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Establishing an Empirical Relationship to Predict the Bonding and Shear Strength of Diffusion Bonded AA7075 Aluminium Alloys

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Abstract

Rolled plates of 5 mm thick AA7075 aluminum alloys were fabricated by diffusion bonding. Empirical relationships were made to predict the bonding and shear strength of AA7075/AA7075 aluminium alloys integrating diffusion bonding parameters such as bonding temperature, bonding pressure and holding time. Metallurgical characterizations were carried out using optical microscopy and SEM-EDS. It is observed that the bonding and shear strength increased with the increase in bonding temperature and bonding pressure mainly due to the diffusion of atoms in the interface. Furthermore, it is observed from the microstructural characterization, the strength achieved were reliant on the interface grain boundary migration and grain growth during the bonding process respectively. Three factors and a central composite design were used to minimize the number of experimental conditions. Response surface method was used to develop their relationship. The developed relationship can be effectively used to predict the strength of diffusive bonded AA7075 aluminium alloys at 95% confidence level.

Keywords: AA7075 aluminium alloy, Diffusion bonding, Response surface methodology, Optical microscopy, SEM-EDS

INTRODUCTION

Aluminium and its alloys are also widely used for structural components in many applications such as automobiles, aerospace, etc. because of their high specific strength and excellent corrosion resistance [1]. When joining aluminium (Al) alloys by fusion welding process lies in the existence of oxide films and formation of brittle intermetallic in the weld region, however, solid state welding process such as friction welding and diffusion bonding are suitable process to join the material. Solid state diffusion bonding is an important advanced technique for joining both similar and dissimilar materials can produce coalescence at temperatures below the melting point of the base materials being joined, without formation of liquid phase during the process of joining [2].

In diffusion bonding process, the application of a moderate pressure causes plastic collapse of contacting asperities leading to the formation of a planar array of interfacial voids. Creep/super plasticity and diffusion processes transport atoms to the void surfaces from adjacent areas, thus reducing interfacial void volume. If sufficient time is given, the voids will be removed and an atom to atom bond across the original interface will result. As bonding does not involve melting or gross macroscopic interface distortion, the microstructure of the bond region is similar to that of regions remote from the joint and has parent metal properties [3]. Diffusion bonding provides a novel joining operation for similar (Al-Al alloys)and dissimilar materials (Al-X alloys) without gross microscopic distortion and with minimum dimensional tolerance, the bond strength increased with the increase in bonding temperature and this is essentially due to the increase in the width of the brittle intermetallic compounds [4, 5]. The bond specific strengths achieved were dependent on interface grain boundary migration and grain growth during the bonding process, and these were considered to be the main mechanisms by which the initial bond interface was removed [6, 7].

Strengths are believed to have occurred because of variations in the amount of liquid gallium used [8]. Bonding temperature due to the formation of finer size intermetallic compounds and good bonding between mating surfaces, Increases in the joining temperature cause the volume fraction of intermetallics to increase. These intermetallics lower the strength of diffusion bonds when proposed at higher temperature [9]. Bonding time increases the hardness of the joint interface increases due to intermetallic compounds formation, with the increasing of bonding time, the shear strength of the joints increases due to diffusion of atoms in the interface [10]. Hence, the researchers [11] recommend diffusion bonding technique to join these dissimilar materials. The selection of diffusion bonding process variables affecting the interface structure, compound formation and morphology is critical to attain good quality bonds. The predominant process parameters in diffusion bonding process are: (bonding) temperature (bonding) pressure and (holding) time [12].

Very few investigations [13-17] evaluated the diffusion bonding of aluminium materials. Moreover, those literatures are focusing on microstructure analysis, phase formation studies, hardness survey at the interface and their subsequent influence on bonding strength. It is further developed diffusion bonding windows for joining AA2024 Al and AZ31B Mg alloys [18]. Hence, the present investigation was carried out to develop an empirical relationship to predict the bonding and shear strength of diffusion bonded joints of aluminium alloys incorporating process parameters like binding temperature, bonding pressure and holding time.

EXPERIMENTAL WORK

Fabricating the joints and preparing the specimens

Rolled plates of 5 mm thick AA7075 aluminium alloys are used in this investigation. The chemical composition and mechanical properties of the base metal are presented in Tables 1 and 2. The optical micrograph of AA 7075 aluminum alloy is shown in Fig. 1.

Table 1. Chemical Composition (wt. %) of AA7075 aluminium alloy

Si	Fe	Cu	Mn	Mg	Zn	Ti	Others	Al
0.40	0.50	1.2	0.3	2.1	5.1	0.20	0.05	Balance

Table 2. Physical and Mechanical Properties of AA7075 aluminium alloy

Density (g/cm^3)	Melting Point (ºC)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Shear Strength (MPa)	Elongation (%)	Poisson's Ratio	Crystal Structure
2.80	635	572	503	331	11	0.33	FCC

