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Design and Optimization of Friction Stir Welding of Al-Cu BUTT Joint Configuration using Taguchi Method

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Abstract

Friction stir welding (FSW) is a solid-state welding technique in which the joint quality was predominantly subjected to heat formation throughout the metal welding process. The weld joint produced from FSW was better than the other fusion welding process. In this research, the base plates AA6101 and C11000 of 5 mm thickness were joined using the hardened oil-hardened non-shrinkable steel(OHNS) tool by the FSW method. The design of experiment (DOE) was used to optimize the input parameters such as tool rotational speed (rpm), feed rate (mm/min), and tool pin offset (mm) on output parameter ultimate tensile strength (UTS). The design of experiment (DOE) was carried out by employing a Taguchi L9 orthogonal array, three factors, and three levels for obtaining a quality joint with good strength. The results of nine trial runs from the Taguchi experimental approach were formulated and analyzed using the statistical tool analysis of variance (ANOVA) using MINITAB 19 software. ANOVA analysis was employed to find the contribution of the input parameters toward the output. The optimized input process parameters will help to create effective weld joints. This study revealed that tool pin offset towards softer metal at medium tool rotational speed would create joints with the highest UTS. Scanning Electron Microscope (SEM) was applied to investigate the structural changes in the FSW of Al-Cu joints.

Keywords: *Friction stir welding; Hardened OHNS steel tool; tool pin offset; Taguchi L9 orthogonal array; ANOVA*

1. 0 Introduction

In 1991, the T.W.I (The welding institute), at Cambridge England, attempted studies upon joining Aluminium alloy. The friction stir welding (FSW) performed better. A more experimental study was carried out on joining materials like titanium, aluminium, copper, composite materials, steel, and similar and dissimilar materials [1][2]. Since problems occur when joining these aluminium alloys with the fusion welding methods. To overcome this issue, FSW was introduced [3]. FSW is the solid-state welding approach that employs a non-consumable tool to fuse the base plates, which causes the mixing of the two plates by generating heat in-between the stirring tool and the base plates [4]. The welding tool rotates and traverses on the joint surface, causing stirring action to carry out the weld. The temperature developed during the FSW was below that of the fusing welding method [5]. Al and Cu were adequate conductive materials with corrosion

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resistance properties and high ductility used in the fewer-cost conductors in electrical applications [6]. During FSW operation, input parameters such as rotating speed, feed rate, tilt angle, tool pin shape, etc., affect the joint strength. The result of input welding parameters upon joint qualities was examined by conducting several experimental analyses [7]. Design of experiment and statistical methods were greatly employed to improve the input welding parameters. Taguchi approach was used as an optimization process because it reduces the number of experiments producing high-quality weld with less cost [8]. The analysis of variance (ANOVA) was introduced to find the significant outcome of input welding parameters upon output response [9].

