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Optimization of the diffusion bonding parameters on aa5083 aluminium alloy using Taguchi's technique

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ABSTRACT

Effect of bonding parameters on the bonding strength of AA5083 aluminium alloys was investigated in the present study. Rolled plates of 5 mm thick AA5083 aluminum alloys were fabricated by diffusion bonding. Bonding temperature, bonding pressure and holding time were considered as the varying process parameters. Experiments are designed as per the Taguchi technique to for the experimentation sequence according to L9 orthogonal array. The desirability approach is used as optimization technique to obtain the maximum bonding strength and bonding strength of the joint. After running through 10 cycles of optimization, the most optimal parameters are bonding temperature of 510 °C, bonding pressure 13 MPa and holding time of 45 min with the desirability of 0.82.

Keywords: *AA5083 aluminium alloy, Diffusion bonding, L9 Orthogonal array, Desirability Approach.*

1. 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 [4-7]. 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 [8, 9]. Strengths are believed to have occurred because of variations in the amount of liquid gallium used [10]. 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 [11]. 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 [12].Hence, the researchers [13] recommend diffusion bonding technique to join AA 5083 aluminium alloy. 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 [14].

There are different mathematical models are available to predict the required output variables and to specify the relationship between the input parameters and output variables. The Taguchi's L9 orthogonal array [15, 16] is used to develop an empirical relationship between the input parameters and the desired output. Hence, in this present study, an effort is made to optimize diffusion bonding process parameters using Taguchi's L9 orthogonal array and desirability approach to attain maximum bonding strength in AA5083 aluminium bonded joints.

2. EXPERIMENTAL WORK

2.1 Fabricating the joints and preparing the specimens

Rolled plates of 5 mm thick AA5083 aluminium alloys are used in this investigation. The chemical composition and mechanical properties of the base metal are presented in Tables 1 and 2.

Table-1 Chemical Composition (wt. %) of AA5083 aluminium alloy

Si	Fe	Cu	Mn	Mg	Zn	Ti	Others	Al
0.26	0.35	0.05	0.6	4.75	0.11	0.05	0.06	Balance

Table-2 Physical and Mechanical Properties of AA5083 aluminium alloy

Density (g/cm3)	Melting Point (ºC)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Shear Strength (MPa)	Elongation (%)	Poisson's Ratio	Crystal Structure
2.80	635	317	229	190	16	0.33	FCC

The optical micrograph of AA5083 aluminum alloy is shown in Chart 1. The microstructure of base metal was exhibiting deformed grain structure with precipitated decorating grain boundaries. 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.

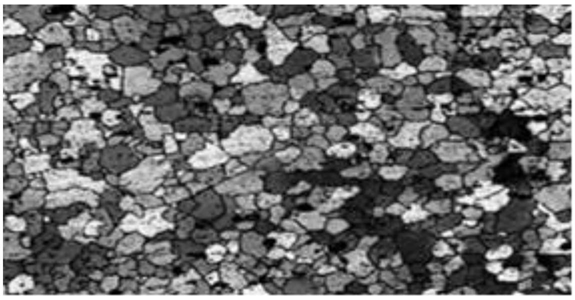

Chart-1 Microstructure of AA5083 aluminium alloy

The surface of the samples was grinded to flat with different SiC papers and acetone wash is required [17]. Now, the samples were dried and the surfaces (top and bottom only) should be covered with mica sheet inside a die made of steel and placed inside a vacuum chamber with a pressure of 29 Hg-mm. Heat the specimen to the bonding temperature specified inside the induction surface by applying 25ºC/min. temperature range. Simultaneously, both bonding pressure and holding time are applied. The samples were cooled to the room temperature inside the vacuum chamber upon successful bonding. Chart 2 shows the experimental setup.

