, in the optical microscopic examinations of the specimens processed under a pressure of 1.5 MPa for 120 min, the welding zone lines were noticeable, and gaps and welding lines could not be eliminated in this zone.



a) b)

Figure 5. Optical microscope images of the AlMg3/SiCp (20%)- AlMg3 couple diffusion welded for 180 min under 1.5 MPa. a) x2.5, b) x100

Figure 6a shows that there were gaps and pores of ~1-5 µm dimensions on the joint line in the bonding zones of the AlMg3/SiCp (vol.20%) - AlMg3specimens that were bonded under a pressure of 2.5 MPa for 120 min, whereas Figure 6b shows that gaps and pores decreased on the joint line in the bonding zones of the AlMg3/SiCp (vol.20%) - AlMg3specimens that were bonded under a pressure of 2.5 MPa for 180 min.



a) b)

Figure 6. SEM images of the bonded joints of AlMg3/SiCp (20%) - AlMg3 samples under a) 2.5 MPa pressure and 120 min. b) 2.5 MPa pressure and 180 min.

Figures 7a and 7b show the bonding zones of the AlMg3 / SiCp (vol.20%)-AlMg3 couple that were bonded for 180 min under a pressure of 3.5 MPa. Bonding occurred in the welding zone, and the line in the interface mostly became unnoticeable.

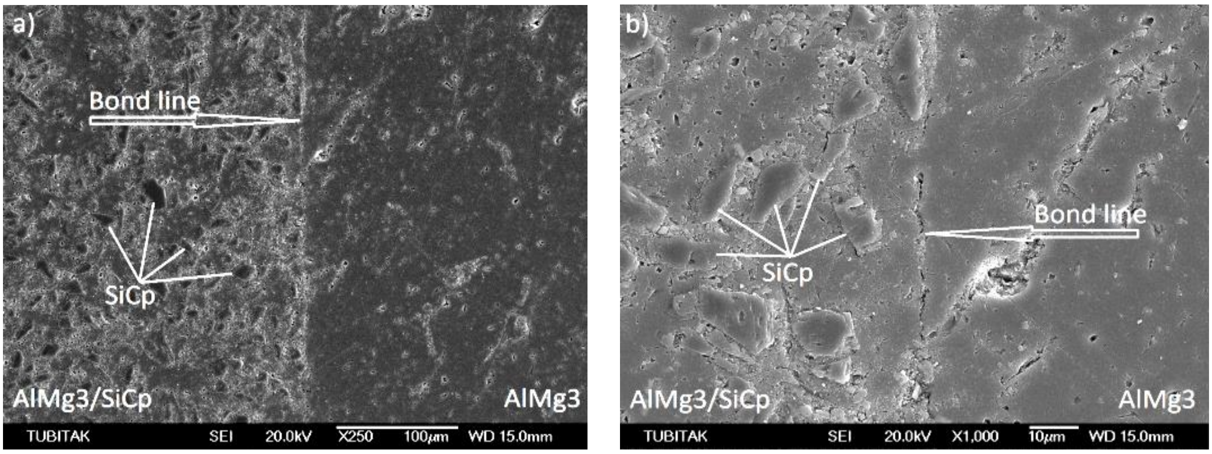


Figure 7. Optical microscope and SEM images of the AlMg3/SiCp (20%) - AlMg3 couple diffusion-welded for 180 min under a pressure of 3.5 MPa. a) X250, b) X1000

As the diffusion welding pressure increased, there were increases in the shear strength of all specimens where bonding occurred. Moreover, in the welding process of the composites with a high reinforcement ratio, the reinforcement particles probably posed an obstacle to diffusion, and lower results were obtained in comparison to the shear strength of the non-reinforced material. When the joined specimens included a high ratio of reinforcement, for example, in the case that both parts included 20% of reinforcement, and 1.5 MPa of pressure and 120 min of time were applied, bonding did not occur completely, and very low shear strength values were obtained. With the increase in the welding time and pressure, bonding occurred in the composite materials with high reinforcement ratios, and the shear strength values increased. The highest shear strength values were obtained in the diffusion welding process of the non-reinforced specimens, while as the welding pressure that was applied increased, the shear strength values showed an increase. These results were in good agreement with the studies by Cooke et al. (2012) and Zhang et al. (1999). In both these studies, it was stated that the strength of diffusion bonded joints decreases with increasing SiCp volume percentage. In the welding of the composite materials with the welding parameters in this study, the highest shear strength was obtained in the specimen couple where AlMg3 / SiCp(vol.10%)-AlMg3 were bonded for 180 min under a pressure of 3.5 MPa. If the shear test results are interpreted, it is seen that the reinforcement rate affected the quality of welding in the diffusion welding process of the particle-reinforced composite materials. In this study that was in parallel with similar studies in the literature, the SiCp particles in the bonding zone affected the success of diffusion welding negatively, and joints with low strengths were obtained. Increased welding pressure and time led to an increase in joint strength [26, 27]. The lowest shear strength was obtained at a 1.5 MPa bonding pressure in the AlMg3 / SiCp (volume 20%) composite couples, and the highest shear strength was obtained at a 3.5 MPa bonding pressure in the AlMg3 / SiCp(vol.10%)-AlMg3 couples. For the bonded joints produced at the bonding time of 120 minutes, not enough diffusion bond was provided for all samples. Figure 8 shows the plot of the change in the shear strength of the samples with the diffusion bonding pressures in 180 minutes of bonding time.