Bhabani Bora et al., [10], have used AA6061-T6 and Cu B370 alloy dimensions of 15×50×3 mm^3 and H13 as workpieces and tools. They carried Taguchi L9 (OA) orthogonal array optimization method with input process parameters were rotating and welding speed. They found that the axial forces attain the highest value when the workpiece makes surface contact with the shoulder portion. Sundaravel Vijayan et al., [11], used 5 mm thick aluminium alloy 5083 and M2 tool steel plates. They performed Taguchi L9 and grey relational method for optimization with input parameters traverse speed, rotational speed, and axial load. They observed that the rotational speed achieved a more significant effect. Anil Kumar. K.S et al., [12], have used AA2024-T351 plates with dimensions of 100×100×6.35 mm^3 with the HSS tool. They conducted an L9 Taguchi design to enhance the input parameters: tool tilt angle, rotating, and welding speed. They found from ANOVA analysis that rotating speed has more percentage contribution towards the tensile strength. Lakshminarayanan. A.K and V. Balasubramanian [13], used RDE-40AA of size 300× 150×6 mm^3 with a high carbon steel tool. They carried the Taguchi L9 optimization approach of welding parameters such as tool rotating, traverse, and axial speed. They observed that rotating speed achieved more contribution towards the ultimate tensile strength. Singha. R et al., [14], have used AA6063 plates with 5 mm thickness. They carried Taguchi L9 optimization with three factors and three levels. Rotational speed (2700, 3500 and 5400 rpm), feed rate (12, 15 and 17 mm/min), and diameter of the tool shoulder (17, 20 and 22 mm). They found optimum tensile strength at 5400 rpm, feed rate 12 mm/min, and 20 mm. Shanmukha Prasad. V et al., [15], used Pure Cu and AA6061-T6 of size 150×50×3 mm^3 with 15 mm thick Zn coating. They performed Taguchi L9 design with input parameters rotation speed, travel speed, pin offset, and fictitious. They found that from ANOVA analysis, the pin offset shows less response. Rengarajan Satish et al., [16], used Al and Cu as the base metals in their work. They conducted a Taguchi L9 design with input parameters rotational speed, upset pressure, friction pressure, and burn-off length. They found that from SEM studies, the sample shows a brittle fracture. Seshu Kumar G. S. V. et al., [17], the authors used AA6061 and AA7075 of size 100×50×6.5 mm^3 with tungsten carbide. They performed Taguchi L27 design with input parameters rotation speed, tool tilt angle, and axial force. They observed that increasing rotation speed increases tensile strength. Abuajila Raweni et al., [18], used AA5083 plates of size 1000×500×5.5 mm^3. They carried Taguchi L16 design with input parameters rotation speed, feed rate, and tilt angle. The authors observed that feed rate had more effect and rotation speed had a more negligible impact. Mustafa Kemal Bilici et al., [19], used HDPE sheets of size 60×150×4 mm^3 and SAE 1050 tool steel. They conducted Taguchi L16 design with process parameters: rotating speed, feed rate, tool shoulder, and pin diameter. They found from the analysis that tool shoulder diameter experiences a more significant effect on tensile strength and high weld quality. Nima Eslami et al., [20], in this work, the authors used Taguchi L25 design with three factors (rotation speed, traverse speed, and pin offset). They observed that the lowest pin offset significantly impacted the mechanical property. Chi-Hui Chien et al., [21], used Taguchi L16 design with four factors: rotating, travel speed, tilt angle, tool pin length, and four levels. They found that optimum parameters were 1800 rpm, 180 mm/min, 1°, and pin length 2.9 mm. Also, from the analysis, a more effective parameter was pin length.

2.0 Experiment

In this research, the AA6101 and C11000 of size 100× 50×5 mm^3 (length, width and thickness) were the base plates used for the FSW process. The materials have good corrosion resistance, low electrical resistance, and excellent electrical conductivity, it was applied for electrical application. The OHNS (Oil Hardened Non-Shrinkable) steel tool with circular pin profile was designed with shoulder-length 70 mm and diameter 20 mm, pin size of length and diameter 5×5 mm^2 with hardness up to 65 HRC was selected as an FSW tool to perform the experiments. The hardened OHNS steel tool provides sufficient hardness, durability, strength, and wear resistance [22][23]. The mechanical properties of UTS on AA6101 were about 174.2 MPa

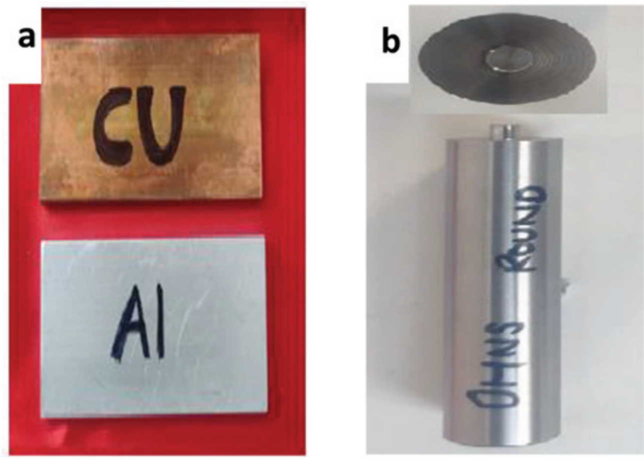

Fig.1. (a) Base plates cut with required dimensions; (b) FSW tool

and for C11000 was 248 MPa. The design of the base plates and FSW tools is shown in Figure 1.

During this experiment, three primary parameters selected were tool rotational speed (rpm), feed rate (mm/min), and tool pin offset (mm). After conducting the literature survey, the FSW input parameters were selected (three-levels and three-factors). The tool rotational speed (TRS) was (800, 1000, 1200 rpm), feed rate (FR) about (30, 40, 50 mm/min) and tool pin offset (TPO) of (-1, 0, 1 mm).