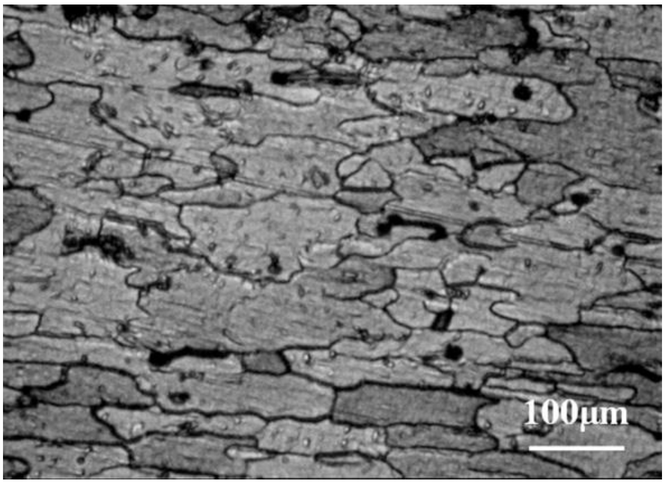


Figure 1. Microstructure of AA7075 aluminium alloy

The microstructure of base metal (AA7075 aluminium alloy) consists of acicular eutectic precipitates $MgZn_2$ embedded in α-aluminium matrix. It should be observed that elongated grains were observed even in the parent material with particular reference to the central zone of the joint section (shown in later part). The plate was cut to the required size (50 x 50 mm) by power hacksaw followed by milling. The bonding surfaces of samples were ground flat by 200, 400 and 600 grit SiC papers and cleaned in acetone prior to diffusion bonding [19]. The polished and chemically treated specimens were covered at the bottom and top with a mica sheet (RUBY) in a die made up of H-13Tool Steel, and were inserted into a vacuum chamber (vacuum pressure of 29 Hg was maintained). The specimen is heated up to the bonding temperature by using the induction furnace with a heating range of 25ºC/min. simultaneously; the required bonding pressure was applied with the holding time. After the completion of bonding, the samples were cooled to room temperature before removal from the chamber. The configuration of the diffusion bonding setup is shown in Fig. 2. The parameters used for the diffusion bonding are bonding temperature, bonding pressure and holding time.

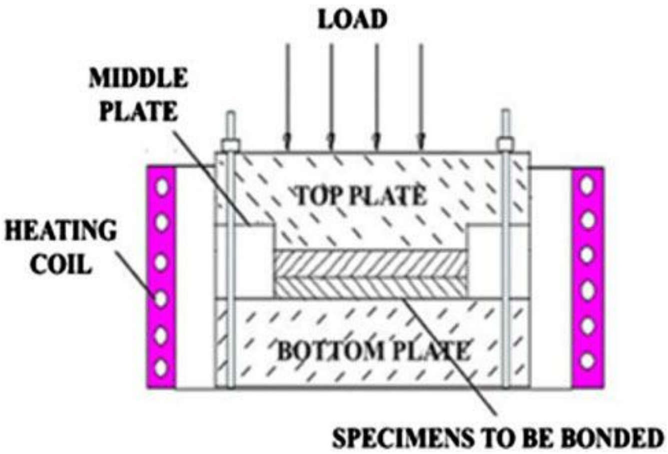


Figure 2. Diffusion Bonding Set up

Finding the limits of diffusion bonding parameters

From the literature [20-22], the predominant factors that have a greater influence on the diffusion bonding of AA7075 aluminium alloy joints had been identified. They were: (i) bonding temperature (T), (ii) bonding pressure (P) and (iii) Holding time (t). Large numbers of trial experiments were conducted to identify the feasible testing conditions using diffusion bonding conditions. The following inferences were obtained:

i. If the bonding temperature was lower than 490˚C, then no bonding was occurred between AA7075/AA7075 aluminium alloy and this was due to the insufficient temperature to cause diffusion of atoms (Fig. 3a).

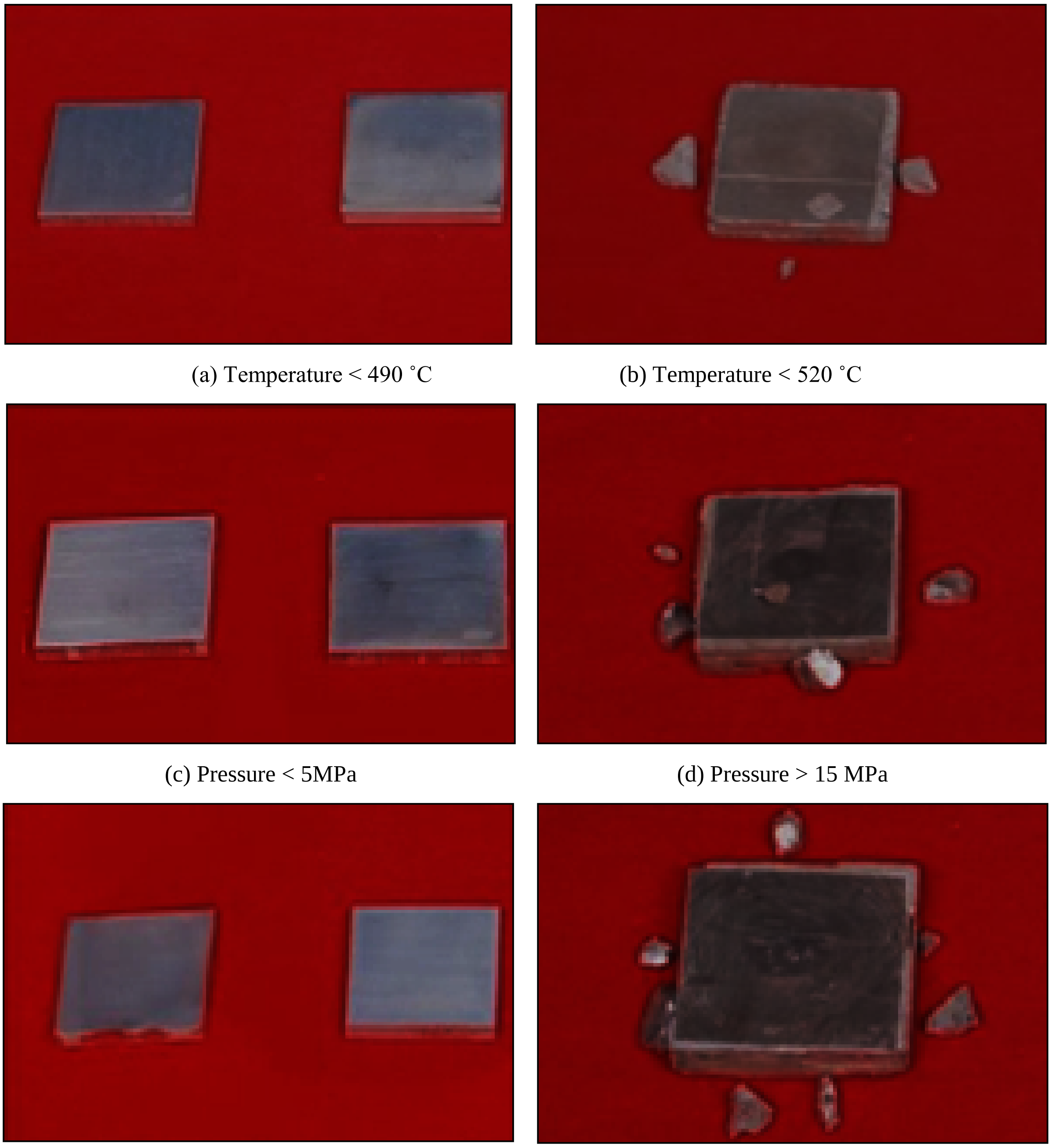
ii. If the bonding temperature was greater than 520 ˚C, then the bonding pressure decreased automatically after few minutes and this was due to the melting of phase particles especially Zn wets the aluminium surface readily and the difficulty associated with diffusion bonding with the Zn particles (Fig. 3b).

