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Impact of Process Parameters on The Friction Stir Butt Welded Aa6061 – Cu Joint Strength

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Abstract – Friction Stir Welding (FSW) is a technique for welding similar and different materials in solid-state joining. FSW is best suited for joining Al alloys sheet and this process allows continuous welding of a different set of materials. In this study, three different tool rotational speeds (710, 900, 1120 rpm), three special tool traverse speeds (20, 50, 100 mm / min) and different tilt angles (00, 1.50) are welded with AA6061 and 90% pure Cu. The impact of the welding parameters on the joints microstructure and mechanical properties was investigated. Tensile and micro hardness are monitored to analyze the mechanical properties. The weld zone microstructures are examined using an optical microscope and Scanning Electron Microscope (SEM) and analyzed using an Energy Dispersed Spectrometer (EDS). Inter-metallic phases are identified using X-ray diffraction (XRD) analysis. With 710 rpm tool rotational speed at 710 rpm, 100 mm / min traverse speed and 1.50 tool tilt angle, the best level to obtain optimal output values. The higher quality of the tensile is attributed to the dispersion of the fine Cu particles circulating over the Al material in the stir zone.

Index Terms – Friction Stir Welding, AA6061, Cu, Mechanical Properties and microstructure.

1. INTRODUCTION

The Welding Institute UK (TWI) invented and patented Friction Stir Welding (FSW) in 1991 [1]. FSW as a solid-state joining process has gotten an extensive measure of noteworthiness on account of its central focuses, for instance, giving good mechanical properties and quality joints especially with aluminum alloys [2, 3, 22]. Compared to conventional welding methods, FSW has many advantages as it will not generate distortion, porosity and hot cracks in the middle of the joining [4, 5]. It will convey Very good quality welding joints with aluminum, magnesium, titanium, copper and steel materials. Recent studies on joining diverse dissimilar materials have been done [6, 8]. In light of its various applications like in the fields of chemical, nuclear, aeronautics, transportation, power generation, and electronic industries getting exact joining of dissimilar materials is important [9,10].

Cu and Al have various applications in the electrical industry on account of their incredible electrical and thermal conductivity, high corrosion resistance, and mechanical properties. Various examinations have been directed to join these two materials for its utilization in high-voltage and direct current distribution lines, and the particular techniques of joining these two materials have transformed into an investigation subject [11]. In any case, due to the wide difference in melting point and physical properties of aluminum and copper thereby encircling hard and brittle inter-metallic compounds (IMCs), it is greatly difficult to join these two materials by fusion welding. Thusly, solid-state joining methodologies have become much thought. These methodologies have few disadvantages in any case. For example, friction welding and roll welding can't produce a high variety of joints, and there are some safety issues drew in with explosive welding [12].

A few examinations have been done to discover on the impact of FSW process parameters of joining disparate aluminum and copper on the microstructure and mechanical properties in the weld zone and the divulgence of between metallic stages that happens in the weld zone [5, 13, 17]. Indeed, in both butt and lap joint configurations, several studies have kept an eye on the dissimilar friction stir welding of these materials. Regardless, Al-Cu's lap joining has been generously researched more than friction stir butt welding, for which only a few tests have been conducted up to this point [8]. In this examination, AA6061 with a thickness of a 3 mm is friction stir butt welded to 90% copper sheets at three particular tool rotation speeds (710,900,1120rpm), three different tool traverse speeds (20,50,100 mm/min), and different tool tilt angles (0^0,1.5^0) finally, the mechanical and micro structural properties of the joint were evaluated.

2. MATERIALS AND METHODS

Commercial copper (90%) and 6061 aluminum alloy plates with a thickness of 3 mm were taken for joining by FSW. For that 100x100mm dimensions were taken. In table no 1 the main mechanical properties of the materials that are used in this study were given.

Table 1. Mechanical properties of AA6061 and 90% Copper

Properties	AA6061	Copper (Cu)
Tensile Strength (MPa)	310	210
Elongation (%)	17	41.03
Hardness (BHN)	95	135

The fixation of the two on the fixture materials should be such that they do not separate during the process and the leaning of hard material should be on the other side of the retreat as shown in Fig. 1.

