International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 8 Issue 4 ǁ 2020 ǁ PP. 11-19

Analysis of diffusion bonding characteristics for different heat treatments in aluminum metal matrix composites (Al/SiCp) with pure Aluminium

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ABSTRACT: *The joining quality of the Al/SiCp MMCs was studied to determine the influences of SiCp particulates with homoge-nization and age hardening on bonding properties. Joining characteristic of SiC particulate reinforced aluminum metal matrix composites (MMCs) with pure aluminum were investigated by diffusion bonding process. The experimental results indicate that the application of aging before and after diffusion bonding decreases SiC particulate accumulation, and increases other elemental concentration at interface. Especially, the application of aging treatment before the diffusion bonding of Al/SiCp MMCs to pure Al, increased Cu% concentration at interface which treats as the insert alloy.*
Keywords: *Metal matrix composites; Diffusion bonding; Heat treatments*

I. INTRODUCTION

The metallic matrix composites materials (MMCs) are becoming more popular as structural materials in industries and so forth, in particular dispersed for the discontinuously rein-forced metallic matrix composites [1]. Recently, MMCs have received substantial attention because of their improve strength, high elastic modulus and increased wear resistance over conventional base alloys [2]. The researches relating joining science and technology for the discontinuously reinforced metallic matrix composites becomes important at engineering application in near future [3].

The usage of the MMCs has a great potential advantages, however they have not reached widespread industrial applica-tion. The limited use of the MMCs is basically due to joining, because, fabrication of virtually any complex structure requires joints to be made. Extensive studies have been done to investigate the appropriate processes to join the similar or dissimilar com-posites [3–5]. We can classify the works on welding of MMCs into two categories: fusion welding, and solid-state welding. The joining of the MMCs has still some problems [3–6]. During welding of conventional welding methods, some problems arise.

Especially this is the difficulty of mixing of composite matrix material with the filler material due to great viscosity and poor flowability of the liquid welding pool. This result brings out unsatisfactory welded joints [1]. In other words, due to rejec-tions of SiC particulates or whiskers by the solidification front, the normal solidification processes of the welding pool were broken down, and this leads to microsegragation or inhomogeneous distribution of reinforcements. At the end, there would be many micro and macro defects in the weld, and the properties of welded joints will be very low [1].

Investigations have shown that it is possible to join SiCp-reinforced aluminum metal matrix composites (A/SiC MMC) by diffusion bonding methods [5–8], friction welding processes [9,10]. In regard to the diffusion bonding of discontinuously reinforced aluminum MMCs, on the surface of composite spec-imen alumina barrier, which would make diffusion bonding process more difficult exists [1]. For this problem, transition liquid phase diffusion bonding is used by using a metal foil insert between the surfaces to be joined [11]. The diffusion bonding of this kind of composites could be realized with satis-factory joining quality. Nevertheless, it is necessary to carry on further fundamental investigation on the joining characteristics of discontinuously reinforced aluminum alloy matrix compos-ites by diffusion bonding process, particularly for detection of the activation energy for dissimilar particulate reinforced alu-minum MMCs with different heat treatments. The bond specific strengths achieved were dependent on interface grain bound-ary migration and grain growth during the bonding process, and these were considered to be main mechanisms by which the initial bond interface was removed [12].

Table 1
Abbreviation for the used names of the specimen and applied heat treatment

Sample symbol	Test specimens		Heat treatment
	Left side	Right side	
S1	2124Al–SiC	Pure Al	As received
S1.1	2124Al–SiC	Pure Al	The left side was solutionized before welding
S1.2	2124Al–SiC	Pure Al	The left side was aged (T6) before welding
S1.3	2124Al–SiC	Pure Al	The bimetal was aged (T6) after welding

In the present research, the argon atmosphere controlled dif-fusion bonding characteristics of the dissimilar Al/SiCp MMCs and pure aluminum with different heat treatment have been investigated in detail. The influence of heat treatments on the grain growth at interface of diffusion bonded joints and bonding quality of joints have also been evaluated.

