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ARTICLE

Application of Taguchi optimization method to the transient liquid phase diffusion bonding process

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Aluminum metal matrix composites (Al-MMCs) find extensive applications in engineering structures requiring good strength-to-weight ratio and corrosion resistance. A major limitation to the widespread use of these materials is the unavailability of a suitable joining process that maximizes their potential. Currently, fusion welding techniques are used to join Al-MMCs, however, the high temperature required for fusion welding processes can cause extensive damage to the strengthening particles thereby changing the microstructure and performance of the joints produced. Transient liquid phase (TLP) bonding has been identified as a suitable alternative, however, the bonding parameters have yet to be optimized. In this study a Taguchi's fractional-factorial design L9 (34–2) of experiments was used to optimize the process parameters of TLP bonding. The results indicated that an optimal joint strength of 142 MPa can be achieved with the bonding temperature of 620°C, bonding pressure of 0.01 MPa, holding time of 30 minutes, and interlayer thickness of 11 µm. Analysis of variance (ANOVA) indicated that bonding temperature had the most significant effect on the joint shear strength.
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KEYWORDS: Taguchi optimization; TLP bonding; aluminum metal matrix composits (AL-MMC); S/N ratio

Aluminum metal matrix composites (Al-MMCs) containing silicon carbide (SiC) or alumina (Al_2O_3) particles have been used extensively in aerospace and automotive industries. The advantages of using these materials are: high strength-to-weight ratio, formability and corrosion resistance [1, 2]. However, the lack of a reliable and economic joining method has restricted their full potential. The literature indicates that fusion welding is the primary joining technique used for particle reinforced Al-MMCs. However the heat generated during fusion welding can result in negative particle-matrix reactions leading to the formation of brittle inter-metallic compounds in the joint region [3, 4].

Through extensive research, transient liquid phase (TLP) bonding by eutectic reaction has been identified as an alternative to fusion welding. Since the process is carried out at lower bonding temperatures negative particle matrix reactions are prevented, thereby improving the mechanical properties of the joint. In this process a thin continuous layer of liquid is formed at the joint interface, which wets the contacting metallic substrates [5-9]. Reinforcing particles are

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incorporated into the bond region either by using a particle reinforced interlayer [10] or by the melt-back of the substrate metal as a result of the eutectic reaction between the interlayer and the aluminum alloy [11]. In the present study, the liquid phase formation was attributed to the diffusion of nickel (Ni) into the Al-6061 base metal leading to the formation of a ternary eutectic liquid between aluminum, nickel and silicon (Al-Ni-Si) [12]. Parameters affecting TLP bonding include: temperature, time, interlayer thickness and pressure. In the last decade extensive studies have been done on TLP bonding of Al-MMCs, however to date a statistical optimization of the process parameters has not been completed.

In this study the bonding parameters of the TLP bonding process were optimized using a Taguchi L9 fractional factorial design of experiment. Taguchi optimization techniques have been applied extensively in advance manufacturing process because of the simplicity with which the processes can be optimized. The Taguchi method employs a generic signal-to-noise (S/N) ratio to quantify the mean and variation in the responses. These values are used to measure the effects of noise factors on performance characteristics and take into account both the amount of variability in the response data and closeness of the average response to a target. There are several S/N ratios available depending on three types of characteristics: smaller is better (SB), nominal is best (NB) and larger is better (LB). In this study, the objective was to maximize the shear strength, hence the larger-is-better characteristic was used.

Materials and methods

Parametric design using the Taguchi Technique

Taguchi's [L9 (3^{4-2})] a fractional-factorial design was used in this study to optimize process parameters of the TLP bonding process. The main process parameters evaluated were: temperature (A), time (B), pressure (C), and interlayer thickness (D). The parameter settings used are shown in **Table 1** and represents three different level settings (level 1, level 2 and level 3). The parameter limits shown in **Table 1** were determined through preliminary investigation . An orthogonal array developed by Taguchi et al. showed the parameter combination for each the nine experimental runs completed (**Table 2**) [13]. Each experimental run shows a combination of parameters at one of the three level settings discussed above (1, 2 or 3). This was done to select the optimal parameter levels of the process. Curves of the average values for each level were plotted to show the influence of each variable on the shear strength of the joints. These curves allow for the analysis of relationships between different parameters.

