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Modelling, Temperature Analysis, and Mechanical Properties of Friction Stir Welding of Al-Cu Joints with Hardened OHNS Steel Tools

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Abstract

Friction stir welding (FSW) is a nearly modern welding method with vital advantages over the conventional welding process, such as lower distortion, enhanced mechanical properties, and eco- friendly. In FSW, the joint characteristics mainly depend on heat development during the joining process due to its solid-state joining method. The basic principles of thermomechanical methods during FSW are unknown since it is a new metal joining method. In this investigation, the 2D and 3D models of the tools with different pin forms were designed using SOLIDWORKS. The ANSYS software was used to investigate the temperature distributions near the weld zones. The fixture was designed and made according to the machine conditions. The base plates used were AA6101 and C11000; the tool material used was the Hardened OHNS steel tool with square and circular pin form. The temperature values were measured in each trial while joining of Al-Cu base plates along the weld line. The results reveal that in the joint area, a trial with high temperature leads to high ultimate tensile strength (UTS) and Charpy impact strength (CIS). Made at tool rotation speed 1200 rpm and feed velocity 20 mm/min of Hardened OHNS steel tool with circular pin form. The obtained UTS value at joints was less than that of Al and Cu base plates. The microhardness value detected at the joint area was higher than the Al and Cu base plates, providing high strength, and irregularly dispersed.

Keywords: *Friction Stir Welding, Solid Modelling, Hardened OHNS steel tool, welding tool pin form, temperature distribution*

1.0 Introduction

The Welding Institute (TWI) developed friction stir welding (FSW) as a novel solid-state joining process in 1991. In FSW, two base plates were butt joined by force and extensive plastic abrasion close to their melting temperatures. The welding tool with cylindrical rotating shoulder and pin form plays a vital role by plunging into the butted plates to develop proper and less defective joints by generating adequate heat [1-3]. Also, friction between tool and plates causes more heat generation while softened underneath the plates by tool rotational and traverse movement along the joint line. The new method of tool offsetting achieved a uniform heat distribution along the weld line. Compared to other conventional metal joining techniques, melting of materials will not occur during this welding. The FSW joints have more excellent mechanical properties, fewer defects, and lower residual stress and it requires less force to make the

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joints [4-5]. Nowadays, many researchers use different methods to hold the base plates, such as fixtures, and to complete the FSW process, a clamping set up was added in the Vertical Milling Machine. The clamping system avoids the pressure gaps created when the tool was pressed into the plates so that the FSW process will be more specific and reliable [6-7]. Another method utilized by the researchers was to clamp the plates of limited size using a milling vice. However, utilizing this vice increases the danger of an accident [8-9]. Hence the fixture plays a vital role in FSW butt joints should be designed using Solidworks, and ANSYS software and manufactured to withstand the maximum loads and temperature during the FSW process. So decent knowledge must progress for adequate clamping of the base plates to be FSW butt welded [10-11]. The designing of tools and tool form plays a vital role in the FSW process. Many researchers used different tools and form for the FSW process, such as the H13 steel tool, EN-31, M2-HSS with square, triangular, tapered, etc. The OHNS includes carbon and alloy steels which were made into the tools because of their special hardenability, stability to abrasion, and resistance to deformation at high temperatures-usually practiced in a heat-treated case [12-14].