II. MATERIALS AND EXPERIMENTAL PROCEDURES

2.1. Test materials and specimen preparation

The test material used in the present work was 25 vol.% SiCp-reinforced 2124 aluminum alloy metallic matrix composites manufactured by means of powder metallurgical method [2,5,13]. The fabrication processes of the presently used composites have been summarized at the preceding manuscript [1].

The diffusion welding was applied to the welding of 2124 aluminum alloy having 25% SiCp to pure Al. During welding four types heat treatment was applied. First of all, the first group of the MMC was diffusion bonded as welded, and then the second group was welded with solution treatment. The third group of the samples was welded with solutionizing + artificial aging heat treatment (T6). Finally, the fourth group was welded, and T6 treatment was applied after weld-ing. The heat treatment of solutionizing was applied as 495 ˚C/1 h. During aging the MMC was aged with the T6 condition, i.e. 175 ˚C for 24 h. The fabricated Al/SiC MMC materials took the cross-section shape of rectangular bar or round bar with the density at least larger than 97%. Four different types of bimetals were obtained in response to the heat treatment conditions. Table 1 shows abbreviated names of the specimens and corresponding heat treatment conditions.

2.2. Diffusion bonding test

The specimen preparation was carried out carefully by grinding and cleaning. Just before diffusion bonding test, the specimens were cleaned carefully by ultra-sonic-cleaning in acetone. The variables used in the present work are as follows:

1. diffusion bonding temperature, 475 ˚C;
2. heating holding time, 30 min;
3. applied pressure, 2.5 MPa;
4. Ar atmosphere, 3 bar.

III. RESULTS AND DISCUSSION

3.1. Diffusion bonding characteristics of Al/SiCp MMCs with pure aluminum

Fig. 1 shows the bond micrographs of the diffusion bonded joints changing with heat treatment, where three different heat treatment before diffusion bonding of Al/SiC MMCs-Al were applied to bond composites with pure aluminum.

Fig. 1a and b manifest the microstructures of diffusion bonded joints with composite without any heat treatment and with solu-tionizing, respectively. It can be seen from the figures that the joint quality decreases apparently with applying homogeniza-tion process before bonding (Fig. 1b). As seen in Fig. 1b the concentration of SiC particulates at interface was increased. Evidently, the joining quality of diffusion bonded joints is also strongly dependent on the joining quality of micro-joining inter-faces of reinforcement/Al interfaces. In Fig. 1a it can be seen clearly that there are several reinforcer SiCp particulates in join-ing interface of the joint specimen. These particulates were just like inclusions, which would generally posses weak joining with aluminum alloy matrix [1]. The presence of higher SiCp volume percentage at interface increases the SiCp reinforcers in join-ing interface of the joints, and then there would be more weak micro-joining interfaces in interface region of the joints, and finally lead to lower joint strength. Additionally, without the use of metallic interlayers, high levels of deformation are required in order to achieve a reasonable level of bonding in reinforced composites, but this deformation changes the reinforcement con-centration [11–15]. The diffusion bonded joint corresponding to Fig. 1c and d is the interface obtained by diffusion bonding after T6 aging heat treatment, and before T6 aging heat treatment, respectively. At the joint having T6 aging heat treatment before welding gave the lowest SiC particulate at interface. However, as represented in Fig. 1, the comparisons between the micrographs shows that while T6 application before welding decreases SiC particulate concentration at interface, also the process increases Cu% concentration at interface. It is known that Cu or Ni are used at interface of the Al based MMCs [15] as interlayer mate-rial. Although diffusion bonding is an essential technique for the primary forming of MMCs, attempts to use the method for secondary processing have not produced satisfactory results. All the attempts to join aluminum matrix MMCs particularly yielded poor joint aluminum matrix MMCs particularly yielded poor joint efficiency. The large deformation or high temperature required to bond aluminum or aluminum alloy matrix MMCs, to eliminate effect of refractory oxide film covering the surface.

EDS analysis have shown that Si and C concentrations have changed in a proportional manner (Fig. 2). Hence, we have con-sidered Si% change as SiC distribution.