Table 1. Experimental levels used for TLP process

Level	Temperature °C **(A)**	Time (min) **(B)**	Pressure (MPa)**(C)**	Interlayer thickness (μm) **(D)**
1	590	5	0.01	9
2	600	10	0.1	11
3	620	30	0.2	13

Table 2. Taguchi L_9 orthogonal array

Experiment	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Alloy Composition

This study used an Al-6061 alloy contained 15 wt% of alumina (Al_2O_3) particles with an average size of 28 μm, the composition of the material is shown in **Table 3**.

Table 3. Composition of Al-6061/15% Al_2O_3 MMC

Composition wt%								
Fe	**Cu**	**Mg**	**Mn**	**Cr**	**Ti**	**Zn**	**Si**	**Al**
0.03	0.11	1.09	0.05	0.08	0.09	0.15	0.69	Bal

Sample preparation and characterization

The specimens were prepared for bonding by cutting to a dimension of 10 x 10 x 5 mm. A hole was drilled to a depth of 3 mm at 1mm from the bonding interface. Specimen surfaces were prepared to 800 grit SiC finish and subsequently polished using 1 μm diamond suspension and then cleaned in an acetone bath. Prior to bonding, one piece of each couple was coated with Ni-coating co-deposited with 500 nm Al_2O_3 particles. The electrodeposition of Ni onto the Al-6061 surfaces was carried out in a 250 ml glass beaker using Watt's nickel bath recipe [14] into which 50g/l of Al_2O_3 particles were suspended. process was completed.

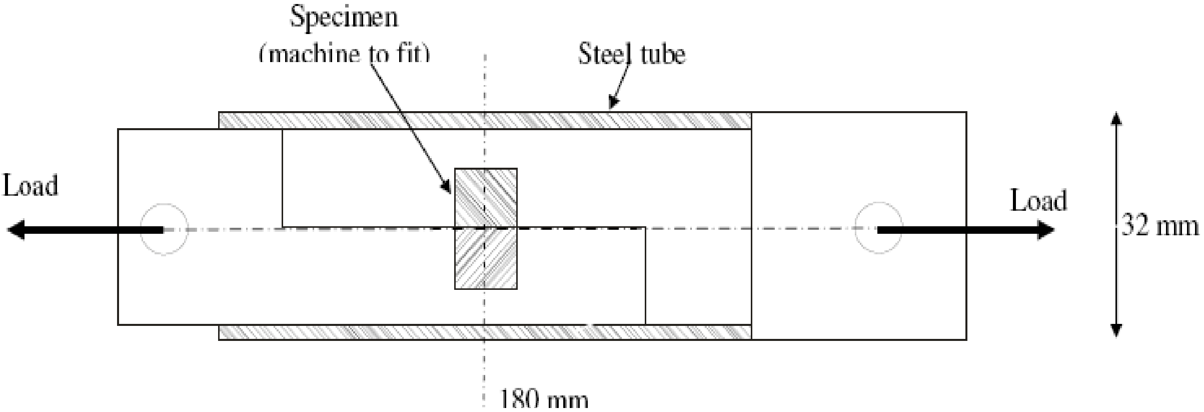

Figure 1. Schematic of shear test rig

The specimens were assembled at room temperature and placed on the lower platen within the induction coil and an ungrounded thermocouple inserted into the hole located approximately 1 mm from the joint interface. Once a vacuum of 4 x 10^{-4} torr (0.053 Pa) was achieved, the assembly was heated to the bonding temperature. The specimens were brought to the joining temperature at a heating rate of 65°C/min and then held at that temperature for 10 minutes. The power was turned off and the specimen was cooled to room temperature in vacuum, once the bonding.