iii. If the bonding pressure was lower than 5 MPa, then no bonding was occurred and this was due to less number of contacting points (between surface asperities) through which diffusion of atoms generally should occur (Fig. 3c).

iv. If the bonding pressure was greater than 15 MPa, then the plates were deformed plastically causing reduction in thickness and bulging at the outer edges (Fig. 3d).

v. If the holding time was less than 15 min, then no bonding was occurred and this was due to the insufficient time allowed for the diffusion reaction to take place (Fig. 3e).

vi. If the holding time was higher than 45 min, then excessive grain growth followed by melting of interphase particles alloy was observed (Fig. 3f).



(a) Temperature < 490 ˚C

(b) Temperature < 520 ˚C

(c) Pressure < 5MPa

(d) Pressure > 15 MPa

(e) Holding time < 15 min.

(f) Holding time > 45 min.

Figure 3. Photographs of Bonds Fabricated using Lower and Upper Limits of Process Parameters

Developing the experimental design matrix

Owing to a wide range of factors, the use of three factors and a central composite rotatable design matrix were chosen to minimize the number of experiments. A design matrix consisting of 20 sets of coded conditions (comprising a full replication three factorial of 8 points, six corner points and six center points) was chosen in this investigation. Table 3 represents the range of factors considered, and Table 4 shows the 20 sets of coded and actual values used to conduct the experiments.

Table 3. Important factors and their levels

S. No	Factor	Unit	Notation	Levels				
				-1.682	**-1**	**0**	**1**	**1.682**
1	Bonding Temperature	°C	T	490	496	505	514	525
2	Bonding Pressure	MPa	P	5	7	10	13	15
3	Holding Time	min.	t	15	21	30	39	45

Table 4. Design matrix and Experimental results

Experiment No.	Bonding Temperature T (°C)	Bonding Pressure P (MPa)	Holding Time T (min.)	Bonding Strength BS (MPa)	Shear Strength SS (MPa)
1	496	7	21	25	108.3
2	514	7	21	33.8	106.4
3	496	13	21	27	113.1
4	514	13	21	31.1	116.1
5	496	7	39	24	112.3
6	514	7	39	32.4	116.2
7	496	13	39	30.4	110.4
8	514	13	39	36.8	115.8
9	490	10	30	25.5	103.5
10	520	10	30	36.2	121.4
11	505	5	30	24.3	106.6
12	505	15	30	29.6	111.5
13	505	10	15	26.3	98.42
14	505	10	45	29.8	112.89
15	505	10	30	28	110
16	505	10	30	27	108
17	505	10	30	26	109
18	505	10	30	26	110
19	505	10	30	26	110
20	505	10	30	26	110

For the convenience of recording and processing experimental data, the upper and lower levels of the factors were coded here as +1.682 and -1.682 respectively. The coded values of any intermediate value could be calculated using the following relationship.

$$X_i = 1.682\ [2X - (X_{max} - X_{min})] / (X_{max} - X_{min})$$

where,

X_i is the required coded value of a variable X and X is any value of the variable from X_{min} to X_{max},

X_{min} is the lower level of the variable,

X_{max} is the upper level of the variable.

Recording the responses

After the bonding process, the samples were prepared from the Al/Al diffusion bonded joints by a wire -cut electric discharge machine, the tensile test was carried out in 50 KN capacity servo controlled universal testing machine. Determine the mechanical properties of the bonding and shear-tensile test were carried out on the diffusion bonded samples, to measure shear strength of the joints, lap joint samples were prepared in accordance with ASTM Standard D1002-99 [23]. Micro structural characterization to examine the diffusion layer formation at the interface was carried out using a light optical microscope (VERSAMET-3) incorporated with an image analysing software (Clemex-vision). The diffusion bonded side was etched with a Keller's solution (3ml HCl, 2 ml HF and 90 ml distilled water) [24]. The test specimens were polished in disc polishing machine for scratch fewer surfaces and the surface was observed at 200X magnification.