In Fig. 3 the Si wt.%, and hardness values of all samples were given across distance. It was seen from the figures that a close relationship between the hardness and Si% concentration of the bimetals is present. As given in Fig. 3c, the application of T6 aging heat treatment to the composite side decreased the Si concentration probably by increasing the strength of the MMCs to withstand against deformation.

3.2. Metallography

Microstructural studies were made on samples, which had been cooled rapidly to room temperature after bonding. Figs. 4 and 5 show micrographs of sections taken through bonds produced for various state of composite + aluminum, at 475 ˚C

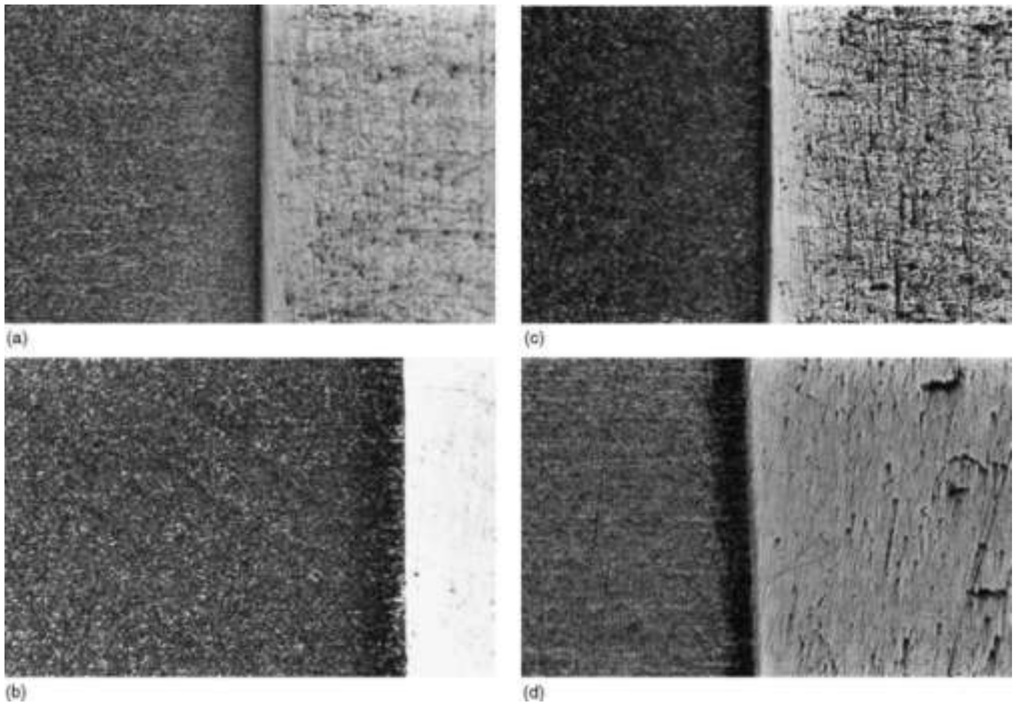


Fig. 1. Microstructure of interface for Al/SiC-Al couple (a) as welded, (b) solutionizing, (c) solutionizing + aging (T6) before welding and (d) as welded + aging (T6) after welding.

temperatures at a pressure of 2.5 MPa in 30 min. It was seen that at conditions for times of greater than 30 min using pressures of >2.5 MPa, and for temperatures of >475 ˚C the bonds hav-ing a microstructure indistinguishable from that of the adjacent parent metal were obtained. Hence, 475 ˚C, 30 min and 2.5 MPa pressures were taken as standard to detect the effect of aging, homogenization on the bond structure. The original interface line was taken as reference point in the center of each photo-graph. Diffusion welding made at temperatures below 475 ˚C