Ahmet Çakan et al.,[15] used AA 7075-T6 and (TS-EN-1652) Cu ETP R240 copper base plates of 138×300 mm² and 3 mm thick size and H13 steel tools for their experiment. In this paper, three variation welding speeds about 660 rpm, 920 rpm, and 1500 rpm, and a constant feed rate of about 32 mm/min were used and 1 mm tool offsets were applied to the Al side. The temperature distributions of plates from the joint line were identified using thermocouples. The maximum temperature was found in the weld line of the Al plate at 1500 rpm and 32 mm/min. Satya Narayana Gupta et al.,[16] used pure Al and Cu base plates of size 150×10×3 mm³ and M2 HSS tool were lap joint by FSW. They used welding process parameters of 1500 rpm, 20 mm/min, plunge depth of 5.9 mm, and tool tilt angle of 30°. The 3D FEM design was made using ANSYS12 and elements SOLID70 to analyse thermal and mechanical properties. The authors found that the maximum temperatures found between 300°C and 400°C. Vipul Pranami [17] used the copper base of 60×20×3.1 mm³ size, and tool rotating speeds were 400 rpm to 1200 rpm. The authors used SOLID226 for thermal analysis. The maximum temperature was found to be 800°C. Aalami-Aleagha et al.,[18] used AA1050-H16 pure copper o size 200×55×3 mm³. They carried different tool offsets with a rotating speed of 1000 rpm and 40 mm/min feed rate. The maximum temperature obtained was different for both Al and Cu plates because of the tool offsets. Naumov et al.,[19], In this experiment carried FSW of AA D16AT plates size of 150×500×2 mm³ with the rotational speed 1000 rpm, welding speed 200,300 and 350 mm/min, force in the perpendicular orientation 11 kN and incline of the tool shaft 2°. The temperature obtained was measured using thermocouples and numerical modelling by the temperature charts in the joint line were measured using FDM. At welding speeds of 300 and 350 mm/min, the highest temperature was found to be 496°C and 494°C, respectively. Muhsin et al.,[20] used AA7020-T53 plates of size 153×95×5 mm³ with three rotational speeds of 900 rpm,1400 rpm, and 1400 rpm with corresponding three traverse speeds of 40 mm/min, 16 mm/min, and 40 mm/min. The ANSYS software and brick element SOLID70 were utilized to investigate the temperature flow along the weld line during welding. The authors found that the high temperature obtained was 369°C at 1400rpm. Yanni Wei et al.,[21] used pure copper T2 and AA1060 of 4mm thickness base plates in this experiment. The authors discovered that at a tool rotational speed of 950 rpm and drift of 0°, tensile strengths were 102 MPa. The stirred zone had greater Vickers microhardness values than the base plates, which were intermittently distributed. Vinayak D Yadav et al. [22] used AA6101 and pure Copper of 5mm thickness metals and H13 steel tool material with circular form by FSW of butt joint configurations. The experiments were run at a spindle speed of 700 rpm and a traverse speed of 11mm/min. The authors noted that the tensile strength at the weld joints was 93.2 MPa which was less than the base plates Al and Cu. Anbukkarasi et al.,[23], in this research article, used 5 mm thick base plates of pure copper and AA2024, H13 steel tool with plain and threaded type form by FSW butt-weld joint for several tools offset and plate conditions. The authors revealed that welds with a stable and constant interface had better characteristics. The high tensile strength obtained at the joints when copper was placed at the advancing side with plain tool form is due to continuous bonding at the weld joint line.

2.0 Experiment

2.1. Selection of base plates, tool materials, and their form for the FSW process

In this research, the AA6101 and C11000 were used as base plates since both materials were used for an electrical application due to their low resistance and

Table 1: Particle distribution of AA6101 and C11000 in percentages from EDAX analysis

Particle	Al	Cu	Fe	Cr	Mg	Zn	Si	Ti	Mn	Ni	P	Pb	Bi	Ag	Sn
AA6101	93.84	0.54	0.32	0.19	1.05	0.22	3.53	0.12	0.18	-	-	-	-	-	-
C11000	-	92.68	0.28	-	-	0.75	1.24	-	0.29	0.39	0.23	2.44	1.08	0.3	0.33

Table 2. Particle distribution of OHNS tool in percentages from EDAX analysis

Particle	C	Cr	Fe	Mo	Sn	Ti	V	Si	Mn	P	Co	Ni	Cu	W
OHNSsteel tool	9.23	1.51	85.39	0.22	0.32	0.15	0.27	0.24	0.68	0.11	0.89	0.18	0.2	0.61