DEVELOPING AN EMPIRICAL RELATIONSHIP

In the present investigation, to correlate the diffusion bonding parameters and the bonding (BS) and shear strength (SS) of the joints, a second order quadratic model was developed. The response (bonding and shear strength) is a function of bonding temperature (T), bonding pressure (P) and holding time (t) and it could be expressed as,

Bonding Strength (BS) = f (T, P, t)

Shear Strength (SS) = f (T, P, t)

The empirical relationship must include the main and interaction effects of all factors and hence the selected polynomial is expressed as follow:

$$Y = bo + \sum bi\ xi + \sum bii\ xi2 + \sum bij\ xi\ xj$$

For three factors, the selected polynomial can be expressed as

$$BS/SS = b0 + b1 (T) + b2 (P) + b3 (t) + b11 (T^2) + b22 (P^2) + b33 (t^2) + b12 (TP) + b13 (Tt) + b23 (Pt)$$

where b0 is the average of responses (BS & SS) and b1, b2, b3… b11, b12, b13… b22, b23, b33, are the coefficient that depend on the respective main and interaction factors, which are calculated using the expression given below,

$$Bi = \sum (Xi,Yi) / n$$

where, ‘i’ varies from 1 to n, in which Xi is the corresponding coded value of a factor and Yi is the corresponding response output value (BS & SS) obtained from the experiment and ‘n’ is the total number of combination considered. All the coefficients were obtained applying central composite rotatable design matrix using the Design Expert statistical software package. After determining the significant coefficients (at 95% confidence level), the final relationship was developed using only these coefficients. The final empirical relationship obtained by the above procedure to estimate the bonding and shear strength of diffusion bondedAA7075 aluminium alloy is given below,

$$\text{Bonding Strength (BS)} = 26.46 + 3.35(T) + 1.39(P) + 0.92(t) - 0.84(TP) + 0.24(Tt) + 1.44\ (Pt) + 1.82(T^2) + 0.44(P^2) + 0.83(t^2)$$

$$\text{Shear Strength (SS)} = 109.69 + 1.73(T) + 1.50(P) + 1.09(t) + 0.80(TP) + 1.03(Tt) - 2.10(Pt) + 2.63(T^2) - 0.34(P^2) + 0.59(C^2)$$

The Analysis of Variance (ANOVA) technique was used to find the significant main and interaction factors. The results of second order response surface model fitting in the form of Analysis of Variance (ANOVA) are given in Table 5.

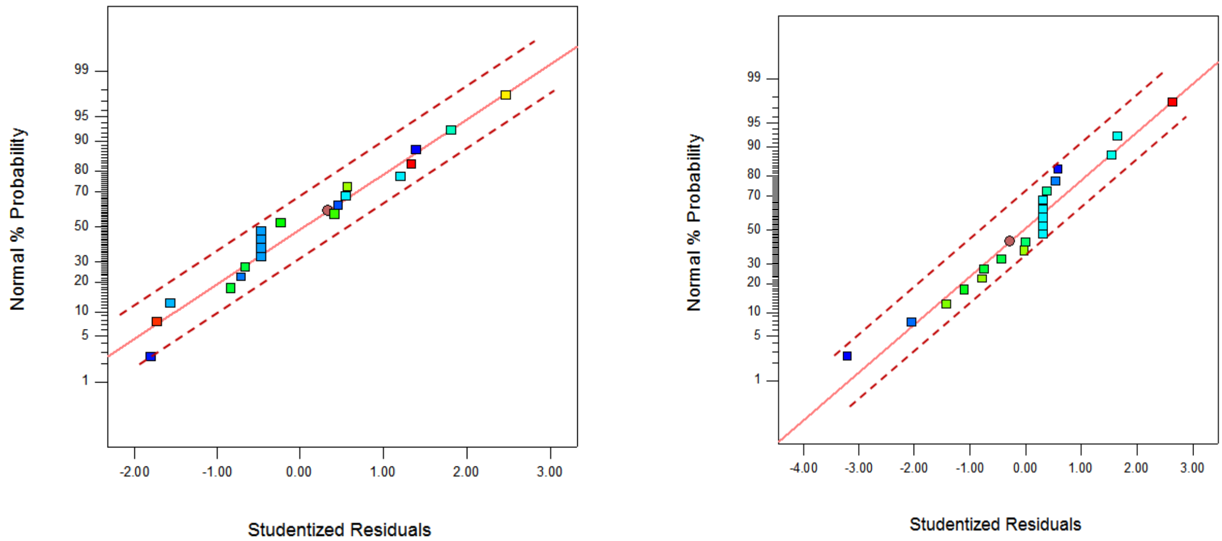
The determination coefficient (r^2) indicated the goodness of fit for the model. The Model F-value of bonding and shear strength are 27.86 and 25.03 implies the model is significant respectively. There is only a 0.01% chance that a ‘‘Model F-Value’’ this large could occur due to noise. Values of ‘‘Prob > F’’ less than 0.0500 indicates model terms are significant. In this case bonding strength includes T, P, t, TP, Pt, T^2 and t^2 are significant model terms, while shear strength includes T, P, t, Tt, Pt and T^2. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model. The ‘‘Lack of Fit F-value’’ of bonding and shear strength are 2.05 and 2.25 implies the Lack of Fit is not significant relative to the pure error respectively. There is a 22.46% and 19.77 chance that a ‘‘Lack of Fit F-value’’ of bonding and shear strength this large could occur due to noise. Non-significant Lack of Fit is good. The Predicted R-Squared of bonding and shear strength are 0.7819 and 0.7490 in reasonable agreement with the Adjusted R-Squared of 0.927 and 0.912; i.e. the differences are less than 0.2. Adeq Precision measures the signal to noise ratio. P ratio greater than 4 is desirable. The ratio for bonding and shear strength are 19.178 and 18.809 indicates an adequate signal. The normal probability of the bonding and shear strength are shown in Fig. 4 reveals the residuals were falling on the straight line, which meant that the errors were distributed normally. All of this indicated an excellent suitability of the regression model. Each of the observed values compared with the experimental values shown in Fig. 5.