Bonded samples were machined to 8 mm diameter to eliminate edge effects. Bonded specimens of approximately 10 mm length and 8 mm diameter were loaded into a specially prepared apparatus, which is schematically shown in **Figure 1**. The grips of the jig were pulled in tension by a Tinius-Olsen tensile testing machine at a cross-head speed of 0.5mm/min in position control mode, such that the specimen experienced pure shear stress across the bond interface. The maximum load was divided by the bond area in order to calculate shear strength. For each bonding condition, two specimens were tested and the average value used to determine the shear strength (bond strength). Examination of the joints microstructure was performed using a Ziess optical microscope and a JEOL 8200 scanning electron probe micro-analyzer (EPMA).

Results and discussion

Microstructure Analysis

Figure 2 shows a typical microstructure and fracture pattern of the joint prior to optimization. The micrograph revealed a band of segregated particles at the interface. WDS spot analysis

WDS spot analysis indicated the presence of pockets of aluminum oxide at the joint interface. The detection of oxides suggests that insufficient liquid formed during bonding and this was not sufficient to remove surface oxides during the bonding process. This has also been observed by other researchers such as Shirzadi and Wallach [11] who suggested that this oxide hinders bond formation and produces a low strength joint.

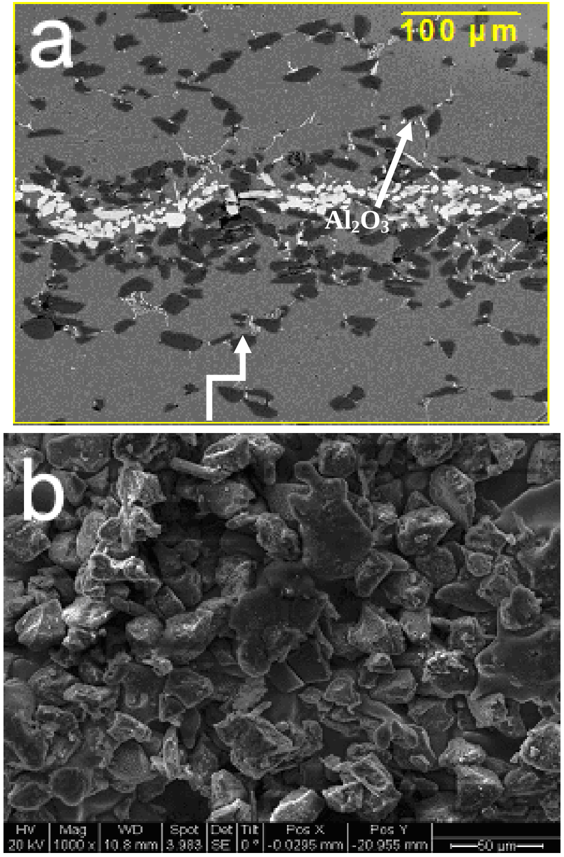

Figure 2. (a) SEM micrograph of the optimized joint (b) SEM micrograph of the fractured surface of the optimized joint.

At coating thickness 9 µm SEM micrographs revealed the presence of Al_2O_3 particle segregation at the bond centerline. The width of the segregated zones was 500µm. WDS analysis of the joint zone gave the concentration of Ni remaining after bonding as 1.06wt%. When thicker coatings are used to form TLP bonded joints WDS analysis of these joints indicate the precipitation of possible nickel aluminides within the joint zone. In addition, the concentration of Ni remaining at the interface showed a slight increase from 1.53 wt% to 1.58 wt%.