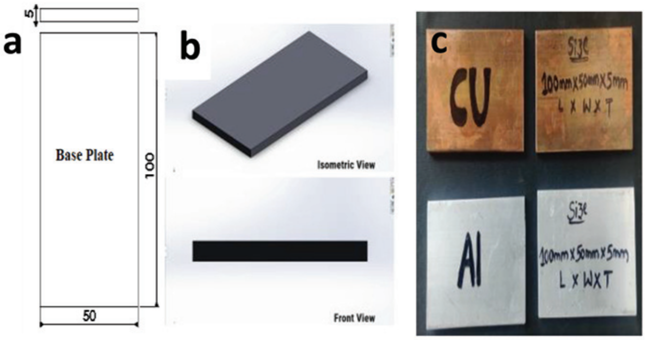

Figure 1: Base plates model (a) 2D model sizes in mm ;(b) 3D model; (c) cut Base plates

superior conductivity. For all of the experiments, the AA6101 was set on the retreating side and the C11000 on the advancing side to operate the FSW. The tool material selected was Hardened OHNS (Oil Hardened Non-Shrinkable) steel with circular and square pin form because of its excellent durability and wear resistance qualities. The particle distribution of base plates AA6101, C11000, and the Hardened OHNS steel tool were presented in Tables 1 and 2.

2.2. Base plates AA6101, C11000, and Hardened OHNS steel tool modelled using Solidworks

In this test, each base plate of the same size 100× 50×5 mm^3 (length, width, and thickness) were chosen. The 2D and 3D models were designed by Solidworks. The base plates were procured and cut as per the required size were demonstrated in Figure 1.

The welding Hardened OHNS steel tools were designed with circular and square pin forms. The tool with circular pin form was modelled with 70 mm length, 20 mm diameter of the shoulder, 5 mm pin length, and 5 mm pin diameter. Similarly, for square pin form 5×5 mm^2 and 5 mm pin length. The 2D and 3D models of the tool with a circular and square pin form were shown in Figure 2.

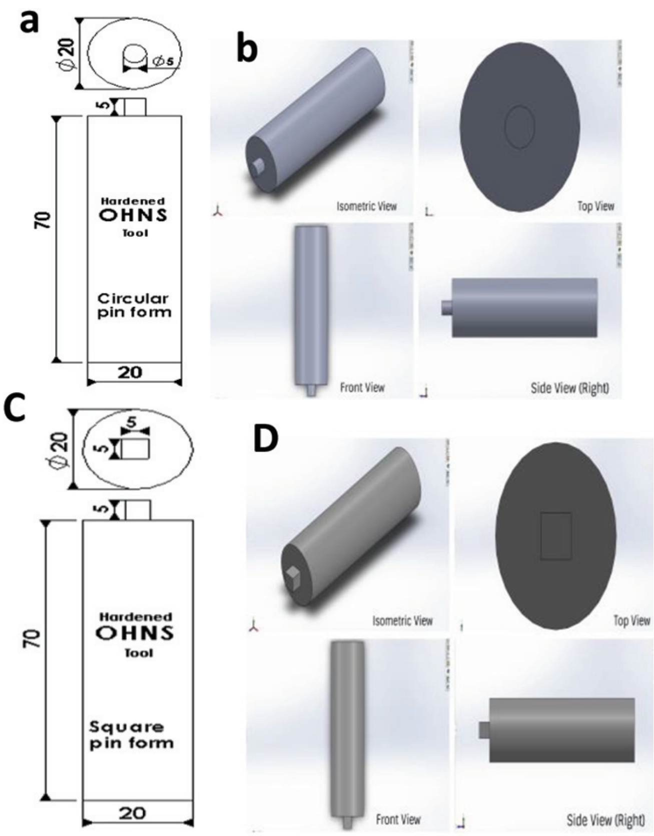

Figure 2: FSW Hardened OHNS steel tool (a) 2D model of Circular pin form in mm; (b)3D model of circular pin form; (c) 2D model of square pin form in mm; (d) 3D model of square pin form

In this research, the tool rotation speed (rpm) and feed velocity (mm/min) on the base plates, the location, and the accuracy of the welding tool are the main criteria while welding. When the welding tool was held over the base plates, there was a forced gap between the tool and plates. Hence to avoid such

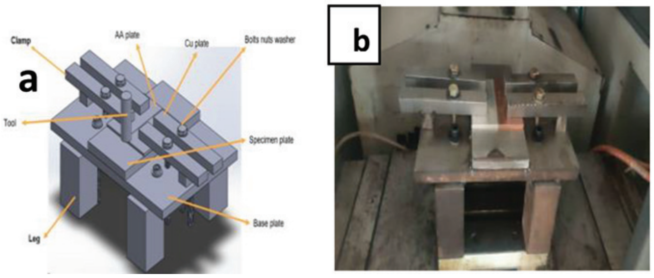

Figure 3: fixture model (a) 3D Solidworks model; (b) fabricated assembly.