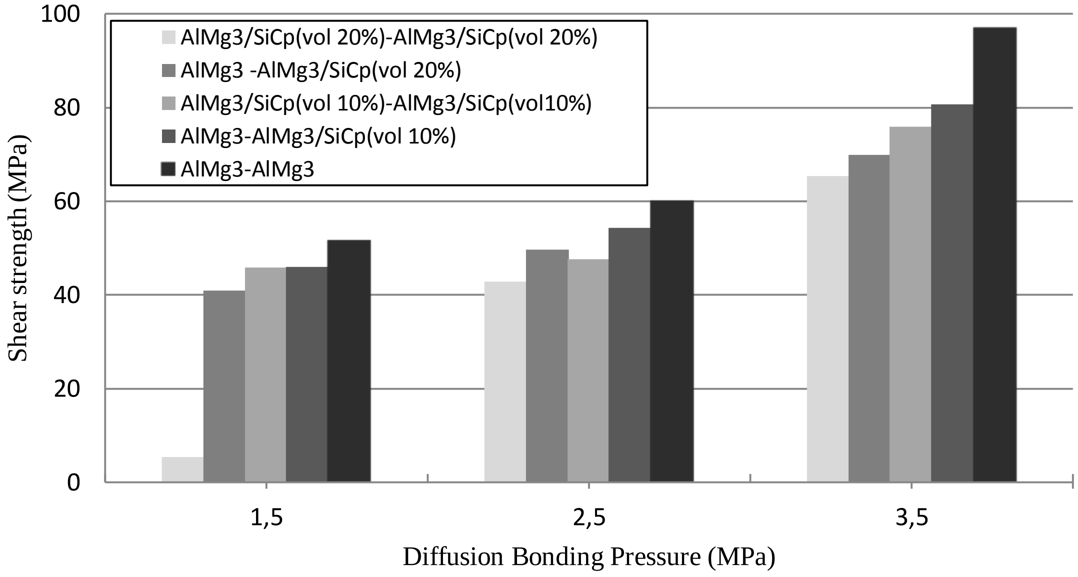
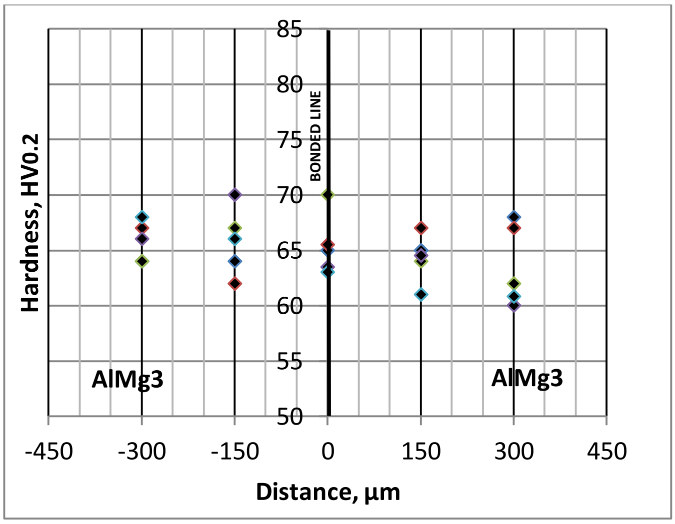
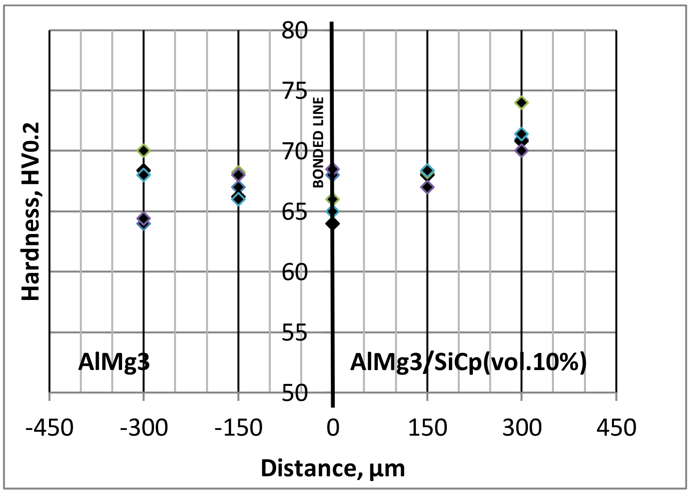