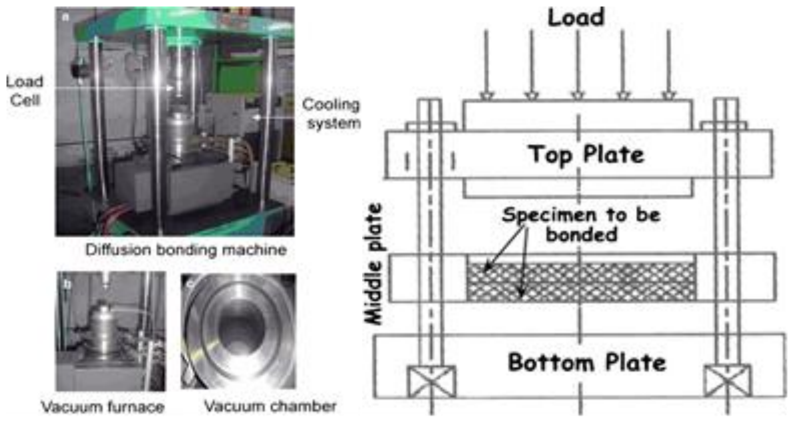

Chart-2 Diffusion Bonding Set Up

2.2 Finding the limits of diffusion bonding parameters

From the literature [18-20], the predominant factors that have a greater influence on the diffusion bonding of AA5083 aluminium alloy joints had been identified. They were: (i) bonding temperature (T), 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 AA5083/AA5083 aluminium alloy and this was due to the insufficient temperature to cause diffusion of atoms.
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.
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.
iv. If the bonding pressure was greater than 15MPa, then the plates were deformed plastically causing reduction in thickness and bulging at the outer edges.
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.
vi. If the holding time was higher than 45 min, then excessive grain growth followed by melting of interphase particles alloy was observed.

2.3 Developing the experimental design matrix

Owing to a wide range of factors, the use of three factors and an orthogonal array matrix were chosen to minimize the number of experiments. Orthogonal arrays of the Taguchi method are highly fractional orthogonal designs. These designs can estimate the main effects of S/N ratios by using only a few experimental runs. In this experiment with three parameters at three levels each, the fractional factorial design used was a standard L9 (33) orthogonal array. 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 Range of parameters considered

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

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)
1	490	5	15	26
2	490	10	30	25
3	490	15	45	31
4	505	5	15	28
5	505	10	30	32
6	505	15	45	34
7	520	5	15	31
8	520	10	30	38
9	520	15	45	35

2.4 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 -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 [21].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 analyzing software (Clemex-vision). The diffusion bonded side was etched with a Keller's solution (3ml HCl, 2 ml HF and 90 ml distilled water) [22]. The test specimens were polished in disc polishing machine for scratch fewer surfaces and the surface was observed at 200X magnification.

3. DEVELOPING AN EMPIRICAL RELATIONSHIP

Simulations are run as per Taguchi experiment plan and bonding strength and the shear strength for each simulation run is converted into their respective S/N ratios as per expression as;

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

Data analysis is made using MINITAB R6 software at 95% of confidence. Main effect plots and interaction plots are used to determine the optimum factor levels for each response and results. The Mean and signal to noise ratio are the two effects which influence the response of the factors. The influencing level of each selected bonding parameter can be identified. The bonding strength and the shear strength of the A5083 aluminium alloys were considered as the output results. The responses for the S/N ratio shows that the bonding temperature ranks first in the contribution of good bonding strength while bonding pressure and holding time take the second and third ranks shown in Table 5. The same trend has been observed in the response table of the mean which is presented in Tables 6. The responses to the plot of the S/N ratio and Mean are shown in Chart.3 & 4 respectively.

Table-5 Response and Rank for S/N

Level	Bonding Temperature (T)	Bonding Pressure (P)	Holding Time (t)
1	1.53	1.78	1.02
2	2.03	1.88	1.71
3	2.35	2.11	1.99
Delta	0.94	0.35	0.29
Rank	1	2	3

Table-6 Response and Rank for Mean values

Level	Bonding Temperature (T)	Bonding Pressure (P)	Holding Time (t)
1	65.24	63.02	71.58
2	67.25	69.8	66.54
3	73.25	70.18	67.89
Delta	8.17	7.67	4.33
Rank	1	2	3