problems, clamps were used. The fixture model reveals that they withstand the maximum forces and high temperatures and firmly hold the base plates. Also, there should be no movements of the base plates during the welding to create more specific and detailed welding. In this experiment, fixtures with a clamping system, base plate holder, leg supports, etc., were modelled using Solidworks. Final assembly of fixture installed in vertical CNC milling machine to run the FSW process. The 3D model and assembly of the fixture was displayed in Figure 3.

The raw material OHNS steel available in the form of the rod was procured and performed turning operations to make FSW tools with circular and square pin forms as per the desired sizes. After that, these tools were strengthened and hardened to get the Hardened OHNS steel tool by the quenching process. Lastly, these tools were polished. The Rockwell Hardness test was performed on the OHNS steel tool before and after the hardening. Before hardening the OHNS steel tool materials were 22 HRC and after hardening was 65 HRC.

2.3. Test set up to perform FSW process

The testing was carried out on a Skanda Mfg. System Pvt. Ltd vertical CNC milling machine with fixtures located in the basement. The variables tool rotation speed (rpm) and feed velocity (mm/min) were computed in the CNC milling controller. The temperatures were measured for each trial at every interval while the tool traversed along the joint line. In this research, the InfraRed thermometer (Model: HTC-IRX 68, Dual laser targeting Infrared and K-Type, IR: -50.0 to 1850°C, K-Type: -50.0 to 1370°C, Response time: 150 ms, Distance: Spot=50:1) were used to investigate the temperature distributions at the joints from start to the end of the weld. The test set up including CNC machine, base plate set up, InfraRed thermometer, and temperature measured during welding is shown in Figure 4.

Figure 4: Test set up to conduct FSW of Al-Cu joint

Table 3: Different trials with corresponding welding tool rotation speed, feed velocity, and tool pin form

Trial	Tool Rotation Speed (rpm)	Feed velocity (mm/min)	Tool Pin Form	Temperature Distributions at weld joint region (°C)
1	1200	15	square	275.3
2	1200	15	circular	280
3	1200	20	circular	302.4
4	1000	10	circular	262
5	1100	15	square	270
6	1200	20	square	292

2.4. Selection of FSW welding process variables and levels, welding tool materials, tool pin form, and locations of the Base Plate

Tool rotation speed (1000 to 1200 rpm) and feed velocity (10-20 mm/min) were used in this test with a Hardened OHNS steel tool with square and circular pin form. For all of the trial runs, the base plates AA6101 were placed on the advancing side and C11000 on the retreating side. Each trial was performed with a different tool rotation speed and feed velocity with different Hardened OHNS steel tool pin forms. For example, trial with 20 mm/min feed velocity, the tool rotation speed of 1200 rpm, and Hardened OHNS steel tool with circular pin form. Table 3 presents the welding trial-run features and temperature distributions at the weld joints.

2.5. Experimental set up for performing mechanical properties test

2.5.1 Hardness test

In this test, the micro indentation on the base plates Al and Cu were performed using a Vickers hardness tester with a model VH1102 and a load range of 10 gf to 1000 gf. For all the trials, the hardness tester was set by the capacity of 1 kg and dwelling period of 10 s. The hardness test analysis was performed for the base plates and at the welded joint area. The test procedure and the specimens were prepared according to the code ASTM E-384 [21][24][28].

2.5.2 Ultimate tensile strength test

In this test, an average of two specimens was taken. The specimens were cut using the wire EDM method (Model DK7732 CONCORD, maximum workpiece thickness-500 mm, maximum speed-400 mm²/min, and thickness of the wire (Molybdenum)-0.18 mm) as per the code ASTM E8-16a [21][23][28]. The tests were conducted using TTM 5 tonnes capacity model. The specimen configuration was presented in Figure 5.