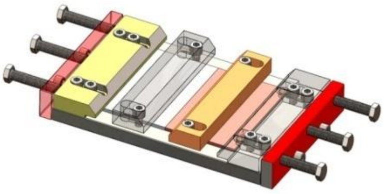


Fig.1. Schematic Representation of the Fixture

Here H13 tool with hardness more than work materials is chosen to stay away from the damage of the pin because of corrosion and chipping off amid task. Heat treatment is done to the tool pin and accomplished a hardness estimation of 62HRc. Using a cylindrical tool with a 2 mm height square pin and 3 mm favor an 18 mm shoulder. By doing the preparatory investigations the welding parameters are resolved and the course of rotation of tool is made steady as the welding parameters are controlled by preparatory clockwise.

Preparatory examinations were performed to discover the importance of the situation of the two materials and different info welding parameters were resolved and appeared in Table 1.2. The classification embraced in the content for demonstrating distinctive welds were related to welding condition. For instance, 710/50/1.5^0 means 710 rpm of rotational speed, 50 mm/min of feed and 1.5^0 of tool tilt angle respectively. Welding was completed by changing the process parameters with a specific end objective to achieve a solid welded joint. Although numerous welded joints were appeared to be great at a macro level there were cracks in the micro level in a few joints as appeared in Fig. 2. The voids and not entirely shaped welding cause low mechanical strength qualities in the welded parts and low micro hardness. Thusly we can state that a portion of the welded joints were not framed completely. Afterward, the examinations were preceded by changing the process parameters.

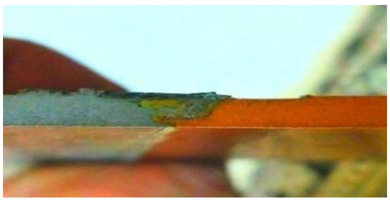


Fig. 2. Defect free Macro level Weld cross section

Table 2. Al – Cu Welding Parameters in Friction Stir Welding (FSW)

Tool Rotational Speed (rpm)	Tool Traverse Speed (mm/min)	Tool Tilt angle
710-900-1120	20	0^0
		1.5^0
	50	0^0
		1.5^0
	100	0^0
		1.5^0

The tensile specimens were extracted from the weld joint and tested according to ISO / IEC 17025:2005 guidelines using an electromechanically controlled universal testing machine. The strain rate was 2 mm/min. Micro-hardness measurement was made from the upper surface of specimens that was perpendicular to the welding section. The measurement was taken at 1 mm below the top surface. Sanding process was performed on the samples taken from welding cross-sections with grit no P220 to P1500 according to ISO6344 grit designation to detect the micro structural changes in the weld zone. The welded area was polished with 3 µm and 1 µm diamond paste and etched. In the etching process; 50 mL of distilled water and 50 mL of nitric acid were used for the Cu side; Keller’s solution was used for Al side, after that the examination of weld zones were carried out with scanning electron microscope(SEM) images in DRDL, Hyderabad, analysis of X-ray diffraction was performed to examine the phase in the weld zone and point and linear EDS(energy dispersed spectrometer) analysis was done to determine the elements in the weld zone and some macro structure images were also taken for detecting the big size voids.

3. RESULTS AND DISCUSSION

Welding cross-section and best weld surfaces of two distinctive weld parameters were photographed and their pictures appeared in Fig. 3. and Fig. 4. By seeing the two surface images the variation in surface finish and mixing of materials can be watched effortlessly. Welding defects like cracks, gaps, and holes were not found on the majority of the welding surfaces, in fact, in Figure 1.4 the weld surface was exceptionally smooth and very much characterized striations were seen in like Cu-Cu FSW consider by Galvão et al. [8]. For welding process, 1120/100/0^0 weld defects were there even though both 710/100/1.5^0 and 1120/100/0^0 have been welded under similar welding conditions. This distinction is because of the high heat contribution to 1120/100/0^0 amid FSW. This outcome is in comparable condition to consider done by Leitão et al. [18] who considered the impact of work material properties on defect formation during FSW of AA5083 and AA6082.

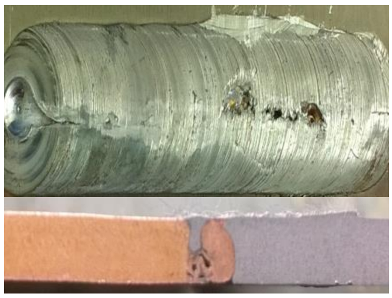


Fig.3. Macrograph of the welded part under 1120/100/0^0 conditions: (a) Upper surface (b) Cross section.