Table 5. ANOVA test results

Source	**Sum of Squares**		**df**	**Mean Square**		**F Value**		**p-value Prob > F**	
	BS	SS	BS/SS	BS	SS	BS	SS	BS	SS
Model	267.73	243.70	9	29.75	27.08	27.86	25.03	< 0.0001	< 0.0001
T	152.89	41.08	1	152.89	41.08	143.18	37.97	< 0.0001	0.0001
P	26.47	30.59	1	26.47	30.59	24.79	28.28	0.0006	0.0003
t	11.60	16.26	1	11.60	16.26	10.86	15.03	0.0081	0.0031
TP	5.61	5.12	1	5.61	5.12	5.25	4.73	0.0448	0.0547
Tt	0.45	8.41	1	0.45	8.41	0.42	7.77	0.5303	0.0192
Pt	16.53	35.28	1	16.53	35.28	15.48	32.61	0.0028	0.0002

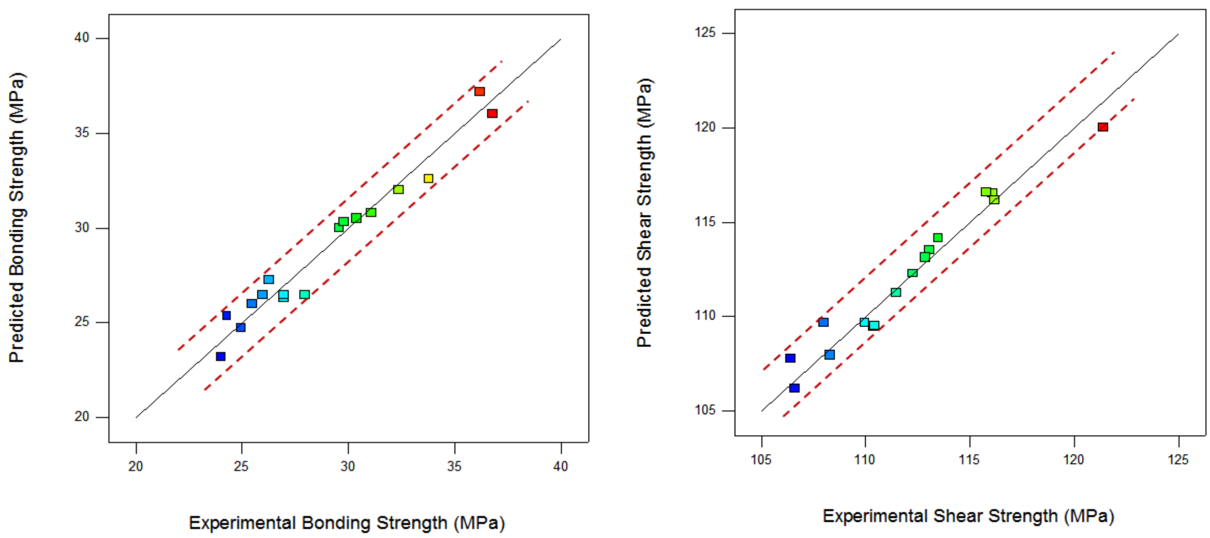
Source	**Sum of Squares**		**df**	**Mean Square**		**F Value**		**p-value Prob > F**	
	BS	SS	BS/SS	BS	SS	BS	SS	BS	SS
T^2	47.52	99.58	1	47.52	99.58	44.51	92.04	< 0.0001	< 0.0001
p^2	2.75	1.68	1	2.75	1.68	2.58	1.55	0.1394	0.2414
t^2	9.83	4.93	1	9.83	4.93	9.21	4.56	0.0126	0.0585
Residual	10.68	10.82	10	1.07	1.08				
Lack of Fit	7.18	7.49	5	1.44	1.50	2.05	2.25	0.2246	0.1977
Pure Error	3.50	3.33	5	0.70	0.67				
Cor Total	278.41	254.52	19						

Table 5 Continued…



(a) Bonding Strength (b) Shear Strength

Figure 4. Normal Probability Plots



(a) Bonding Strength (b) Shear Strength

Figure 5. Correlation of the Response (Bonding and Shear Strength)

RESULTS AND DISCUSSION

Effect of bonding temperature

Fig. 6 shows the effect of temperature on bonding and the shear strength at bonding pressure 10 MPa and holding time 30 min. It is observed that, with the increase in temperature, the bonding and shear strength increases. This is attributed to the grain growth. It is also observed that, an increase in temperature from 490 to 505°C was accompanied by only a small increase in strength, while a rapid increase in strength occurred when the bonding temperature was raised from 505 to 520°C, which is close to the optimum superplastic temperature range. Further increase in temperature reduced the variability in specific strength with little effect on the average values. Fig. 7 shows the effect of microstructure on the bonding temperature. Bonds having a microstructure indistinguishable from that of the adjacent parent metal were obtained at different temperatures. The original bond line was positioned vertically in the centre of each micrograph. There is also clear evidence of local migration of interface boundaries leading to the formation of triple point junctions between grains across the interface.