Shear strength measurements

Table 4 shows a summary of the shear strength values recorded for the nine experimental runs. The results indicated that the shear strength values ranged from 81.5 MPa to 134.9 MPa. From the results it is seen that experiment 1 had the lowest shear strength while experiment 6 had the highest. By utilizing the shear strength values shown in **Table 4**, the optimum bonding parameters were determined by calculating the signal-to-noise (S/N) ratio and the level averages for each experimental run. The S/N ratio (η) represents both the average and variation of the experimental results and can be calculated using **Equation 1**[15].

$$\eta = -10\log(\mathrm{M.S.D}) \text{------------ } \textbf{(Eq. 1)}$$

Where, M.S.D. is the Mean-Square Deviation for the output characteristic. Since the aim of this study is to maximize the shear strength of the joints, the larger the better quality characteristic was selected and can be determined using **Equation 2** [15].

$$\mathrm{MSD} = \frac{1}{\mathrm{n}}\sum_{i=1}^{n}\frac{1}{y_i^2} \text{---------------- } \textbf{(Eq. 2)}$$

Where, y_i is the value of shear strength for the *ith* test; n is the number of tests. The shear strength values measured from the experiments and the S/N ratio values are listed in **Table 4** for the nine different experiments performed according to the design parameter combinations shown in the orthogonal array **Table 2**.

A response table for the parameter at levels 1, 2, and 3 was created by using the information shown in **Table 4**. The S/N ratio response table for each level of the process parameters (temperature, time, pressure and interlayer thickness) is shown in **Table 5**.

In order to estimate the effect of each factor, the average value of the response variable at each parameter level was determined by applying equation 3 [15] to each parameter level for each factor. The estimated effects of the parameters on the S/N ratio are presented graphically in **Figure 3.**

$$m_{A1} = \frac{1}{3}(\eta_1 + \eta_2 + \eta_3) \text{--------------- } \textbf{(Eq. 3)}$$

Table 4. Measured results of response variables and S/N ratios

Experiment	A (°C)	B (min)	C (MPa)	D (μm)	Y_1 (MPa)	Y_2 (MPa)	Y_A (MPa)	S/N (η) (dB)
1	590	5	0.01	9	79	84	81.5	38.21
2	590	10	0.1	11	103	79.5	91.25	38.99
3	590	30	0.2	13	81	93	87	38.73
4	600	5	0.1	13	93	107.4	100.2	39.95
5	600	10	0.2	9	129	95	112	40.68
6	600	30	0.01	11	148	121.8	134.9	42.48
7	620	5	0.2	11	113	131.5	122.25	41.67
8	620	10	0.01	13	149	84.8	116.9	40.36
9	620	30	0.1	9	135	119.6	127.3	42.05

$Y_{(1\text{-}9)}$= Shear strength for each experimental run, Y_A average shear strength

Table 5. Mean values of S/N ratios (dB) for each level

Factors	Code	Parameter levels		
		1	2	3
Temperature	A	38.64	41.0	41.36
Time	B	39.94	40.01	41.08
Pressure	C	40.35	40.33	40.36
Interlayer thickness	D	40.31	41.05	39.68

Evaluation of **Figure 3** shows that the shear strength increased with increasing both bonding temperature and bonding time. While a maximum shear strength can be achieved when the interlayer is used at level 2. The bonding pressure on the other hand was seen to little effect on the resulting S/N ratio. The results suggest that the bonding temperature and time had the most significant effect on shear strength. Similar observations were made by Shirzadi [11] who found that during TLP bonding pressure had the least effect on joint strength. The results collected indicate that the optimum S/N ratio can be obtained if the following parameter settings are used: A1, B3, and D2.