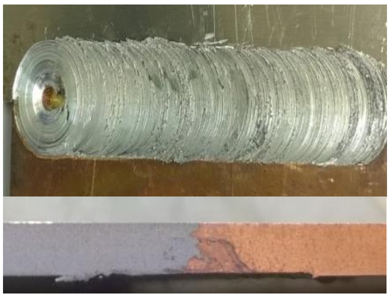


Fig. 4. Welded part macro-images under 710/100/0^0 condition (a) Upper surface; (b) Cross section.

By comparing the macrographs of cross-sections of the two welds shown in Fig. 3 (b) and Fig. 4(b) important contrasts in the morphology and structure also possible to observed in welding area. The Fig. 3(b) of 1120/100/0^0 weld demonstrates that the association zone of this weld is in only the pin influence zone and a confirmation of low mixing by the pin can be observed the inefficient mixing of copper and aluminum comes about a substantial discontinuity which making the ineffective joining of the sheets. In fact from Fig. 3, the joining of the two materials happened only at the advancing side of the tool. Here the advancing side material is copper, along these lines, the aluminum is pushed toward copper. From Fig. 4(b) the macrograph cross-section of the 710/100/1.5^0 weld it can be observed that the aluminum and copper interaction volume for the 710/100/1.5^0 weld is larger than that observed for 1120/100/0^0 weld.

The tensile test specimen is shown in Fig. 5, the tensile strength test consequences of different rotational speeds are appeared in Fig. 6, 7 and 8. The tensile strength estimations of base materials AA6061 and Cu were observed to be 310 MPa and 210 MPa individually. As found in the tensile strength graph the most astounding tensile strength acquired with the parameters 710/100/1.5^0 and esteem is observed to be 135.36 MPa and the least esteem is 55.5 MPa in the 1120/100/0^0 specimen. Analyzing the variations in Fig. 6, the tensile strength was increased when tool feed is increased from 20 mm/min to 100 mm/min and with some tool tilt angle for the consistent turn speed of 710 rpm. Additionally, for 900 rpm by expanding the feed tensile strength was expanded up to 50 mm/min past that strength was diminished for 100 mm/min feed. Also, it is presumed that tensile strength esteems were diminished with the expansion in tool rotational speed. Higher strength esteems were acquired with low speed, high feed and with some tool tilt angle. Since these conditions prompt adequate welding width and adequate stirring of materials.

The most elevated strength values in welded parts came at 710 rpm rotational speed as appeared in Fig. 6. Perfect temperatures happened in Al – Cu FSW at this rotational speed, so that a thinly dispersed and homogeneous mixture is gotten. The strength of inter-metallic phase increments with the impact of heat during FSW, however, it won't be brittle, and this accommodates with the literature [13, 14].

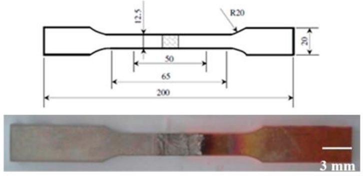


Fig. 5. Dimensions and Macro Image of the Tensile Specimen

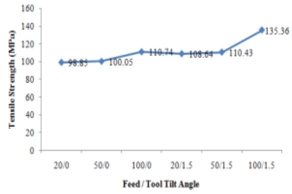


Fig. 6. Tensile test results of 710 rpm

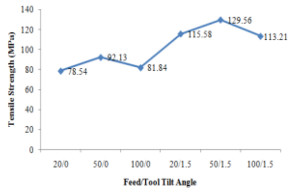


Fig. 7. Tensile test results of 900 rpm

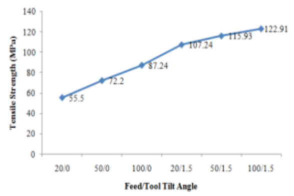


Fig. 8. Tensile test results of 1120 rpm

Fig. 8 shows the studies with the highest rotational speed (1120 rpm), and it is observed that the tensile strength of the welded part is rapidly increased with the tool tilt angle to low feed and the strength decreased with increased traverse speed. High tensile strength was gotten as can be found in Fig. 8, and 122.91 MPa of tensile strength is obtained with 20mm/min traverse speed and 1.5^0 tilt angle. The tensile strength value is observed to decrease below the high traverse speed (100 mm / min) and 0^0 tilt angles. The reason for this is the lack of development of any homogeneous mixture area in the weld zone and the lack of optimum temperature for the joint. It is also viewed as expanding the thickness of inter-metallic phases under high traverse speeds (100 mm / min) due to high heat contribution.