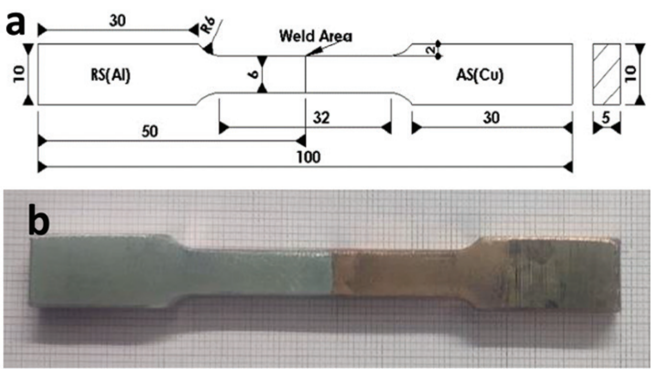

Figure 5: (a) Specimen configuration; (b) specimen cut for tensile test

2.5.3 Charpy impact strength test

In this test, an average of two specimens was applied. Each specimen was cut using the wire EDM method (Model DK7732 CONCORD) with dimensions of 55×10×5 mm³ (length × width × thickness) according to the code ASTM E23. The test was performed on the model VI-30 Charpy impact test machine. The V-Notch with a model BMF-M was done at the center of the weld joint at 27.5 mm of the total length of 55 mm as shown in Figure 6 [25-27]. The total energy consumed by the specimen during breakdown was analyzed.

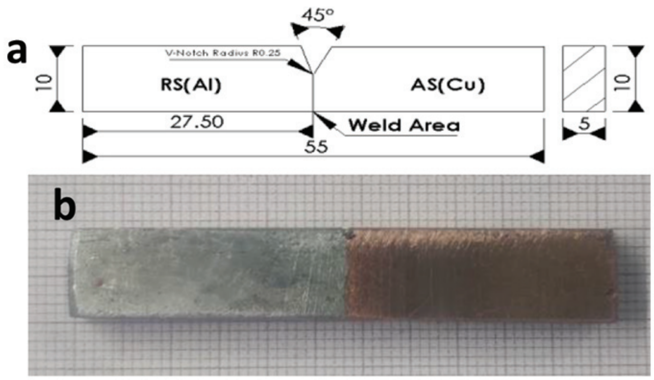

Figure 6: (a) Method of specimen making; (b) V-Notch at the center of the specimen

3. Results and Discussions

3.1. Simulation of FSW welding tool (Hardened OHNS steel) with base plates (AA6101 and C11000)

Solidworks was used to create the 3D model of the welding tool and base plates, which was then exported as an IGS file. The material parameters of the Hardened OHNS steel tool, base plates Al (AA6101), and Cu (C11000) were documented in the engineering database using the ANSYS workstation. The steady-state thermal analysis was performed on the designed geometry. Hardened OHNS steel tools, Cu (C11000), and Al (AA6101) are the materials assigned to the welding tool and base plates, respectively. The final geometry models were meshing with a 0.006 m element size. A boundary condition was set for each trial, with the initial temperature set at 24°C and the tool temperature (highest temperature obtained of each trial) set for each trial. Every trial's temperature

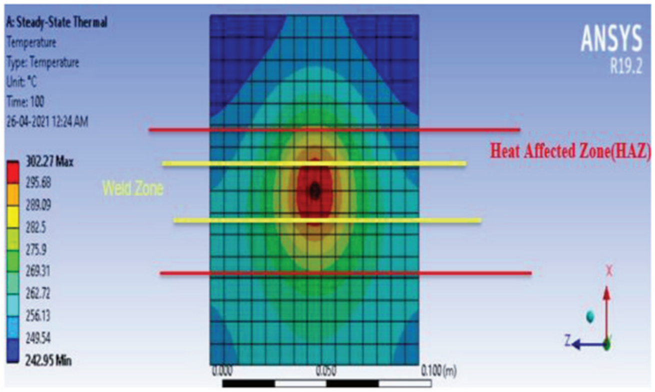

Figure 7: Temperature distribution with hardened OHNS steel tool (circular pin form) when tool temperature was 302.4°C