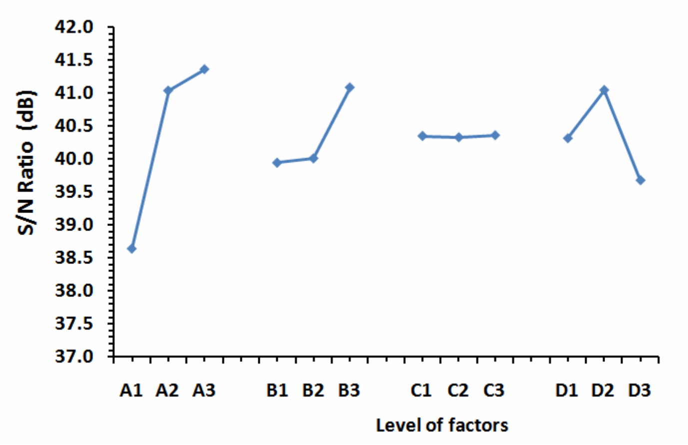

Figure 3. Response graph of S/N ratio for investigated parameters

Analysis of the level averages

A second analysis using the level averaging technique was also completed. The level average response analysis is based on averaging the experimental results achieved at each level for the respective parameter. A summary of these calculations are shown in **Table 6**. A graphical plot of these averages are presented in **Figure 4** and shows that the joint shear strength of TLP bonds increased with increasing bonding time and temperature. The results confirmed the optimum parameters identified when the S/N ratio are used.

Table 6. Mean values of shear strength (MPa) for each level

Factors	Code	Parameter levels		
		1	2	3
Temperature	A	86.58	115.70	122.15
Time	B	101.32	106.72	116.40
Pressure	C	111.10	106.25	107.08
Interlayer thickness	D	106.93	116.13	101.37

Similar results were obtained by Zhou et al [7] who showed that bonding time and temperature had the most significant effect on the mechanical properties of the joints produced during TLP bonding. Cooke et al [16] showed that interlayer thickness is also of critical importance since it determines the width of the liquid phase that forms during bonding.

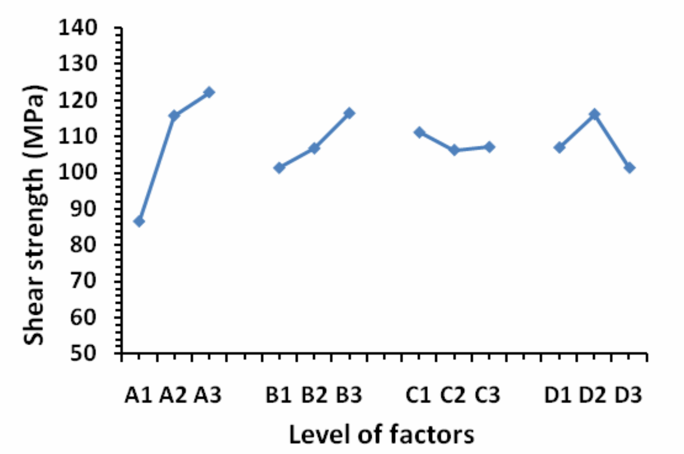

Figure 4. Response graph of shear strength averages for the investigated parameters

Analysis of variance (ANOVA)

In this study, ANOVA was carried out to examine the influence of the process parameters on quality characteristics. If some parameters do not significantly affect shear strength, they can be fixed to a minimum level and excluded from the optimization process, thereby increasing the efficiency of the optimization process. The percent contribution of variance was calculated by determining the total sum of squared deviation and the individual contribution of each parameter to the sum of squared deviations. These variables were calculated using the following **Equations** [15]:

$$SS_T = \frac{1}{n}\sum_{i=1}^{9} (\eta_i - \overline{\eta})^2 \text{ --------------------- } \textbf{(Eq. 4)}$$

$$\overline{\eta} = \frac{1}{9}\sum_{i=1}^{9} \eta_i \text{ -------------------------------- } \textbf{(Eq. 5)}$$

$$SS_d = 3x\,(\eta_{A1} - \overline{\eta})^2 + 3x\,(\eta_{A2} - \overline{\eta})^2 + 3x\,(\eta_{A3} - \overline{\eta})^2 \text{ -------------- } \textbf{(Eq. 6)}$$

The percentage contribution (ρ) of each factor to the overall response is determined using Equation 7 and is shown in **Table 7** [15].