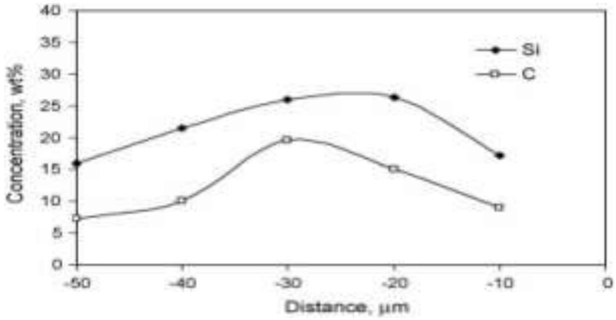
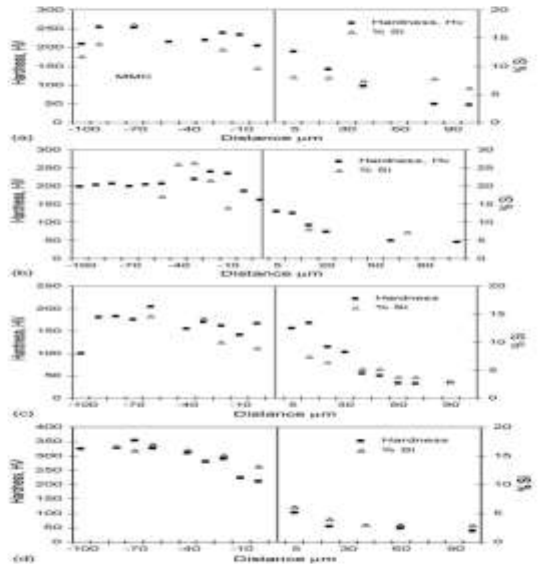


Fig. 2. Distribution of Si and C at MMC side for sample S1.

usually showed clear evidence of the interface line. The initial microstructure of the composite had an average grain size of 6 mm, however the bimetals welded at increasing temperatures showed different microstructural changes. It can be seen from Figs. 4 and 5 that a relatively constant grain size was maintained, but from the figures it can be seen that local migration of inter-face boundaries lead to the formation of triple point junctions between grains across the interface. It is probable that similar behavior occurred at pure aluminum side but was followed by rapid grain growth. It may be clear evidence to postulate that SiC particulates affected the grain growth at MMC side. As a result, it was considered that the size of the grains was not changed at interface of MMC side, however at the side of the pure Al grain size was changed.

The microstructural results of this study have shown that no distinct voids were observed in the bond interfaces, only linear regions of disband was observed. This is consistent with some earlier work on the diffusion bonding [16]. Calculations based on relationships given in Ref. [16] showed that the combinations of bonding conditions used in the present work were in excess of those required to bring the two surfaces into full physical contact.

The present work has identified a range of heat treatment conditions under which Cu% concentration and SiC% partic-ulate concentration affected the quality of the sound diffusion bonds (Fig. 6). However, it should be recognized that not all of



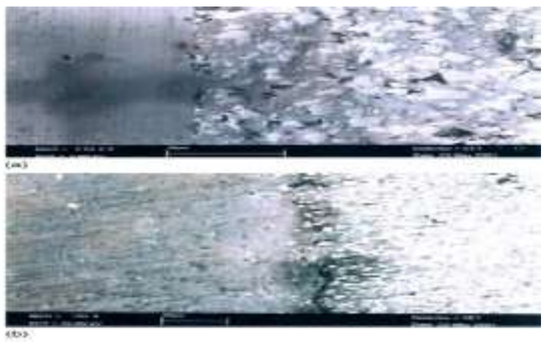
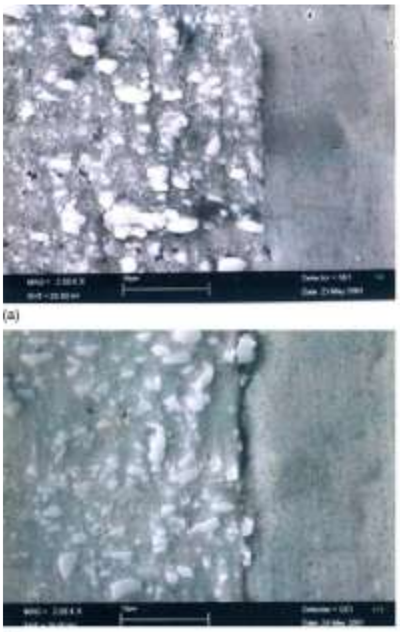


Fig. 3. The change of Si%, Cu, and hardness of bimetal with distance (a) as welded, (b) solutionizing, (c) solutionizing + age (T6) before welding and (d) as welded + age (T6) after welding.