The increased tensile strength of the Al-Cu weld joints depends primarily on the circulation of fine Cu particles and the development of low inter-metallic thickness and grain boundaries in the nugget zone. The Cu particles were divided from the Cu side and appropriated in the stir zone due to the stirring produced by the tool. Due to the interfacial reaction with the Al matrix [5, 19], these fine Cu particles were completely transformed into hard fragile inter-metallic. The tensile tests as a whole demonstrate that there is satisfactory temperature during FSW thus the homogeneous blend conditions prompting an Al-Cu reaction are come to. Because of tensile tests, breaks for the most part happen in weld zone and heat influenced zone (HAZ) in aluminum welds. In the literature, the explanation behind Al side's ruptures is clarified by the factor that the base material Al's tensile strength is lower than the other base material Cu [11]. For the assessment, ruptured surfaces of the specimens with the highest and lowest tensile strength are considered. SEM images are shown in Fig. 9 and 10 of the cracked surfaces. When analyzing the SEM images, it is inferred that the specimen's ruptured surface (Fig. 9) with higher mechanical properties is ductile, while the other specimen (Fig. 10) is weak. The $1120/100/0^0$ specimen contains numerous dimples on the Al side of the break surface and a small measure of dimples on the cracked surface of the $710/100/1.5^0$ specimen. Three-point bending tests are carried out on the specimens cut from the welded joints in 20 x 100 mm dimensions with a wire cut EDM. Images tested for the base materials can also be found in Fig. 11(a). The welded samples will be loaded until a U-shape is taken or a failure is observed. As shown in Fig. 11(b), after the bending test, there is no failure on the $710/100/1.5^0$ specimen. On the other hand, fractures and failures occur in HAZ and welded areas, especially on specimens with low tensile strength. On the transverse cross-sectional area of welded parts, hardness values are evaluated. Hardness values are represented in Fig. 12–14 from the top surfaces of different parameters. The base metals micro-hardness estimates were 150 HV for Cu and 105 HV for Al.

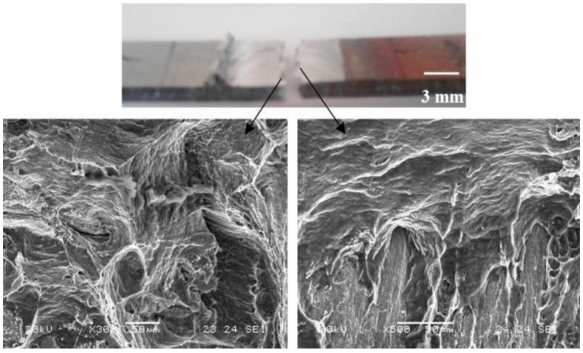


Fig. 9. Surface images after tensile tests and scanning electron microscope (SEM) images of ruptured surface of welded joints in the $710/100/1.5^0$ specimen

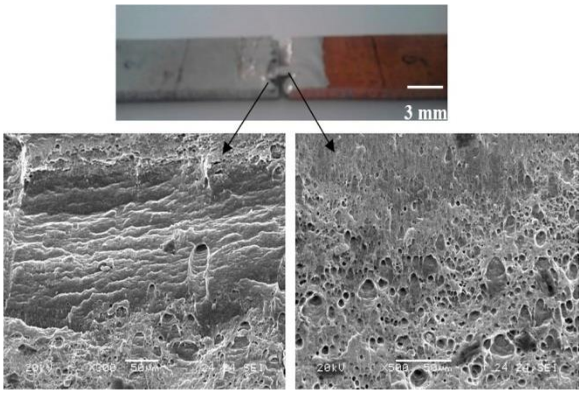


Fig. 10. Surface images after tensile tests and SEM images of ruptured surface of welded joints in the $1120/100/0^0$ specimen