$$\rho = \frac{SS_d}{SS_T} x\ 100 \text{ ----------------- } \textbf{(Eq. 7)}$$

Table 7. ANOVA for each parameter

Factors	Code	DOF*	Sum of squares	Variance	% Cont.**
Temp.	A	2.00	7.5	3.75	40.56
Time	B	2.00	6.84	3.42	37.00
Pressure	C	2.00	0.37	0.19	2.02
Interlayer thickness	D	2.00	3.78	1.89	20.42

DOF;* degrees of freedom; ***Cont;* contribution

The ANOVA is shown in **Table 7** in terms of percentage contribution. Percent (%) is defined as the significance rate of the process parameters on the joint shear strength. The percent numbers indicates that bonding parameters, bonding temperature, bonding time pressure and interlayer thickness have significant effects on joint shear strength. From the table it can be seen that the bonding temperature had the most significant effect on the S/N ratio accounting for 40.56% contribution to the response variable. In comparison, time (B), pressure (C) and interlayer thickness (D) affect joint shear strength by 37.00%, 2.02% and 20.42% respectively. The results indicate that during TLP bonding using the effects of the bonding pressure (within the tested limits) on the joint strength is insignificant. Tuah-Poku et al [6] suggested that high bonding pressure cannot be used for TLP bonding since the shear force developed in the liquid layer can result in liquid expulsion from the joint region.

Selection of the optimum parameters

In order to select the optimum parameters settings, level average calculations were done for the signal-to-noise ratio according to the "larger-is-better" characteristics. **Table 8** shows a summary of the optimized parameter levels as predicted by both calculation methods. The table indicates one conflict in the optimized levels recommended for factor C (pressure). Analysis of the S/N ratio indicated that a bonding pressure of level-3 would result in maximum output however analysis of the shear strength indicated that a setting at level-1 would be more appropriate. The results suggest that within the parameter levels tested, bonding pressure had the least effect on the joint shear strength. Therefore, either level-1 or level-3 can be used.

Table 8. Summary of the factor analysis

Factors	Code	Optimized levels	
		$\overline{Y}$	S/N ratio
Temperature	A	3	3
Time	B	3	3
Pressure	C	1	3
Interlayer thickness	D	2	2

Confirmation testing

Experimental validation of the Taguchi optimization process was necessary in order determine if the maximum joint shear strengths could be achieved using the optimum bonding parameters. Therefore, a confirmation experiment was conducted with the levels of optimal process parameters (A3, B3, C1, D2) resulting from the optimization process. Two shear strength values were determined (146 and 141 MPa) and the average of these values was found to be 143.5 MPa. A SEM micrograph of the optimized joint is shown in **Figure 5a**. A micrograph of the fractured surface is shown in **Figure 5b** and indicated that fracture occurred in the base metal adjacent to the bond-line. When compared to the non-optimized micrograph shown in **Figure 2** WDS results revealed that only 0.53 wt% Ni of remained in the joint center at the end of the bonding process which implies an increase in the diffusion rate during bonding. The fractured surface shown in **Figure 5b** is characterized by an undulating appearance, indicative of mixed mode of failure.