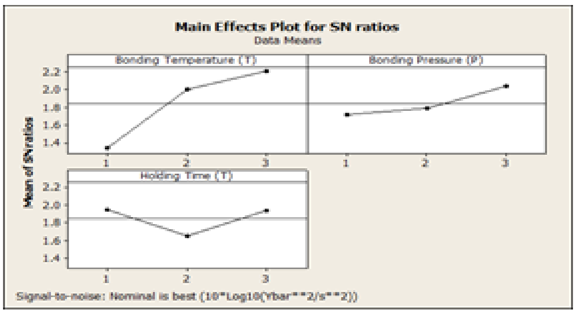

Chart-3 Response Plot for S/N Values

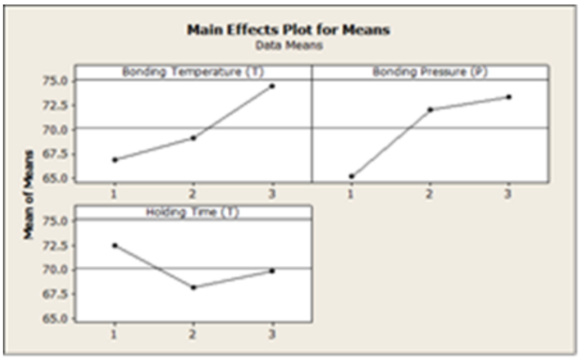

Chart-4 Response Plot for Mean Values

Relative influence of each factor is determined by analysis of variance method (ANOVA) and results are presented in Table 7. The fitness of the models is determined using R2 (standard deviation). Using the F-test the bonding strength models show highly significant.

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
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	**	**	**	**	**	**

The probability of significance of the model terms should be less than 0.05, as 95% of the confidence level is considered. In this case bonding strength includes T, P and t are significant model terms. The ‘‘Lack of Fit F-value’’ of bonding strength are 2.05 implies the Lack of Fit is not significant relative to the pure error respectively. Non-significant Lack of Fit is good. The Predicted R-Squared of bonding strength is 0.7819 relative to the adjusted root mean square of 0.927. The target for the root means square is less than 0.2 the probability ratio for bonding strength are 19.178 shows better fitness. The normal probability and residual plots of the bonding strength are shown in Fig. 5 and 6 respectively. It is found that the residuals arrayed in a straight line, which show the errors, were distributed normally.

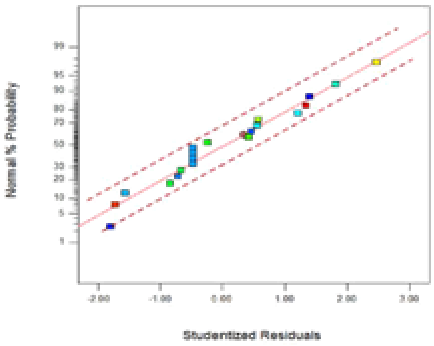

Chart-5 Normal Probability Plots

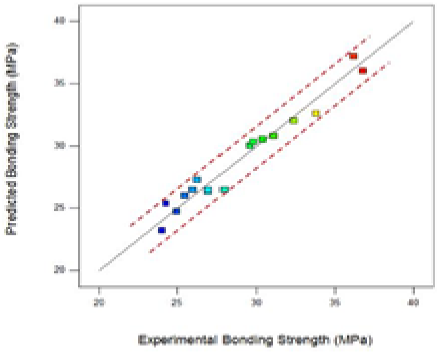

Chart-6 Correlation of the Response

4. OPTIMIZING THE DIFFUSION BONDING PARAMETERS

In this investigation, the L9 orthogonal array was used to optimize the diffusion bonding parameters [16]. The response plots developed from the S/N ratio and mean values indicating the maximum and minimum output responses and the empirical relationship was made shown in Fig. 3 & 4respectively. Maximum achievable bonding strength observed from the apex of the response surface shown the figures. The bonding strength is very low beyond the lower limit of temperature and pressure. This is mainly due to the fact, at low temperature, the flowability of the metal is substantial; yet, the yield strength of base materials still remains high, which leads to an incomplete coalescence of the mating surfaces [23] The bonding strength is relatively high with the increase in temperature. It is found from the study; the diffusion of the atom from metal to metal is more feasible with higher temperature. This enhances the chemical bonding. With the increase in temperature beyond 520°C, the bonding strength deteriorates. The deterioration of strength is mainly due to the mass transfer of alloying element across the interface. This cause embrittlement of the joints by causing the increase in volume fraction of the inter phase particle. The effect of bonding pressure on strength is less when compared to temperature and time. At a bonding pressure less than 5 MPa, minimum shear strength and bonding strength are obtained. Higher shear strength is obtained at a pressure of 10 MPa. Increase in pressure develops a higher rate of plastic deformation at contact sites, which increases the contact areas of clean surfaces and hence diffusion rate changes abruptly [24]. Further increase of pressure to 15 MPa resulted in a decrease of shear strength. The property of the bonded joints also depends on the thickness of the intermetallic compounds. At less than 15 min of holding time, the shear strength and bonding strength reduced, respectively. At 30 min of holding time, maximum strengths were obtained due to the growth of intermetallic compounds. But the shear strength of the joints is increasing with increase in holding time, irrespective of temperature and pressure. This is mainly because the holding time has an effect on the creep of the protrusions and the quantity of atomic diffusion [25]. At 45 min of holding time, the decline in strength was obtained due to the growth of intermetallic compounds.