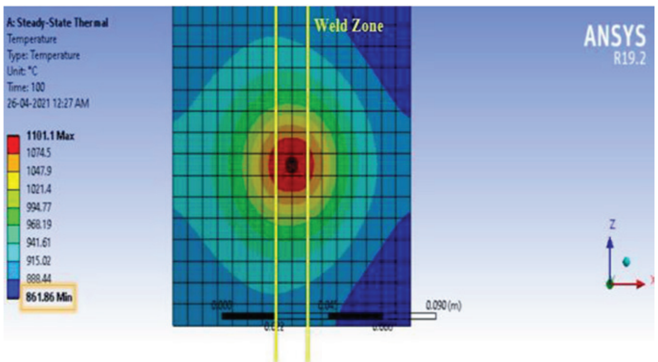

Figure 8: Temperature distribution of conventional flame welding when tool temperature was 1100°C

distribution research was matched and reviewed.

Figure 7 depicts the temperature distribution of the Hardened OHNS steel tool with circular pin form,1200 rpm tool rotation speed, and 20 mm/min feed velocity. The tool temperature of 302.4°C was fixed at the boundary condition.

The temperature distribution analysis between the base plates and tool was detected on the graph of the temperature profile.

Figure 8 shows the temperature distribution of the conventional welding technique. The tool temperatures of 1100°C were fixed at boundary conditions. This welding process was simulated and compared to the friction stir welding technique.

In this research, the FSW process is compared to the conventional welding technique by performing a temperature distribution analysis. During the FSW, the temperatures developed on the tool and base plates were relatively low. This analysis was simulated in an ANSYS workbench with different tool temperatures obtained and tool pin form. Table 3 shows the minimum and maximum temperature values of 275.3°C, 280°C, and 302.4°C. In this case, the maximum temperature was achieved from Figure 7 due to high tool rotation speed and feed velocity with the Hardened OHNS steel tool (Circular pin form). But heat input and heat-affected zone are lower using the FSW process than the conventional welding technique. To remove the structural integrity of the workpieces, the FSW occurs with a lower critical temperature of AA6101 and C11000 base plates. From Figure 8, during the conventional welding process, the minimum temperature was 861°C and the maximum temperature was 1100°C. In this case, heat-affected zone, heat generation was very high, which affects the structural integrity of the base plates and improper mixing occurs. The melting point of AA6101 was 654°C and the C11000 was 1085°C. Due to melting point variations, it was challenging to weld the aluminium alloy with copper alloy by the conventional welding method. Hence to overcome this problem, the FSW method was adopted in this research to improve proper mixing near the Al-Cu joints.

3.2. Mechanical characteristics of the base plates Al-Cu joints

3.2.1. Microhardness determinations

The micro indentation was performed for the Al-Cu joint plots of the first three trials made from different tool rotation speeds (rpm), feed velocity (mm/min), and tool pin forms. The experiments were conducted for the joint area and the base plates (from the joint area to each base plate of 5 mm distance). In the first three trials, the average microhardness value of the base plates detected was Al-52.76 HV, Cu-89.13 HV, and the joint region was 105.93 HV was higher than the values of the Al and Cu base plates. The average microhardness value at the thermo-mechanically affected zone (TMAZ) was 79.46 HV on the base plate Cu view, while the heat-affected zone (HAZ) was 89.5 HV. From the Al-Cu joint region to the Cu base plate, there is a change in hardness value. The average microhardness at TMAZ was 65.1 HV and HAZ was 56.66 HV in the base plate Al perspective, indicating a hardness value variation from the junction to the Al base plate. The presence of microhardness was sporadic. The TMAZ and HAZ microhardness values of both base plates were lower than the Al-Cu interface region. Also, by comparing trial 3 with trial 1 and trial 2, trial 3 achieved high microhardness value than the other two trials due to increased tool rotation speed of

1200 rpm, feed velocity of 20 mm/min, and circular tool pin form. In this case, proper mixing and heat generation occurs at the interface area.