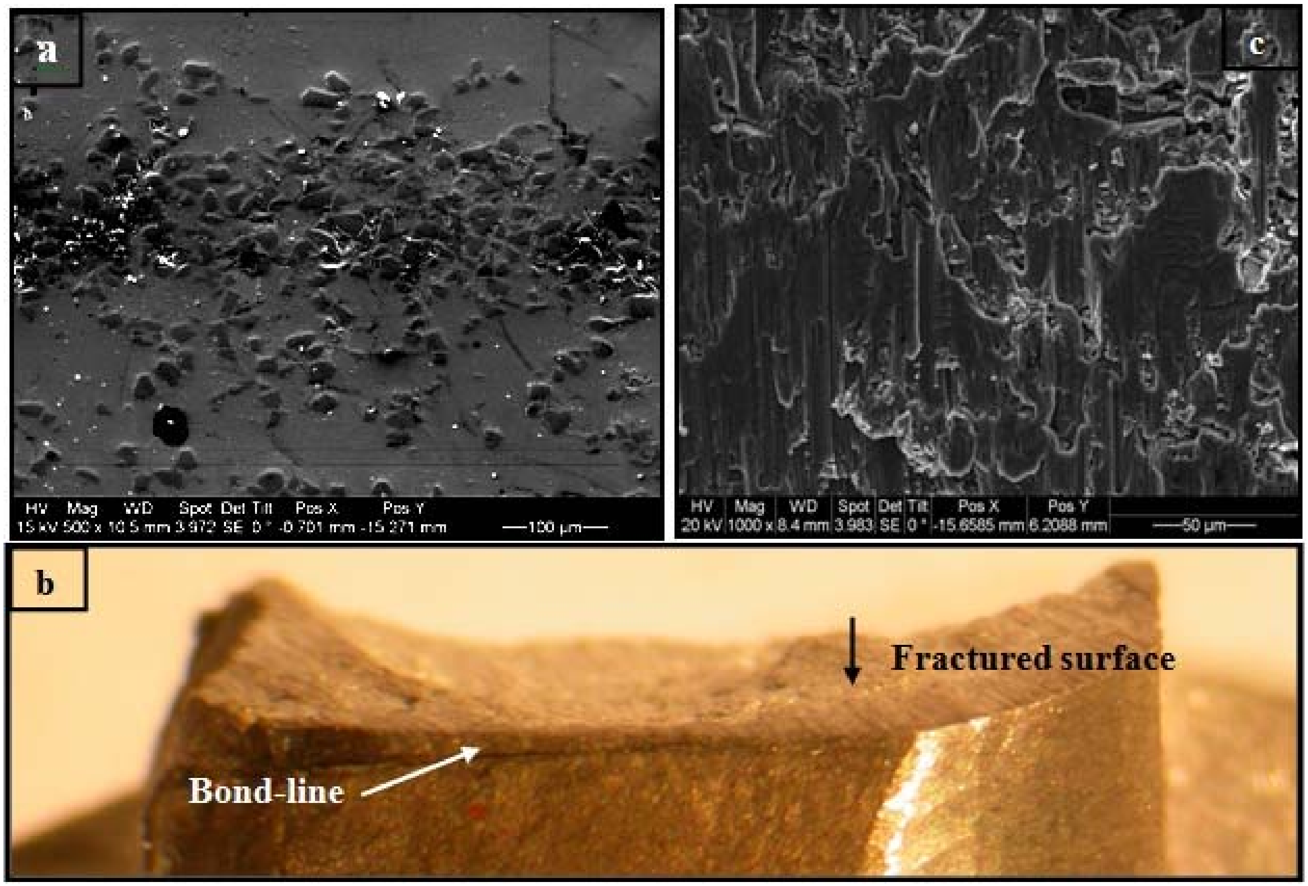

Figure 5. (a) SEM micrograph of the optimized joint (b) SEM micrograph of the fractured surface of the optimized joint. (c) SEM micrograph of the fractured surface bonded at the optimized conditions

Conclusion

Taguchi Methods were successfully used to optimize the transient liquid phase bonding of aluminum metal matrix composites using an electrodeposited Ni-Al_2O_3 composite interlayer. Due to material limitations, however, the experiment was restricted to the use of only two samples per condition.

Increasing the bonding temperature and bonding time caused a corresponding increase in the joint shear strength. The results also show that increasing interlayer thickness beyond 11 µm decreased the joint strength. Bonding pressure was the parameter having the least effect on the joint shear strength of TLP bonded joints.

The optimum bonding parameter combination within the experimental level ranges was found to be a bonding temperature of 620 °C, bonding time of 30 minutes, low bonding pressure and an interlayer thickness of 11 µm.

Within the experimental level ranges, the most significant influencing parameter was temperature, which accounted for 47.95% of the total effect, followed by interlayer thickness (20.15%), bonding time and pressure accounted for 19.24 and 12.67% respectively.

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