2.1 Design of Experiment (DOE)

Taguchi technique is a proficient problem- solving and quality optimization technique. This method was used in many industries to solve complex problems from the experimental design [24]. Also, this method decides the major effective input parameters by comprehensive execution. Taguchi uses an orthogonal array to lower the number of trials in which the combinations of experiments were not repeated; hence it is adopted for this research [25][26]. In this experiment, input process parameters such as tool rotational speed, feed rate, and tool pin offset were observed as the main factors influencing Al-Cu joints' quality. The nine-run with three factors and three levels was designed using MINITAB 19 software following Taguchi's experiments design (L9 - 3^3), which is given in Table 1 [27].

2.2. Experimental set up to carry FSW process and to perform mechanical properties test

The base plates AA6101 and C11000 were welded by the FSW process (Existing designed FSW machine) using the Hardened OHNS steel tool was shown in Figure 2(b). The Taguchi nine-run experiments were performed according to the design pattern from Table 1. From the literature reviews, all the trial runs were performed during this experiment by placing base plates of softer metal (AA6101) on the retreating side and harder metal (C11000) on the advancing side. The tool pin offset (-1 mm, 0 mm, and 1 mm) was set on the base plate joints, -1 mm (towards softer material), 0 mm (at the center of base plates), and 1 mm (towards harder material) was shown in Figure 2(a).

In this experiment, an average of two specimens were used for each trial run. The samples were cut by wire EDM method (Model DK7732 CONCORD, maximum workpiece thickness-500 mm, maximum speed-400 mm^2/min, and thickness of the wire (Molybdenum)-0.18 mm) according to the code ASTM E8-16a as shown in Figure 2 (c).UTS test was performed on the MTS Landmark servo-hydraulic systems machine (Model 370.25, Load frame capacity 250 kN).

In this experiment, Scanning Electron Microscope

Table 1: Taguchi L9 (3^3) pattern form with input parameters value and UTS value

Trial No	TRS (rpm)	FR (mm/min)	TPO (mm)	UTS (MPa)	%Elongation
1	800	30	-1	110	8.72
2	800	40	0	118.75	9.68
3	800	50	1	115.12	8.84
4	1000	30	0	124	10.24
5	1000	40	1	120.56	9.84
6	1000	50	-1	131.2	10.48
7	1200	30	1	92	7.92
8	1200	40	-1	102.06	8.48
9	1200	50	0	108	8.32

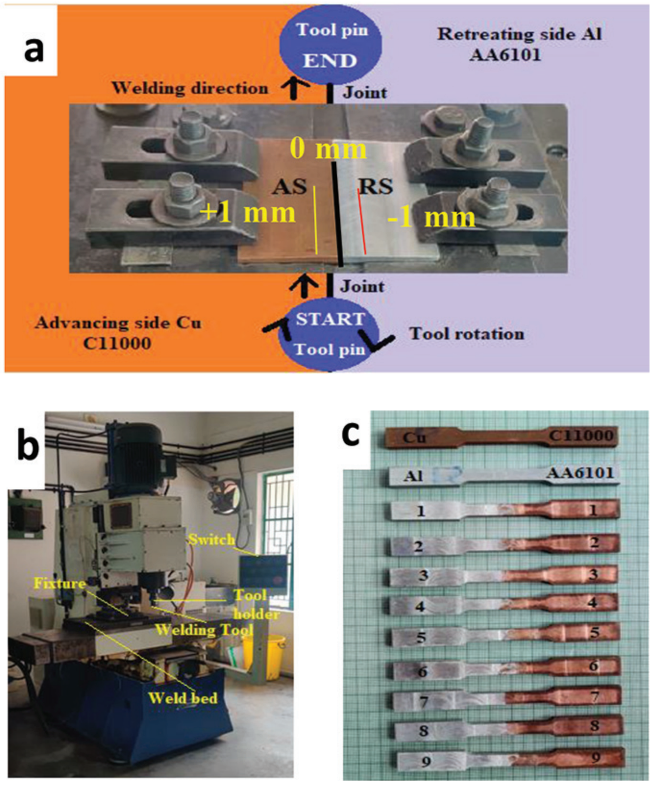

Fig.2.(a)Set up conditions (b) Existing designed FSW machine; (c) Sample preparation from wire EDM process for UTS test

(SEM) was used to observe the structural changes within Al-Cu joint area. The microstructure analysis was conducted from SEM (Model: TESCAN-VEGA3 LMU, Resolution-3.0 nm to 30 KV). X-ray diffractometer (XRD), generator 30 mA, 40 kV were used to analyse the existence of different IMCs within the joint area. The SEM and Energy-dispersive X-ray Spectroscopy (EDS) analyzed the weight percentage of obtained individual IMCs layers.