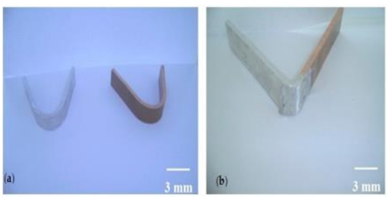


Fig. 11. Bending test results of (a) base materials, (b) welded part

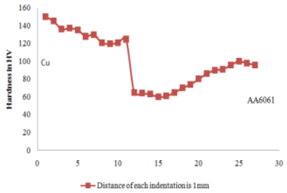


Fig. 12. Hardness profile of the $1120/20/0^0$ transverse cross section

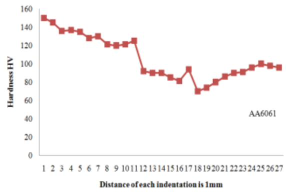


Fig. 13. Hardness profile of the$710/100/1.5^0$ transverse cross section

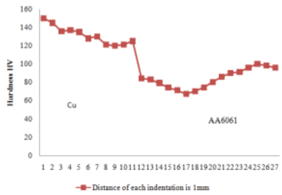


Fig. 14. Hardness profile of the $900/50/1.5^0$ transverse cross section

In Fig. 12, it is observed that the formed weld zone is significantly thin when analyzing the hardness changes of the specimen $1120/100/0^0$, which has high rpm and low traverse speed. Accordingly, the data in Fig. 13 and 14 shows that specimens with low and medium traverse speeds ($710/100/1.5^0$ and $900/50/1.5^0$) have higher tensile strengths and form larger welded areas compared to the $1120/100/0^0$ specimen. A wide welding zone shows that the full mix of materials exists. The sudden increase in hardness values in the welding zone is considered due to the inter-metallic phases between Al-Cu affected by heat during the welding process. The composite structure's hardness values were significantly higher than those of the Al side. This improved Al matrix hardness should be predominantly attributed to the ultrafine grain reinforcement. This high durability estimation of the layered structure therefore started primarily from the Al-Cu IMCs.

In this study, all specimens are examined in detail in the microstructures of HAZ on the Al side, Cu side, and weld zones. Through these studies, a uniform blend (appeared in Fig. 4(b)) with low velocity and high feed with some tool tilt angle is discovered to form the weld zone. In addition, in Al-Cu FSW joining, the composite structure between aluminum and copper is remarkable.

The microstructure of the specimens with the most noteworthy and least tensile strength was taken with a specific end goal to compare and evaluate strength changes and structural changes in weld zones. In Fig. 15(a) 15(b), the microstructure of base materials is delineated, the microstructure of the specimen is given in Fig. 16 and 17 represent the microstructure of the $710/100/1.5^0$ specimen.

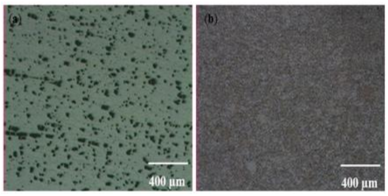


Fig. 15 Microstructures of base materials:
(a) AA6061 & (b) Cu

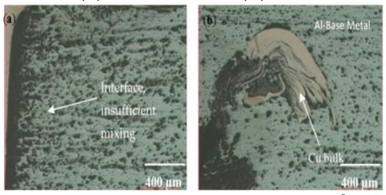
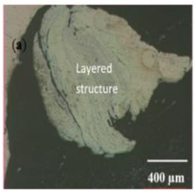
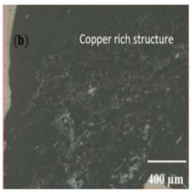


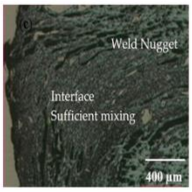
Fig. 16 Welded zone of the 1120/100/0^0 specimen:
(a) Al side & (b) Nugget Zone



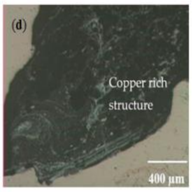
(a) Al side top area



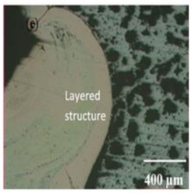
(b) Al side mid-area



(c) Weld Nugget



(d) Al side bottom area



(e) Al base material transition
Fig. 17 Welded zone of the 710/100/1.5^0 specimen

The material flows at the front end of the tool from the forward side to the retreating side. That makes the advancing side a vacancy. The materials are transported from the retreating side to the forward side at the rear end. If the transported material is not large enough to fill the vacancy, there will be a tunnel defect. The low material flow is observed under the 1120/100/0^0 parameters due to rapid mixing prompts copper to leave the weld zone. As can be seen in Fig. 16(a) & 16 (b), cavities and inadequate blend are observed, and these are the reasons that clarify the low strength values.