Fig. 4. SEM microstructure of interface obtained by: (a) as welding and (b) solutionizing and then welding, for Al/SiC composite-Al couple.

these conditions would be suitable for the DB stage, because the involving temperatures and/or times could lead to grain growth of the bimetals in a different manner by a significant reduction in the deformation potential of the material.

It is generally considered that a sound bond has been obtained when there is no metallographic evidence of the bond line [1]. The elimination of interfacial voids or achievements of full interfacial contact are the criteria normally adopted in predictive models of diffusion bonding. However, contami-nation of surfaces to be joined is often unavoidable in real bonding situations, therefore neither an interface-free bond nor the strength of the bond are problematic [12]. A metal to metal bond will, of course, form if two physically clean surfaces are brought into contact with each other. It is known that the bond quality were basically dependent on the extent of removal of the initial bond interface [20]. This is consistent with observations made in some other works [21]. The mechanism(s) by which the bond interfaces eliminated is that recrystalization which was initiated in the bond region caused the elimination of the bond interface and led to high bond strengths. The trend in the effect of grain growth in Fig. 5 suggests that the bond quality is related to grain growth. Hence, based on the temperature,



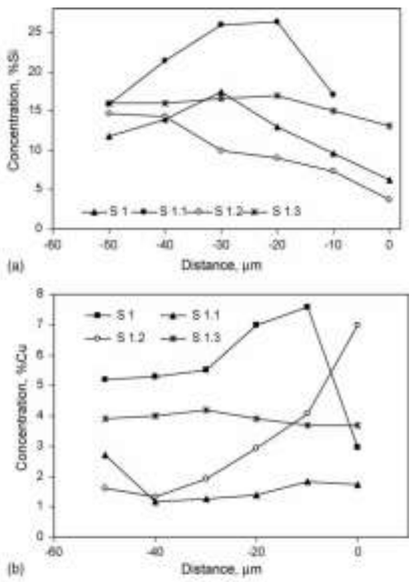


Fig. 5. SEM microstructure of the interface obtained by welding (a) after solu-tinizing + aging (T6) heat treatments, (b) before solutinizing + aging (T6) heat treatments, for Al/SiC composite-Al couple.

Fig. 6. Concentration change of: (a) Si% and (b) Cu% with distance and heat treatments.

time dependent, grain growth, and on the bond microstructures, it is reasonable to conclude that grain growth is an important process in the removal of the initial bond interface leading to full bonding [21]. This result suggests a transition in grain growth behavior depending on temperature. However, at 475 ˚C and above, there was clear evidence of the formation of new triple point junctions between grains across the interface by grain boundary motion (Figs. 4 and 5). Similar observations were reported recently by Hu et al. [22]. It was proposed that grain boundary surface tension and grain boundary mobility were the controlling factors for the initial movement of interface grain boundaries. In the present work, boundary mobility at 450 ˚C and below was relatively low and parent metal strength could not be achieved in reasonable times. In contrast, at 475 ˚C and above, while the initial stages of bonding could involve migration of interface grain boundaries as above, the higher rate of grain growth would lead to rapid removal of evidence of the pre-existing bond line, and to parent metal microstructure.

The optimum bonding temperatures at which grain growth occurred were identical with those for Al based MMCs flow, suggesting the behavior of the alloy may have also contributed to the bonding process. Atomic flow could have certainly made some contributions to the removal of the bond line even though the strains involved in the diffusion bonding procedure were rel-atively low (<5%). However, since grain boundary sliding makes a substantial contribution to the accumulation of the strain during atomic flow, grain boundary displacements in the region of the bond line could help to disrupt its continuity and, in combination with grain growth, aid its removal.