3.2.2. Ultimate tensile strength test (UTS) and Charpy impact strength test (CIS) determinations

Figure 9 shows the Trials (tool rotation speed, feed velocity, and tool pin profile) vs UTS (MPa) and CIS (kJ/m^2) were performed for FSW samples of the initial three trials. At a low tool rotation speed of 1000 -1100 rpm, in this case, the temperature developed was not sufficient and improper mixing leads to the joints' low UTS and impact strength. At a tool rotation speed of 1200 rpm, a low feed velocity of 15 mm/min with a Hardened OHNS steel tool (square and circular pin form), the UTS was found to be 72-92 MPa, Elongation was 6-7 %. The CIS was found to be 112.5 kJ/m^2 and 135 kJ/m^2 on absorbed energy of 4.5J and 5.4J, respectively. This change is due to medium heat input and temperature distribution at the weld joint area. The square pin form causes burrs leading to the loss of materials at the joints and produces exterior scratch defects and low joint strength. At a tool rotation speed of 1200 rpm, a high feed velocity of 20 mm/min with a circular pin form, the UTS was found to be 98.2 MPa, and Elongation was 7.46%. The impact velocity was 5.347 m/sec, and the impact strength was strong at 170 kJ/m^2 on absorbed energy of 6.8J. This change was due to maximum tool rotation speed, feed velocity, and the maximum temperature obtained at the joints. The circular pin form, which removes the burrs and exterior scratch defects, leads to the uniform mixing, and bonding interface, and the proper heat input at the joint leads to high joint strength.

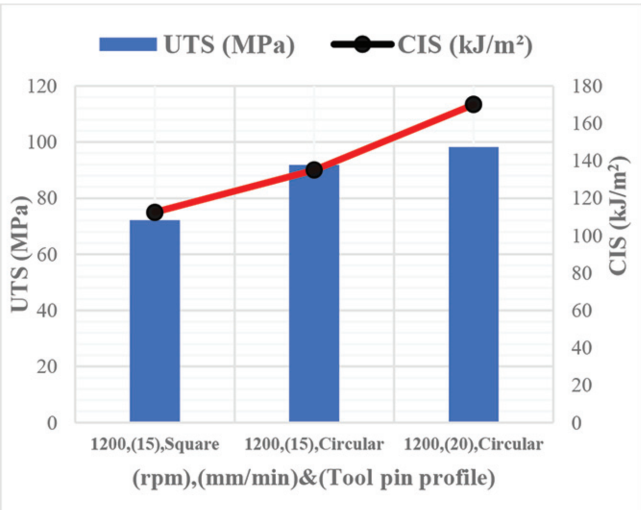

Figure 9: Trials vs UTS (MPa) and CIS (kJ/m^2)

The joint strength increased when the tool rotation speed and feed velocity were increased and the circular tool pin form. When the tool rotation speed and feed velocity are decreased, square tool pin profile, the joint strength decreases.

4. Conclusions

The temperature distribution study of FSW of Al-Cu joints was clearly discussed in this experiment, which was then compared to the traditional welding method. When using the FSW technique to combine Al and Cu base plates, welding process factors such as tool rotation speed (rpm), feed velocity (mm/min), tool material, and tool pin form are critical. The following observations were made as a result:

1. From the investigation, while comparing FSW with the conventional welding method, during traditional welding methods, the temperature was high at 861°C. Here, the temperature at the heat-affected zones was high, which led to changing the structural integrity of the base plates Al-Cu. During FSW of Al-Cu joints, the temperature at the heat-affected zones was lower, which does not alter the structural integrity of the base plates Al and Cu.
2. The average Vickers microhardness of the weld joint area was 105.93 HV, which is greater than the base plates Al and Cu and unevenly distributed at tool rotation speed 1200 rpm and feed velocity 20 mm/min, circular pin form.
3. The ultimate tensile strength value of the Al-Cu joint obtained was high 98.2 MPa, and the highest impact strength obtained was 170 kJ/m^2 when the tool rotation speed was 1200 rpm, and the feed velocity was 20 mm/min, the maximum temperature of 302.4°C was noted at the Al-Cu joint line using circular pin form. Out of the six trials, it was stated that this trial produced a more reliable weld joint because of uniform mixing and proper bonding at the Al-Cu joints.
4. When the tool rotation speed was 1000 rpm and 10 mm/min feed velocity, the minimum temperature of 262°C was noted at the Al-Cu joint line using circular pin form. It was stated that improper bonding at the weld joints.
5. Based on the preceding considerations, rigid butt joint development necessitates either high tool rotation speed and high feed velocity combinations or low tool rotation speed and high feed velocity with varied tool offsets.

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