3.0 Results and Discussion

3.1. Analysis of Ultimate Tensile Strength (UTS)(MPa) Test

From the analysis of ANOVA, the tool rotational speed (rpm) had more contribution of about 79.94 %, followed by a feed rate (mm/min) of 11.76 %. Over the three input parameters, tool pin offset (mm) contributes very low percentage of 8.105 %, was shown in Table 4. Further, it was confirmed from the response table of SN ratios and means that tool rotational speed had rank one, followed by feed rate of rank two. Among these three input parameters, tool pin offset had rank three, shown in Tables 2 and 3.

Table 2: Response table for SN ratios

Level	rpm	mm/min	mm
1	41.18	40.66	41.12
2	41.95	41.10	41.34
3	40.04	41.42	40.71
Delta	1.91	0.76	0.64
Rank	1	2	3

Table 3: Response table for Means

Level	rpm	mm/min	mm
1	114.6	108.7	114.4
2	125.3	113.8	116.9
3	100.7	118.1	109.2
Delta	24.6	9.4	7.7
Rank	1	2	3

Table 4: Percentage Contribution of Input parameters on UTS from ANOVA analysis

Factors	Adj SS	% Contribution
Tool rotational speed (rpm)	910.75	79.94
Feed rate (mm/min)	134.00	11.76
Tool pin offset (mm)	92.34	8.105
Other error	2.11	0.185
Total	1139.19	100

Figure 3 (a) and (b), show the SN ratio and Means plot, it was detected that the tool rotational speed expands via 800 rpm to 1000 rpm and then decreases from 1000 rpm to 1200 rpm. The feed rate expands via 30 mm/min to 40 mm/min and again expands via 40 mm/min to 50 mm/min. Tool pin offset increases from -1 mm to 0 mm and decreases from 0 to 1 mm. Hence tool rotational speed of 1000 rpm, feed rate of 50 mm/min, and 0 mm tool pin offset was the best welding parameters to achieve a maximum UTS.

3.2 Effect on Ultimate Tensile Strength (UTS)

Figure 4 (a), (b), and Figure 5 (a), (b) show the axial force vs axial displacement and stress vs strain curve for medium and high tool rotational speeds 1000 rpm and 1200 rpm.