The quenching from the solutionizing temperature of a metal matrix composite reinforced with particulates will introduce a high dislocation density into the matrix of the composite because of the differences in the values of the coefficients of thermal expansion of the matrix and the reinforcement [23]. Experiments on Al-2124 alloy reinforced with SiCp have shown that the pres-ence of excess matrix dislocations in the composite leads to a reduction in the incubation time for heterogeneous nucleation of the strengthening precipitates and thus accelerates the aging kinetics of the composite [24]. The excess matrix dislocations may act as short-circuiting paths for solute diffusion, thereby enhancing the precipitate growth rate [25]. In addition, an impor-tant feature of T6 heat-treated Al MMCs is their fine equiaxed grain structures, which contain a large proportion of high angle boundaries. In a diffusion bonding context the microstructures not only supplies paths for the rapid mass transfer but also pro-vides favorable conditions for the micro-creep/atomic flow of contacting surface asperities [1]. This proceeds to full interfa-cial contact more rapidly than can be achieved for the more usual microstrucutral conditions. It is also well established that strain enhances grain growth and this is a very common feature of atomic flow [13]. The microstructural instability during atomic flow have shown that grain boundary migration enhances grain growth has the form:

$$G = \frac{D_b E_s}{kT\lambda} \qquad (1)$$

where G is the grain growth rate at a given strain energy, E_s, D_b diffusion rate at grain boundaries and k a constant, and λ is grain boundary thickness. The rate of grain growth depends linearly on strain rate (k = 1). In addition as seen from the microstructural photographs except the bimetal welded after T6 heat treatment, all of the bimetals have a region having high fraction of SiC particulates. These particles will produce a force per unit area restraining the grain boundary motion of

When this force balances the pressure force due to curvature, grain growth will stop and we will obtain a limiting grain size. It can be say that grain size will be proportional to [26]; $R \propto r/f$ where f is fraction of SiC particulates and r is size of particulates. This shows that the accumulation of SiC particulates at interface decreases grain boundary motion and the bond quality of the weld.

3.3. Microhardness and compositional profiles across welding interface

The microhardness profiles for each heat treatment across the interface (i.e. the visible fusion line) for the MMCs + aluminum are shown in Fig. 7. In Fig. 7, a hardness peak can be observed close to the interface for the specimen without heat treatment. This indicates the presence of a hard zone, i.e. hardness exceed-ing 260 HV1. A higher hardness (240 HV1) as in the sample with homogenization was observed. At the specimen with T6 heat treatment before and after welding the peak hardness (i.e. maximum hardness of the hard zone) was less and soft zone was

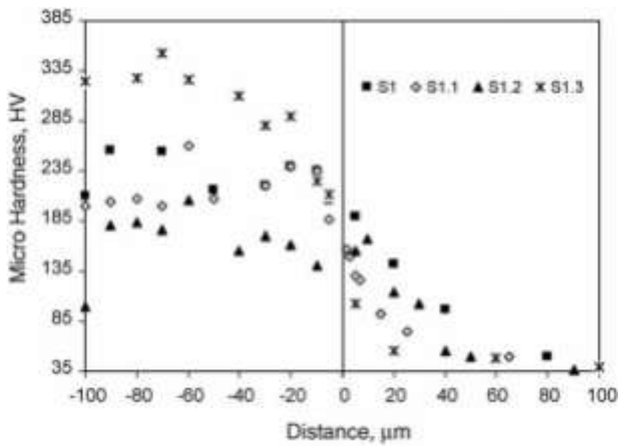


Fig. 7. Microhardness profiles across visible welding interface for different heat treatments.

Table 2

The change of H_m, and H_0 for samples

Microhardness

Hv Samples

	S1	S1.1	S1.2	S1.3
H_m	265	255	240	365
H_0	190	175	155	230

not detected. But perhaps of more interest is the observation that Cu concentrations were significantly higher and Si concentra-tion was lower at the interface zones of T6 heat treatment before welding. Except for his somewhat strange higher in Cu concen-trations and dip in Si Concentration, which coincided with a significantly higher hardness (see Fig. 1b). The variations in Cu, and Si concentrations were gradual across the visible welding interface (Fig. 6).