Fig. 17 shows the microstructure image of the Al-Cu interface. The perfect extent of heat was adequate to plasticize the Cu material close to the area of the interface. In this way, the fine irregular Cu particles were detached and appropriated in the stir zone. There was a prominent interface between the Al matrix and the Cu bulk, and under the Al-Cu interface a layered structure could be found in the Cu bulk. Fig. 17(a) & 17(d) shows the intensified view of the Al matrix-Cu bulk interface. As shown in Fig. 17, there was a clearer nugget zone that contrasts with the 1120/100/0^0 low tensile specimen. Moreover, the homogeneous distribution of Cu bulk in Al extended the mechanical properties of the 710/100/1.5^0 specimen.

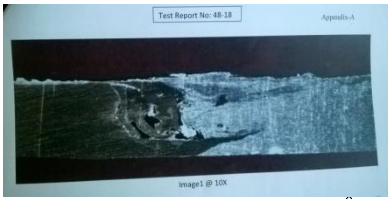


Fig. 18 Welded zone of the 1120/100/0^0 specimen

The mixture was not fully formed at the time when the SEM images of welded zones are evaluated, as shown in Fig. 19(a) and only a small portion of this occurred in the Al side for the 1120/100/0^0 specimen. Again, Fig. 19(b) states that for the 710/100/1.5^0 specimen, which has a higher tensile strength value, the blend occurred at the desired level in the Al side. Following a point and linear analysis of the EDS shown in Fig. 20 & 21, it is observed that the concentration of Al and Cu at zone no. 1 in 1120/100/0^0 is low, as shown in Fig. 20. In contrast, Al and Cu concentrations were found to be dense in the 710/100/1.5^0 specimen in zone no.1, as shown in Fig. 21, and EDS analyzes are shown in Fig. 20 & 21. In comparing the EDS analysis of the 1120/100/0^0 and the 710/100/1.5^0 specimens, it is observed that the quantity of copper was lower and that the mixture of materials was not ample enough in the 1120/100/0^0 specimen with a lower tensile resistance. The lack of a full blend between Al-Cu and the high warmth input are the explanations for the low rigidity that was gotten from the joints with a 1120 rpm rotational speed, appeared differently in relation to other apparatus rotational rates (710 and 900 rpm). Furthermore, adequate warmth input and the making of a composite structure between Al-Cu are the contentions for achieving high tensile strength after the welding with 710 rpm instrument rotational speed, appeared differently in relation to pliable characteristics that were gotten from welding with paces of 1120 and 900 rpm. The mechanical properties resulting from rotational speeds of 900 rpm are slightly lower than 710 rpm. Due to the increase in heat input and the formation of more inter-metallic compounds at the Al-Cu interface, the fragility is increased and the cause of the decrease in tensile strength is considered. As shown in various investigations [5, 12], there is a decline in the joint's tensile strength with the increase in inter-metallic phase thickness.

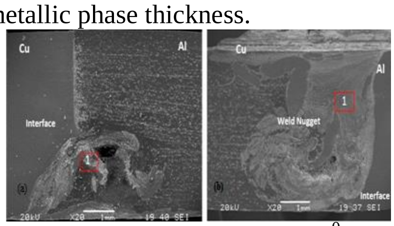


Fig. 19 SEM images of (a) 1120/100/0^0 specimen &

(b) $710/100/1.5^0$ specimen

The literature shows that inter-metallic phases like Al_2Cu, Al_4Cu_9, Cu-Al, Al_2Cu_3, and $AlCu_4$ will occur with the aluminum-copper temperature increase. Phases of Al_2Cu occur at 150^0C, while phases of Al_4Cu_9 occur at 350^0C. The strength of the bond shows a sharp decline [5, 20] at the point when the inter-metallic stage reaches 10 μm in thickness. The XRD investigation was carried out with a view to the final objective of determining the inter-metallic phases that may occur in the weld zone due to the high mechanical properties. Temperature and holding time depend on the thickness of the inter-metallic compound layer. The nuclear dissemination of Cu and Al through the inter-metallic compound is the guideline controlling technique for the development of inter-metallic compounds [12, 21]. The investigation leads to the analysis of Figure 1.22 and according to the literature, the inter-metallic phases $CuAl_2$ and Al_4Cu_9 are determined in the weld zone.