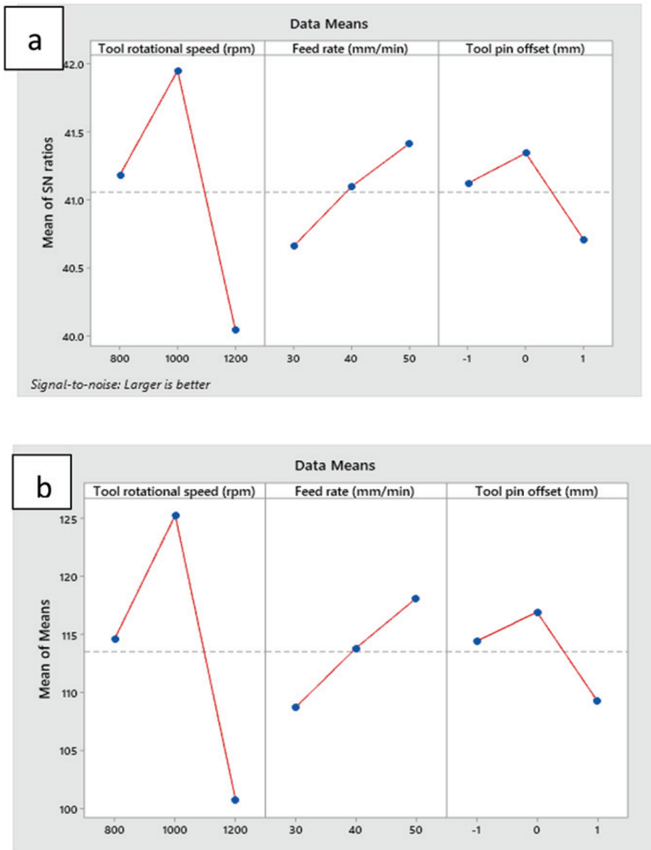

Fig.3.UTS, Main effects plot (a) SN ratios; (b) Means

At low 800 rpm tool rotational speed, 30 mm/min feed rate, and -1 mm tool pin offset towards softer metal (AA6101), UTS was found to be 110 MPa. This movement is because of low heat generation at the Al-Cu weld joint area and improper mixing account for low-quality joints. At medium 1000 rpm tool rotational speed, 50 mm/min feed rate, and -1 mm tool pin offset towards softer metal (AA6101), the UTS was found to be 131.2 MPa, and % Elongation was 10.48, which causes easy deformation from Al to Cu side. Also, high-strength Al pieces move towards the Cu bulk matrix and cause proper mixing. The and stress-strain curve under high tensile force as seen in Figures 4 (a), and (b). This movement is due to medium heat generation at the Al-Cu weld joint area and the absence of surface groves. At maximum 1200 rpm tool rotational offset towards harder metal (C11000), the UTS was found to be 92 MPa, % Elongation 7.92. This movement is because Cu metal is hard to deform and the material trend towards the Al matrix when the high temperature occurs near the Al-Cu joint. Also, owing to improper mixing near weld joints, the fluctuation in the displacement curve with low tensile force act on the sample which was shown in Figures 5 (a), and (b). The ultimate tensile strength (MPa) of the Al-Cu FSW joint increases when medium tool rotational speed, feed rate, and tool pin offset towards softer metal. The UTS of the Al-Cu weld joint decreases at low and high tool rotational speed.

In the FSW process, during the stirring action of the tool, which causes a metallurgical response, a distinct intermetallic compounds (IMCs) substrate was developed on Al-Cu joints. The formation of these IMCs depends on tool rotational speed. As the rotational speed increases the huge number of IMCs with larger thickness formation affect the Al-Cu FSW joints. Figure 6(a) reveals the diffraction model of the tensile test fractured sample to identify phase composition (IMCs) from the XRD examination. It was found that the most

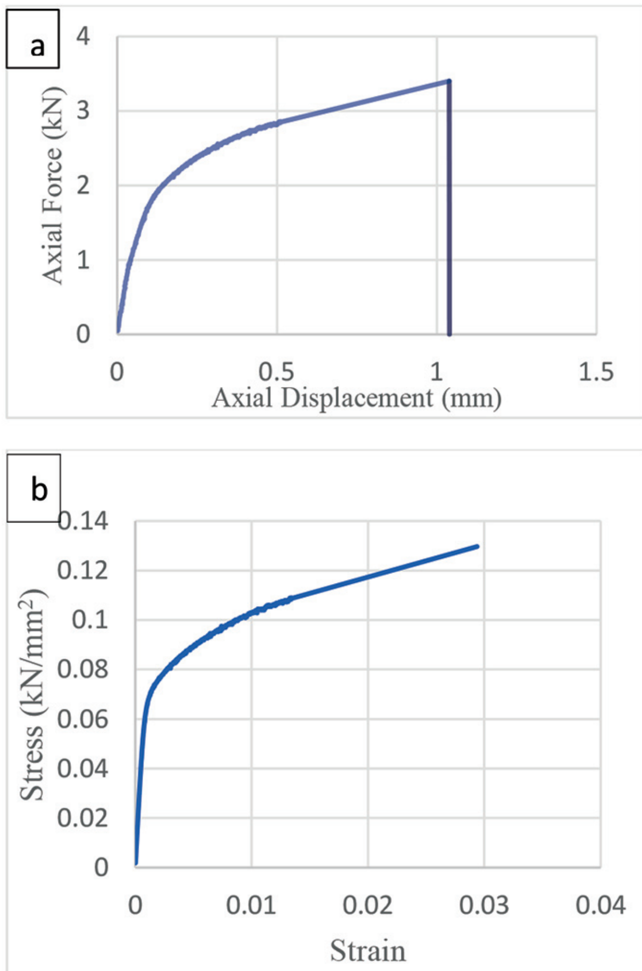

Fig.4. For 1000 rpm,50 mm/min and -1 mm (a) A.force vs A.displacement curve; (b)Stress vs Strain curve

common IMCs were $A_{14}Cu_9$ and Al_1Cu_3 on Al and Cu joints during the FSW process will execute a strong metallurgical bonding leading to maximum joint strength. Further, among these two IMCs, Al_4Cu_9 formed was high in percentage than the Al_1Cu_3. This substantiates from the SEM and EDS analysis was revealed in Figure 6(b), Figures 7(a) and (b). The Al (%) and Cu (%) of the IMCs at the Al-Cu joint area were displayed in Table 5.