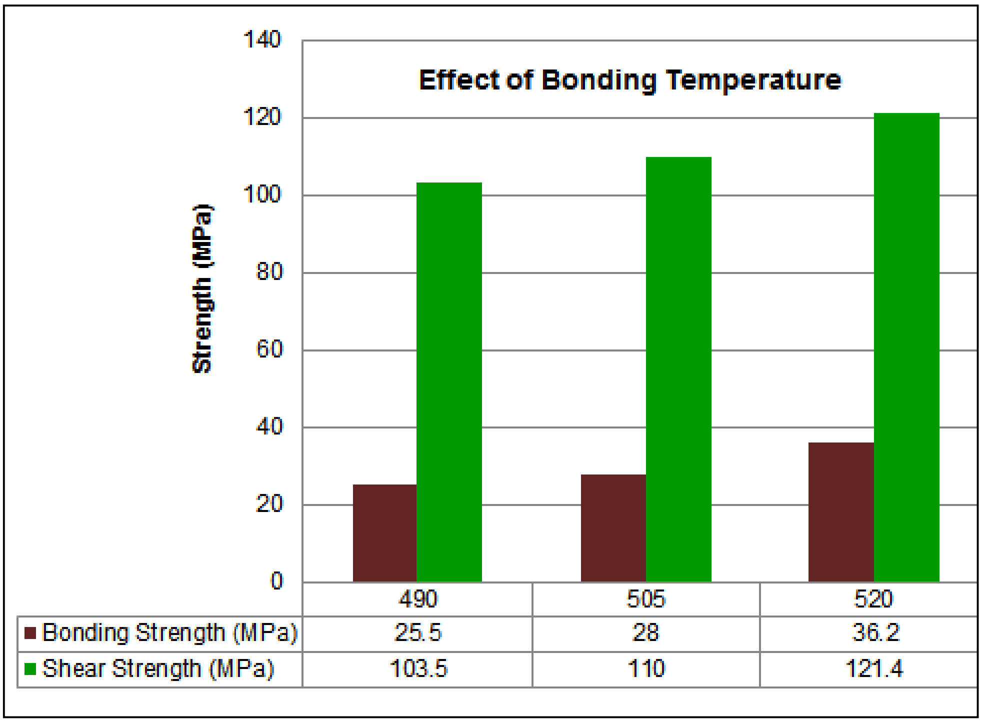


Figure 6. Effect of Bonding Temperature on Bonding and Shear strength

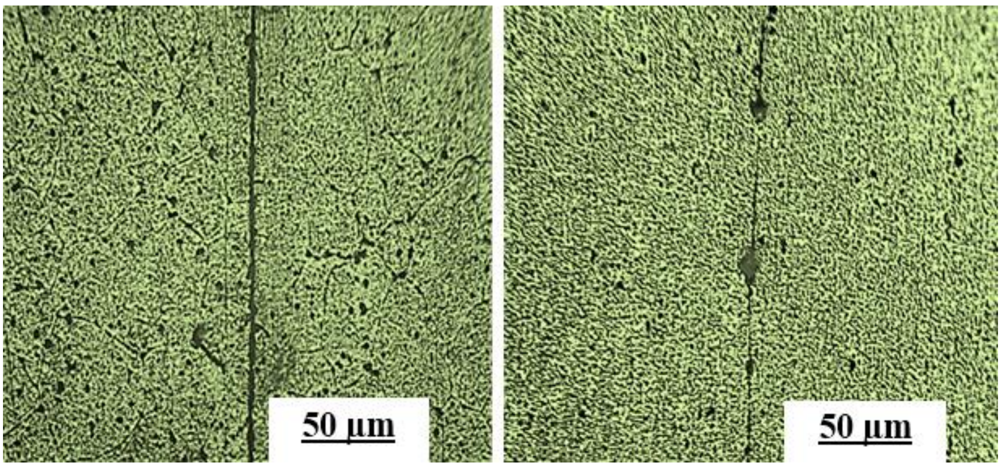
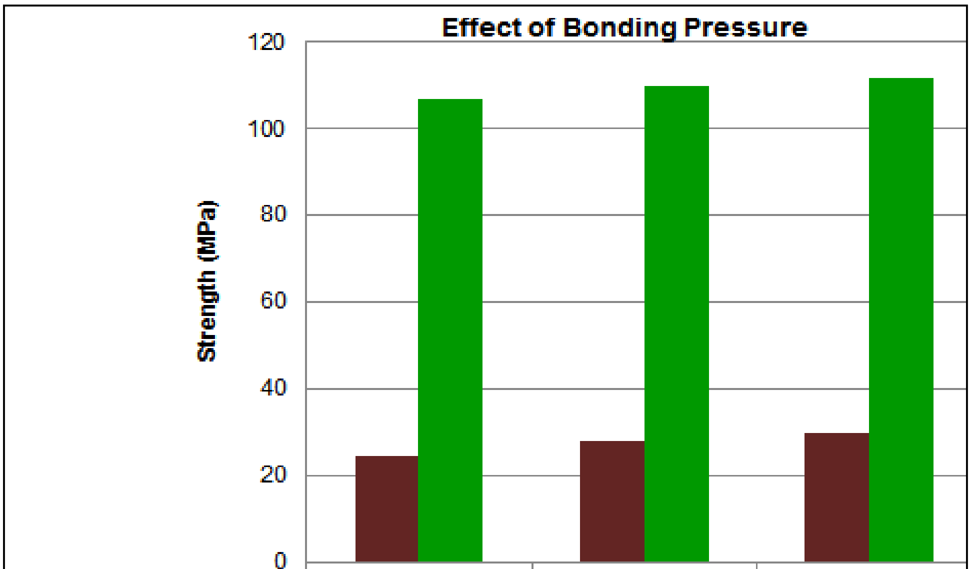


Figure 7. Effect of Microstructure on Bonding Temperature

This is evident from the other similar research [25]. It is probable that similar behaviour occurred at the higher bonding temperatures but was followed by rapid grain growth. It is also observed that during testing all samples failed through the bonded region because the shear force was concentrated along the bond plane. It is found that, the diffusion layer seems diminishing with the increase of temperature. At higher bonding temperatures at which grain growth occurred were identical with those for superplastic flow, suggesting the superplastic behavior of the alloy may have also contributed to the bonding process. Superplastic (SP) flow could have certainly made some contributions to the removal of the bond line even though the SP strains involved in the DB procedure were relatively low [26]. However, since grain boundary sliding makes a substantial contribution to the accumulation of strain during SP 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.