In order to optimize the process parameters to maximize the mechanical characteristics such as bonding strength, a combined analysis is done based on their desirability criteria. Desirabilities range from zero to one for any given response. The greatest overall desirability obtained by associating the individual objectives into single objectives, later transform it into single desirability. The program combines the individual desirabilities into a single number and then searches for the greatest overall desirability [18]. A value of one represents the ideal case. More the number of cycles will develop better optimal solutions.

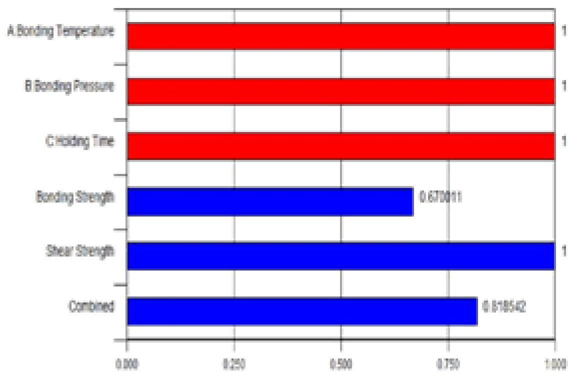

Chart-7 Desirability chart for the optimal solution

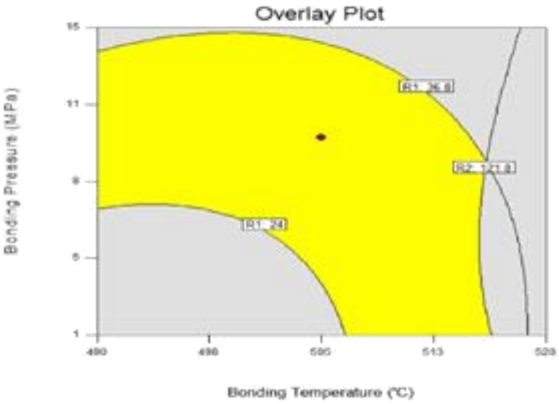

Chart-8 Overlay plot for the optimal solution

The Duplicate solution filter establishes the epsilon (minimum difference) for eliminating duplicate solutions. The program using Design-Expert software randomly picks a set of conditions from which to start its search for desirable results. After running through 10 cycles of optimization, the results appear as the most optimal parameters are bonding temperature of 510 °C, bonding pressure 13 MPa and holding time of 45 min with the desirability of 0.82. Fig.7 shows histogram of desirability is generated for the optimal solution of process parameters found via numerical optimization. The graphical optimization is also generated by overlaying the plot shown in Fig. 8.

6. CONCLUSIONS

• A maximum bonding strength of 34 MPa obtained under the condition of bonding temperature 520 °C, bonding pressure 10 MPa and holding time 30 min.
• Bonding temperature was found to have a greater influence on bonding strength of the joints followed by bonding pressure and holding time.
• From the ANOVA results, the most significant model parameters for bonding strength are bonding temperature (T), bonding pressure (P), holding time (t). Similarly, the interactive parameters such as bonding temperature-bonding pressure (TP) and bonding pressure-holding time (Pt) are the significant model terms for both bonding strength.
• After running through 10 cycles of optimization, the most optimal parameters are the bonding temperature of 510 °C, bonding pressure 13 MPa and holding time of 45 min with the desirability of 0.82.

7. ACKNOWLEDGEMENT

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