From the contour plots, it was observed that the gloomy red colour shows the highest UTS and the gloomy black colour shows the low UTS as shown in Figures 8 (a), (b), and (c).

Table 5: EDS point analysis

Selected area	Cu %	Al %	Phase formed
1	72.32	27.68	Al_4Cu_9
2	65.51	34.49	Al_1Cu_3

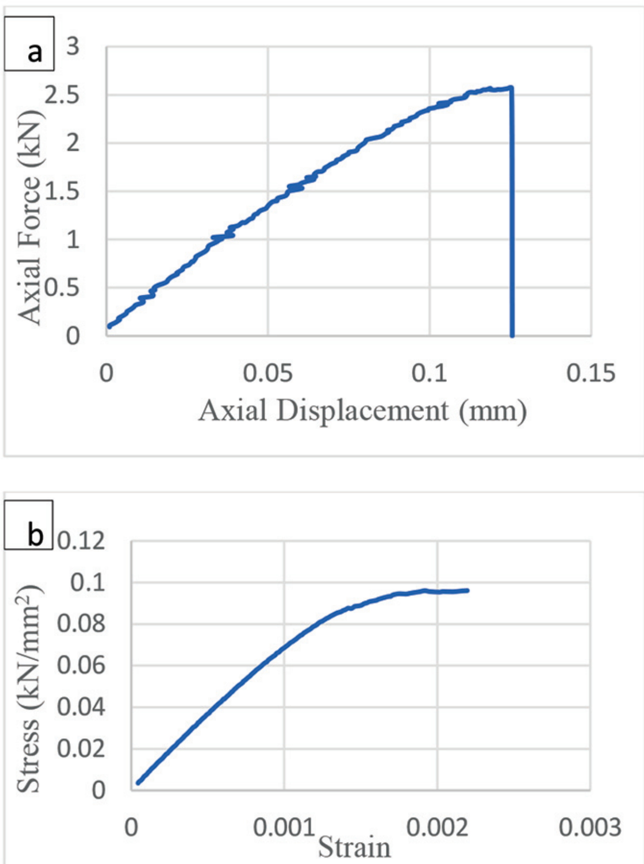

Fig.5 For 1200 rpm,30 mm/min and 1 mm (a) A. force vs A. displacement curve ;(b)Stress vs Strain curve

3.3 Analysis of SEM studies on tensile strength test fracture samples

The surface analysis of fracture of the nine samples indicates an increase in brittleness or from ductile and ductile-brittle mixed fracture to brittleness from low

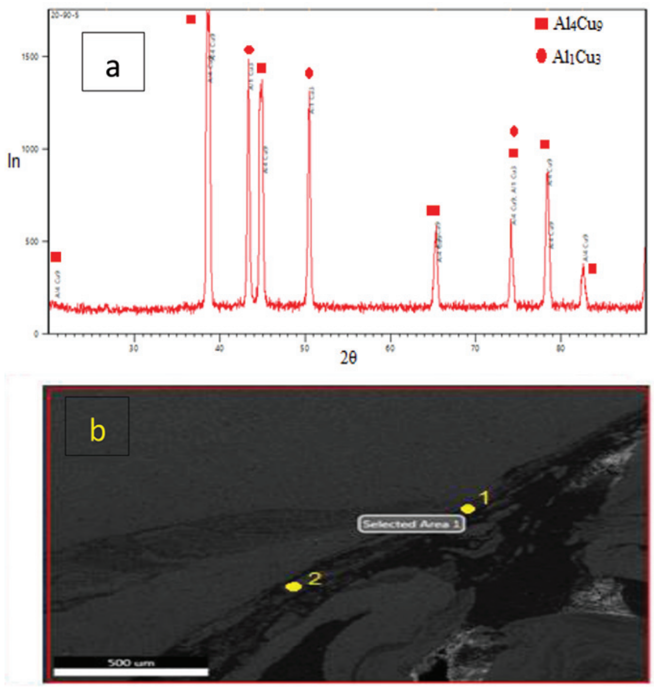

Fig.6.XRD analysis of fractured surface for phase identification; (b) SEM analysis