Effect of bonding pressure

The effect of bonding pressure on bonding and shear strength with bonding temperature 505 °C and holding time 30 min are shown in the Fig. 8. It is observed that the bonding and shear strength increases with the increase of time. If bonding pressure increases, the holding time required to get good bonds decreases, irrespective of bonding temperature. However, the bonding pressure does not have significant influence on bonding temperature shown in the Table 5. The maximum and minimum bonding temperature to get good bonds remain unaltered, irrespective of bonding pressure [27]. Fig. 9 shows the microstructures of the joints bonded different bonding pressure. A microstructure analysis indicates that change in grain morphology is more obvious for AA7075 alloy with the increasing bonding pressure. Equiaxed and more homogeneous grains are seen in these specimens due to absence of HAZ (heat affected zone) exist in the fusion welding methods. Grain growth in the bonded materials can be attributed to recrystallization and to the enveloping of small grains by bigger ones. The tendency for grain growth with increase in pressure is related to grain boundary energy. In order to obtain a lower level of energy, total grain boundary per unit volume needs decreasing and this, in turn, requires the growth of grains [28, 29]. From the test results, it is evident that shear strength of the bonds depends on bonding pressure. However, shear strength cannot be used to evaluate the extent of bonding because the specimens may have different tempered conditions. But it was reported [30] that the actual shear strength requirements of the bonds for aircraft structures are generally in the order of 10–20 MPa. Hence, in this investigation, the shear strength of the bonds was evaluated by conducting lap shear tensile strength.