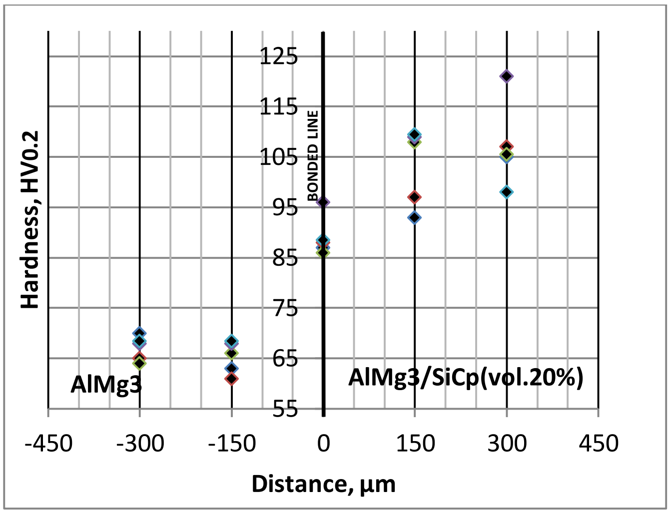
Figure 8. Shear test results at different bonding pressures and the welding duration of 180 min



(a)



(b)



(c)

Fig.9. Hardness profiles across the bonded line, (a) AlMg3-AlMg3 (b) AlMg3-AlMg3/SiCp (vol.10%) (c) AlMg3-AlMg3/SiCp (vol.20%)

The microhardness profiles for across the bond line for the AlMg3/AlMg3 and AlMg3/SiCp-AlMg3 couples (3.5 MPa/180min) are shown in Fig. 9. In all conditions, the hardness values in all regions were higher than the hardness values of the base (AlMg3) materials. Fig. 9a shows the cross-section of the bond line of the AlMg3-AlMg3 couple. The hardness profile shows the almost homogeneous distribution in the bond regions of these samples. The highest hardness value as 70 HV0.2 was measured in this sample. In welded joints formed used the AlMg3/SiCp composites and the AlMg3 matrix alloys, the hardness values in the bond region were measured as higher than the matrix material's hardness values. The highest hardness value on the side of the AlMg3/SiCp (vol.10%) composite was found as 74 HV0.2, and the hardness value on bonded line was 68 HV0.2 (Fig. 9b). Fig. 9c shows the cross-section of the bond line of the AlMg3-AlMg3/SiCp (vol%20) couple. In this sample, a hardness peak was observed close to the interface on the composite side. When the holding time was increased from 120 min to 180 min, hardness was also increased. Likewise, by increasing the welding pressure from 2.5 MPa to 3.5 MPa, hardness was also increased. It was found that the side of the AlMg3/SiCp (vol.20%) composite at a 3.5 MPa pressure had the maximum hardness value as 124 HV0.2. Moreover, the hardness value on the AlMg3 matrix alloy was 68.5 HV0.2, and the hardness value on the bonded zone was nearly the same values. These results were in good agreement with the studies by Muratoglu et al. (2006) and Mollaoglu et al. (2006). In both these studies, it was stated that the hardness values of diffusion bonded joints increase by increasing SiCp volume percentage, and when the bonding time increases, the bonding strength increases, too. Bonding time has a significant effect on the diffusion bonding process.

4. Conclusions

The following conclusions may be drawn from this study:

a) The AlMg3 / SiCp - AlMg3 couples were successfully diffusion-bonded for all welding pressures at a 580ºC bonding temperature for 180 min holding times. The AlMg3couples were bonded with diffusion at lower pressures in comparison to the composite samples. It was observed that their shear strength was higher than the composite couples.

b) The shear strength of the AlMg3 / SiCp (vol.20%) composite couples was lower than the AlMg3 / SiCp (vol.10%) and AlMg3 couples at all pressures. As the reinforcement rate was increased in the composite samples, deformation decreased at all bonding pressures.

c) As the diffusion pressure and bonding time increased, the shear strength increased in all samples.

d) The strength of the diffusion-bonded joints decreased with increasing SiCp volume percentage. The hardness values of the diffusion bonded joints increased with increasing the SiCp volume percentage. Moreover, bonding time had a significant effect on the diffusion bonding process.

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