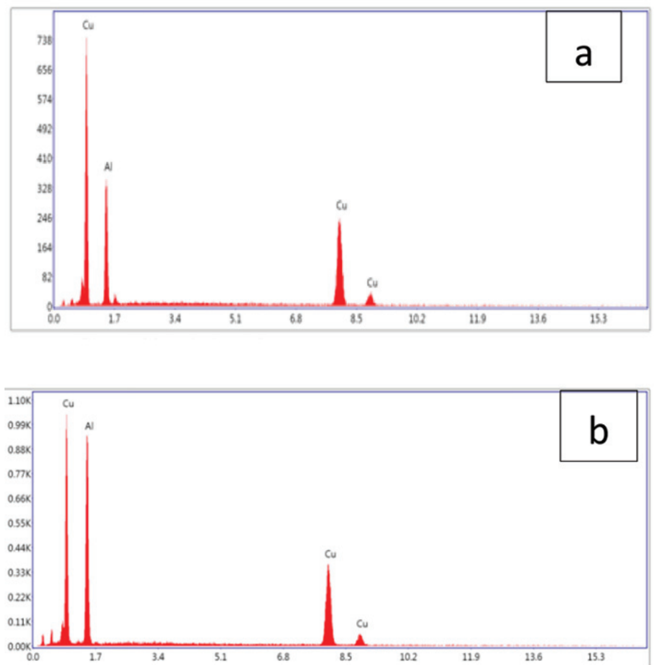

Fig.7: EDS analysis of IMCs (b) at point 1 (c) at point 2

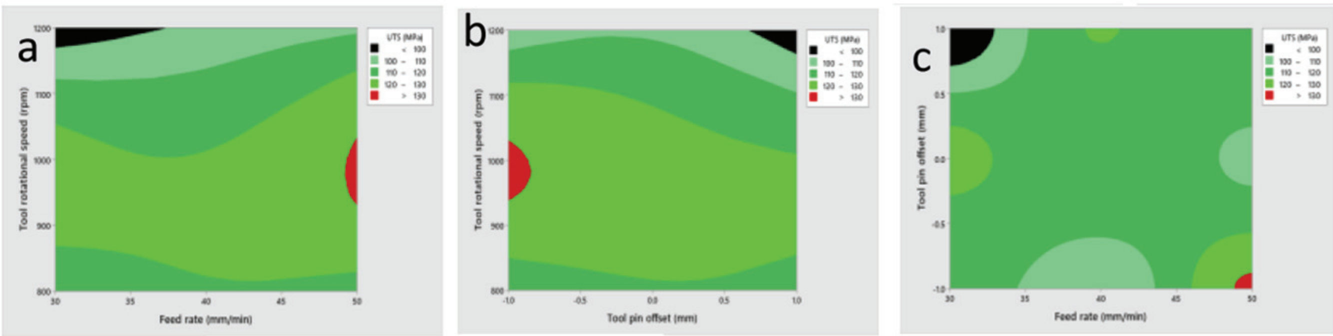

Fig.8. Contour plots for UTS (MPa) (a) rpm vs mm/min; (b) rpm vs mm; (c) mm vs mm/min

to high tool rotational speed. Figures 9 (a), and (b) indicate the fracture surface of Al-Cu FSW joints for the highest and lowest tensile strength test (trial 6 and trial 7), respectively. At medium tool rotational speed 1000 rpm, 50 mm/min, -1 mm tool pin offset, it was observed that cup and cone style ridges. In addition to the small cleavage-like features, dimples of a large number of different sizes were seen on the fracture surface. The fracture surface mechanisms had the ductile-brittle approach was shown in Figure 9 (a). At higher speed 1200 rpm, feed rate 30 mm/min, tool pin offset 1 mm. In this case, almost flat cleavage, which indicates the weld sample failed through brittle fracture was shown in Figure 9 (b). As the tensile force increases, the small cracks formed in the joint area and expand immediately, these tiny holes and ruptures cause start the crack generation over tensile fracture of the sample which shows brittle fractures. The development of brittle IMCs at the weld joint area was the foremost important cause for the tensile test samples of low ductility. Other factors, such as the heat input, non-uniform structure, and impurities at the weld region, firmly act on the failed sample's aspect. Also, tiny cracks of different sizes and shapes and large dimples can be observed on the welded joint's fracture surface. Further, the formation of dimples reduces the ductile nature of the samples and weakens the weld joint area. From this research work, when tool rotational speed (rpm) expands, samples failed from first ductile- brittle disparate fracture to brittle fracture. Accordingly, further the generation of IMCs brittleness, weld defect was the direct cause for the exact reduction in UTS (MPa) and % elongation. It was concluded that when the tool pin offset -1 mm (softer metal), medium tool rotational speed (rpm), the Al-Cu FSW joint becomes a ductile-brittle mixed fracture approach with a maximum ultimate tensile strength (UTS).