	5	10	15
Bonding Strength (MPa)	24.3	28	29.6
Shear Strength (MPa)	106.6	110	111.5

Figure 8. Effect of Bonding Pressure on Bonding and Shear strength

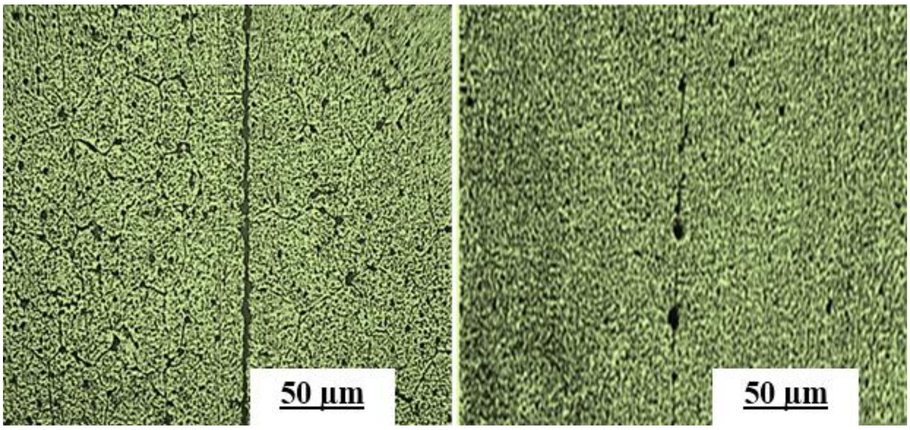


Figure 9. Effect of Microstructure on Bonding Pressure

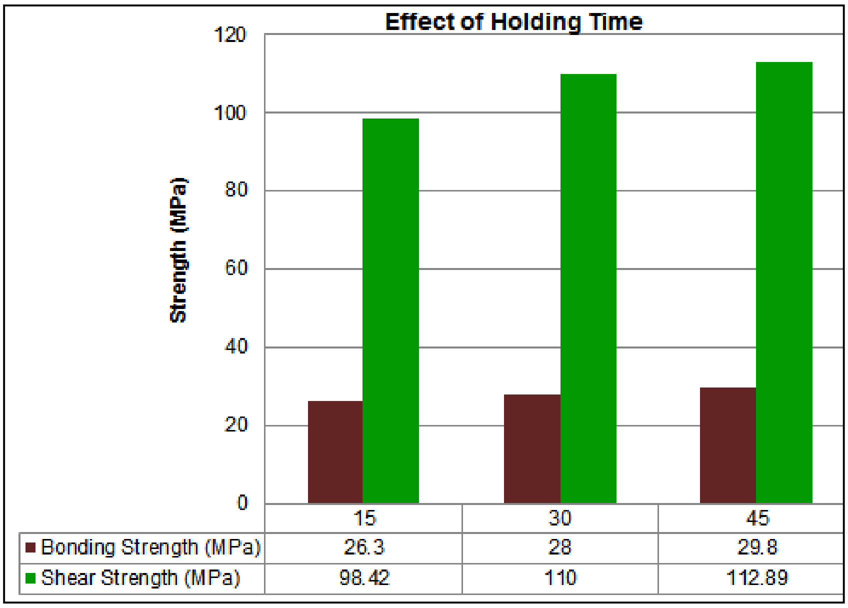


Figure 10. Effect of Holding Time on Bonding and Shear strength

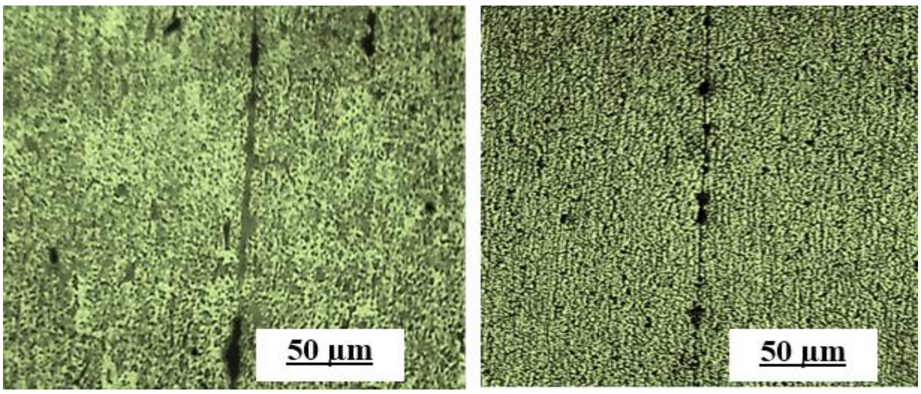


Figure 11. Effect of Microstructure on Holding Time

Effect of holding time

Fig. 10 shows the effect of holding time on bonding and shear strength of AA7075 aluminium alloy with bonding temperature 505 °C and pressure 10 MPa respectively.. It is seen that, with the increment in time, the strength increases. It is observed that result showed that the grain growth would obstruct the diffusion bonding quality. As the holding time increases, the grain size of the annealed material much time coarser than that for lesser holding time. The effect of microstructure on the holding time at a fixed temperature and pressure is included in Fig. 11. It can be seen from the figure that grain growth starts off slowly, and increases more rapidly up to 45 min. It can also be seen that bonding for 45 min leads to a strength approaching that of the parent metal and a microstructure showing the diminishing of the bond line. Longer bonding times show a continuing grain growth enhances the bonding and shear strength. During the present studies no distinct voids were observed in the bond interfaces, only linear regions of disbond. This is consistent with earlier work on the diffusion bonding of AA7475 carried out without a protective coating, although the bonding pressures used in this work was greater (5–20 MPa) [31]. Calculations based on relationships given in [31] 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.

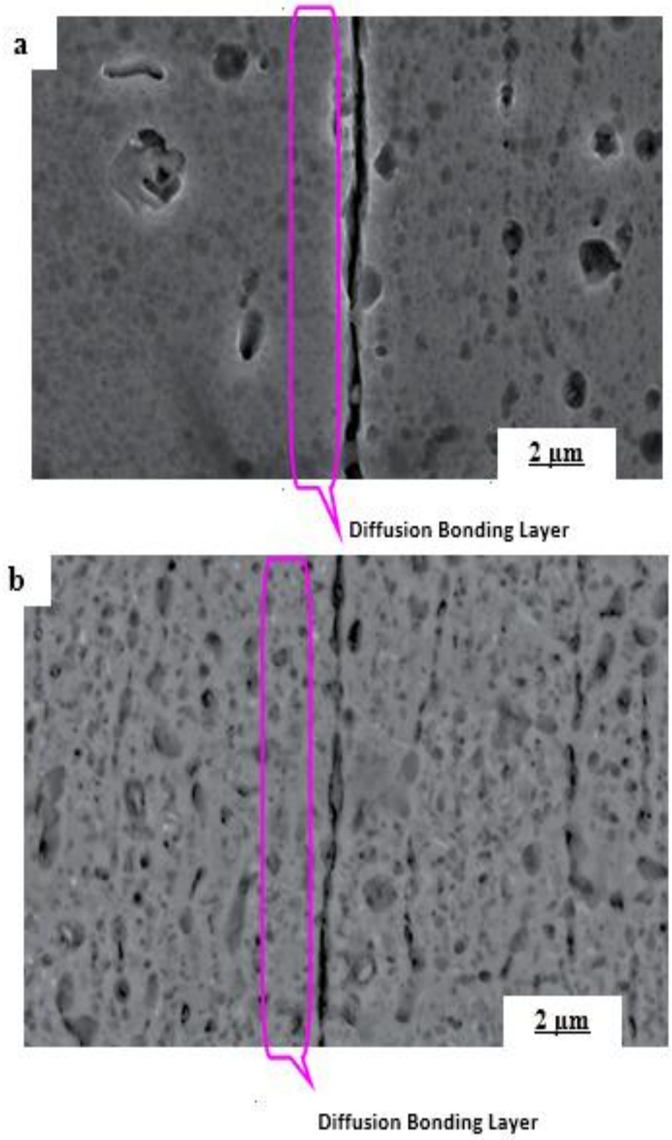


Figure 12. SEM images of diffusion bonded AA7075 aluminium alloy joints

Scanning Electron Microscopy

Fig. 12 shows the SEM images of diffusion bonded AA7075 aluminium alloy joints with respect to the temperature. The present work has identified a range of conditions under which sound diffusion bonds can be obtained. However, it should be recognized that those involving high temperatures could lead to a significant reduction in the SP deformation potential of the material because of grain growth. Although the limiting grain size above which SPF of the material would no longer be feasible would need to be determined experimentally. It is observed from the SEM and further suggested that bonding conditions which led to grain sizes in excess of 12–14 mm would not be suitable. For all the diffusion process, it is found that the diffusion bonding layer is uniform in width. With the increase of the temperature, the width of the diffusion bond layer was decreased. At temperature 490 °C, the width is measured as 15 to 18 microns. But the eutectic particles on either side of the AA 7075 are uniform and the heat of diffusion resulted in grain growth. Similarly, the width of the diffusion bonding layer is observed at 5 to 7 microns with the temperature exposed to 520 °C. It is also observed that, the both sides of the parent metal show identical microstructure with constituents of eutectics in primary aluminium solid solution. The interface zone showed finer constituents of the eutectics which have dissolved and precipitated. The original grain orientation of the material is completely vanished at the diffusion zone.

CONCLUSIONS

- Empirical relationships were developed to predict the bonding and shear strength of the diffusion bonded joints of AA7075 aluminium alloys incorporating important parameters. The developed relationship can be effectively used to predict the bonding and shear strength of diffusion bonds at 95% confidence level.
- A maximum bonding strength of 36.8 MPa obtained under the condition of bonding temperature 514 °C, bonding pressure 13 MPa and holding time 39 min. While, the maximum shear strength of 121.4 at bonding temperature 520 °C, bonding pressure 10 MPa and holding time 30 min.
- The bonding and shear strength increases with the increase of temperature, pressure and holding time. Bonding temperature was found to have greater influence on shear strength and bonding strength of the joints followed by bonding pressure and holding time.

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