The normal temperatures estimated from the welding zones extended around 300^0C and 461^0C depending on the welding parameters during the friction stir welding process. These temperature values, as determined by XRD investigation, are adequate for the development of Al_2Cu and Al_4Cu_9 phases in most parameters. Depending on welding parameters, changes in the strength values of welded specimens are explained by the differences in temperature in the weld zone. The material's elasticity at low temperatures cannot be achieved with the objective that an additional homogeneous weld zone cannot be achieved. On the other hand, due to the increase of inter-metallic phases, brittleness is formed at high temperatures. According to the literature studies, the lowest tensile strengths in the welding zone were below the $1120/100/0^0$ with the highest temperature value (300^0C). It is observed that there is not enough heat created for the Al_4Cu_9 stage development. In addition, a decrease in tensile strength is observed as the thickness of the inter-metallic phases is increased under the $900/50/1.5^0$ parameter, which reaches the highest temperature (461^0C).

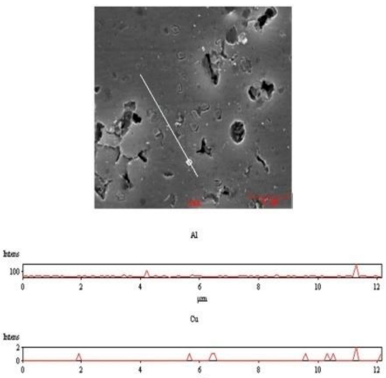


Fig. 20 Energy dispersed spectrometer (EDS) linear analysis ($1120/100/0^0$ specimen, zone No. 1)

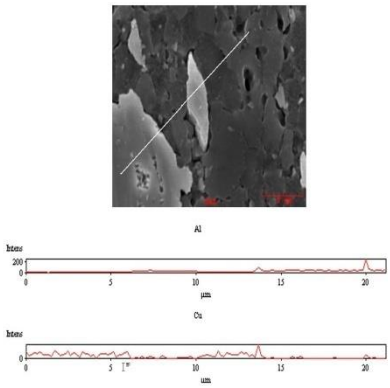


Fig. 21 EDS linear analysis
($710/100/1.5^0$ specimen, zone No. 1)

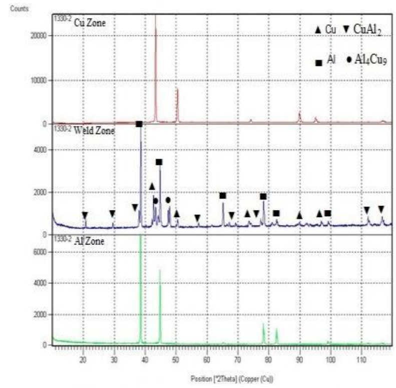


Fig. 22 X-ray diffraction (XRD) graphs of base materials and weld zone

4. CONCLUSIONS

- In this investigation, the friction stir butt weldability of 90% Cu and AA6061 alloy was inspected, and it was effectively refined under various parameters by utilizing a square pin tool. Disappointments were seen in the welding that has a fast condition. Macro-level welding abandons were not seen on the welded surfaces on account of joints of low strength likewise however, micro-level holes were seen in low tensile strength examples.
- Tensile and bending tests, and also hardness estimations, were made with a specific end goal to decide the mechanical properties of joints. At the point when the welding execution of joints was assessed, the greatest esteem was observed to be 64% with a 710 rpm tool rotational speed, a 100 mm/min navigate speed and a 1.5^0 tool tilt edge design. Because of the tensile test, it was watched that bursts for the most part happened in joint zones.
- Because of the layered structure of Al-Cu in the weld focus and inter-metallic stages, an increase in durability was observed in the weld zone. This had the impact of mixing particles that were moving in the withdrawing side from the copper in the propelling side into the aluminum network. The Cu mass in the Al network and inter-metallic stages expanded in hardness as the weld zone was framed on the Al side. The weld zones were seen to be larger in examples of high tensile strength.

- According to point and straight EDS examination, Al and Cu were distinguished on the cross areas and crack surfaces of joints that were gotten after tensile tests. The Cu content in the weld zones was observed to be lower in examples with low tensile strength compared to high tensile strength examples.
- $CuAl_2$ and Al_4Cu_9 inter-metallic stages were resolved in the stage investigation that was performed utilizing X-beam diffraction (XRD). Delicacy and strength were reduced by the expansion of the inter-metallic stage.

ABBREVIATIONS

This manuscript uses the following abbreviations:

FSW	-	Friction Stir Welding
EDS	-	Energy Dispersed Spectrometer
SEM	-	Scanning Electron Microscope
XRD	-	X-ray Diffractometer
IMCs	-	Inter-metallic Compounds
HAZ	-	Heat Affected Zone

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