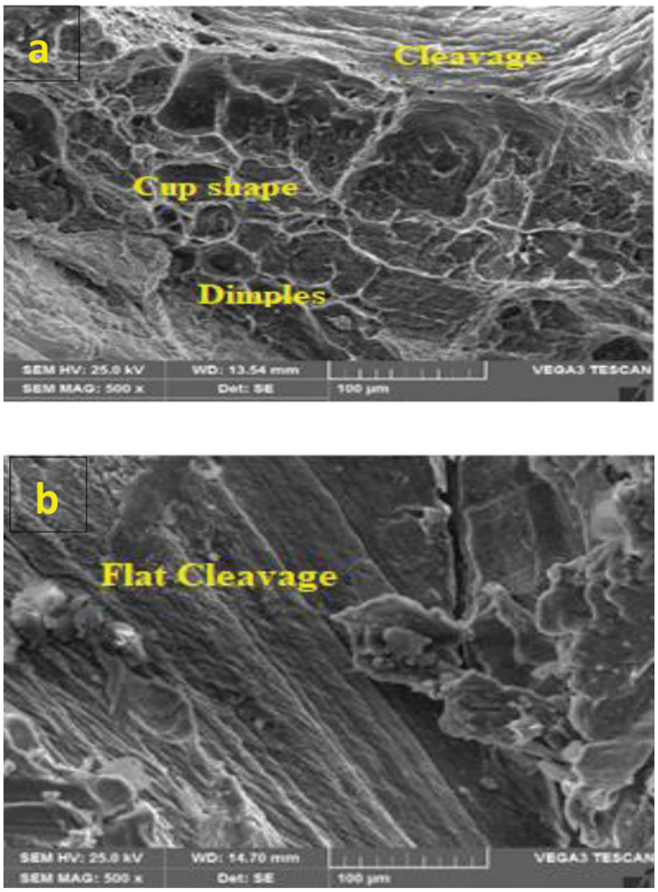

Fig.9. SEM analysis of fracture surface (a) Medium 1000 rpm; (b) High 1200 rpm.

4.0 Conclusions

The experiments were directed to manufacture butt joints of AA6101 and C11000 by FSW process using distinct levels of input parameters from the design of Taguchi L9 OA (orthogonal array). The outcomes of the experimental approach were analyzed using ANOVA. The following observations were obtained from this research:

1. From the experimental approach, at 1000 rpm tool rotational speed, 50 mm/min feed rate, and -1 mm tool pin offset will have the highest UTS was about 131.2 MPa (75% of the Al base plate). From the optimization method, 1000 rpm, feed rate 50 mm/min and tool pin offset 0 mm will attain high joint strength.
2. From the ANOVA analysis, tool rotational speed encounters high significant effects upon UTS, about 79.94 %. The feed rate (mm/min) has medium significance effects on UTS of 11.76 %. The tool pin offset (mm) will have the least significance on output parameters. Further from the response table of SN ratios and means for UTS, tool rotational speed had rank one, feed rate rank two, and tool pin offset rank three. The tool pin offset had significantly less effects on UTS.
3. SEM studies of the fracture surfaces showed that when medium tool rotational speed 1000 rpm and tool offset towards softer base plate. The failure approach was a ductile-brittle character, and the UTS obtained was high. Although, the ultimate tensile strength was decreased at tool pin offset about the more complex base plate and high tool rotational speed of 1200 rpm. In this case, the failure approach was a brittle character.
4. In this research, the Taguchi method helps lower the number of trials to find optimum input parameters for tool rotational speed, feed rate, and tool pin offset for quality weld Al-Cu FSW joints. During this research, the contour plots study displays the effect of three process parameters, including tool rotational speed, feed rate, and tool pin offset upon UTS for Al-Cu FSW joints.
5. To obtain the Al-Cu rigid joints, the FSW carried with the conditions that the tool pin offset towards softer material can be slightly increased, rotational tool speed can be lowered with increasing feed rate with appropriate tool tilt angle.

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