It was thought that the treatments that bimetal have effects the mechanical behavior of the bonded zone. Hence, for each specimen the residual stress rate was calculated by microhard-ness values taken from across composite side. The residual stress rate determined as

$$R = \frac{H_m - H_f}{H_m - H_0}$$

where H_m is microhardness after deformation formed before diffusion bonding, H_f microhardness after diffusion bonding, and H_0 is microhardness before deformation forming during diffusion bonding (Tables 2 and 3).

The residual stress rate for each sample was given in Fig. 8. From the figure it can be seen that the stress rate decreased close to interface for the sample having T6 heat treatment before and after welding process. On the other hand for the sample hav-ing homogenization heat treatment, the stress close to interface increased. This is thought to be due to accumulation of the SiC carbides at interface for homogenized sample.

It was considered that the T6 heat treatment before welding increased the grain growth at the boundary line during welding (Fig. 5). The main grain diameter increases with time depends on the grain boundary mobility and the driving force for boundary migration [17]. The velocity of the grain boundary migration is not linear function of driving force; the mobility varies with

Table 3

The change of H_f of the samples

Distance	H_f			
	S1	S1.1	S1.2	S1.3
−100	210	199	189	325
−90	255	204	181	327
−80	257	207	183	328
−70	254	200	176	353
−60	238	205	205	326
−50	216	207	187	312
−40	219	210	175	310
−30	220	220	170	280
−20	240	240	163	290
−10	235	235	161	244
−5	205	187	167	232

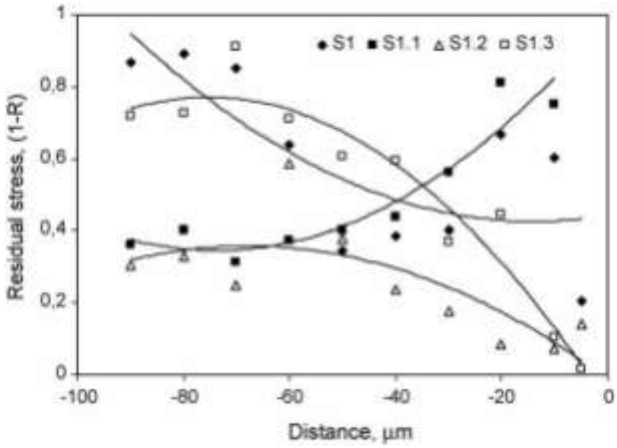


Fig. 8. The change of residual stress at samples as function of distance from interface.

free energy change and also diffusion rate. Such a variation of mobility could arise from solute drag effects [18]. It was defined that diffusion rate is proportional to strain energy and mobility [19]. Finally, we can say that T6 heat treatment before welding increases the amount of stored energy, so that one might expect the growth rate and diffusion rate to increase.

IV. CONCLUSION

1. The joining quality of diffusion bonded joints is strongly dependent on the joining quality of micro-joining interfaces of reinforcer/Al interfaces. The joint having T6 aging heat treatment before welding gave the lowest SiC particulate at interface, in other words T6 aging application before welding not only decreased SiCp concentration at interface, but also increased Cu% concentration at interface.
2. A close relationship between the hardness and Si% concen-tration of the bimetals was seen. At conditions for times of greater than 30 min using pressures of >2.5 MPa, and for temperatures of >475 °C the bonds having a microstructure indistinguishable from that of the adjacent parent metal were obtained
3. SiC particulates affected the grain growth at MMC side. As a result, it was seen that the size of the grains were changed at interface and MMC side more than at the side of the pure Al side.
4. T6 heat treatment before welding increased the amount of stored energy, so that the growth rate was increased. With increased growth rate the diffusion coefficient of Cu increased. In addition, it was seen that the application of T6 heat treatment before welding increased Cu% concentrations significantly, on the other hand decreased Si concentration at the interface zones.

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