



## FRACTURE BEHAVIOR AND MECHANICAL PERFORMANCE OF DISSIMILAR FRICTION STIR CLINCHED CU/AL JOINT

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### Abstract

The friction stir clinching (FSC) of C10100 and AA5456 alloys was investigated to improve the weld performance of the Al/Cu joint via the combined effect of protrusion-induced mechanical interlocking and metallurgical bonding. The microstructure, tensile, and fracture results of the friction stir clinched C10100/AA5456 joints were studied. The in-situ local temperature histories of the joints were recorded via the use of K-type thermocouples connected to a data logger. The peak temperatures of the joints at 900 rpm, 1120 rpm, and 1400 rpm are 332.4°C, 399.8°C, and 577.1°C respectively. The increase in the plunge depth (0.5 -1.5 mm) increases the amount of the extruded surface flash and the weld failure load of the joint while the increase in the tool rotational speed (900 - 1400 rpm) hampers the resultant failure load of the joint. The highest and the least failure loads of the joints are 2282 N and 1060 N respectively. The fracture modes of the joints include partially sheared protrusion, completely sheared protrusion, and undamaged protrusion/protrusion pullout. The completely sheared protrusion fracture mode produced the maximum failure load owing to the combined effect of protrusion-induced interlocking and metallurgical bonding. It is recommended to weld Al and Cu alloys at low tool rotational speed and high plunge depth for desirable metallurgical bond and Al/Cu interlock.

**Keywords:** Friction stir clinching; copper alloy; aluminum alloy; microstructure; mechanical properties; fracture

### Introduction

Hybrid Al/Cu structures have found extensive applications in the transportation, electronics/electric power, and aerospace industries due to their unique electrical and thermal properties (Zhou *et al.*, 2019; Li *et al.*, 2019; Panaskara *et al.*, 2017). Al/Cu components are extensively used in the industrial sectors for the fabrication of tube sheets, electrical connectors, refrigeration tubes, and heat exchanger tubes (Hou *et al.*, 2020). The potentials of hybrid Al/Cu metallic couples in the industries are yet to be fully exploited due to their joining difficulty. The disparity between the physical and mechanical properties of Al and Cu alloys and the high chemical affinity at higher temperatures enhance the formation of unwanted brittle intermetallic compounds (IMCs) in the fusion-welded Al/Cu joints (Galvão *et al.*, 2012) with other (inherent) fusion-based defects such as porosity and solidification cracking (Muthu *et al.*, 2015). Underwater welding or solid-state joining processes such as friction stir welding, explosive welding, and forge welding are approaches that can mitigate the formation of intermetallic compounds (IMCs) in Al/Cu joints (Moaref *et al.*, 2020).

An assessment of the solid-state friction stir-based welding processes shows that several studies and

reviews have been carried out on the friction stir lap welding, friction stir welding, and friction stir spot welding of Al and Cu alloys (Sharma *et al.*, 2017; Mubiayi *et al.*, 2018; Garg and Bhattacharya, 2017; Galvão *et al.*, 2013; Akinlabi *et al.*, 2014; Kumar *et al.*, 2018; Akinlabi *et al.*, 2017; Siddharth and Senthilkumar, 2018; Rao *et al.*, 2017; Mubiayi and Akinlabi, 2016; Mehta and Badheka, 2017; Siddharth *et al.*, 2017). Shankar *et al.* (2019) investigated the dissimilar friction stir welded AA1050/oxygen-free copper joints. The Al<sub>2</sub>Cu and Al<sub>4</sub>Cu<sub>9</sub> intermetallic compounds were reported to be formed at varied welding speeds. The performance of the joint was hampered by the large presence of IMCs while process parameters such as welding speed and tool offset significantly affected the mechanical properties of the joint. Muthu and Jayabalan (2015) reported that the lower thickness of intermetallic compounds (AlCu, Al<sub>2</sub>Cu, and Al<sub>4</sub>Cu<sub>9</sub>) is promoted by the reduced diffusion rate in the Al/Cu joint and this attribute is responsible for higher joint efficiency (tensile strength). Sinha *et al.* (2016) described that the interfacial weld regions of the friction stir welded Al/Cu joint contained AlCu, Al<sub>2</sub>Cu, Al<sub>2</sub>Cu<sub>3</sub>, and Al<sub>4</sub>Cu<sub>9</sub> phases. Intermetallic phases of AlCu<sub>3</sub>, Al<sub>2</sub>Cu, Al<sub>2</sub>Cu<sub>3</sub>, and Al<sub>4</sub>Cu<sub>9</sub> were also reported to be the most common IMCs in friction stir spot welded Al/Cu joints

(Mubiayi and Akinlabi, 2017). The fine grain sizes and the presence of these IMCs at the stir zone of the Al/Cu joint were responsible for hardness improvement at this zone as compared to other zones of the joint. Rzaev *et al.* (2019) reported that shear-banded (layered) structures and alternating layers were formed in the weld nugget of the friction stir welded Al/Cu joint due to the solid/superplastic state inter-material flow. Xia-Wei *et al.* (2012) reported the occurrence of a relatively homogeneous lamella structure in the bottom section of the weld nugget while a complex swirl and vortex-like flow pattern ensues in the dissimilar friction stir welded Cu/AA1350 joints. Khojastehnezhad and Pouras (2018) reported that the synergy of high dislocation density and intermetallic compounds caused an increase in the hardness values of the 6061-T6/Cu/6061-T6 joint.

The synergy of mechanical interlocking and material intermingling-aided bonding is a unique approach that can further improve the performance of Al/Cu joints. This approach can be achieved by combining friction stir spot welding and mechanical clinching methods. A process that combines these methods is referred to as the friction stir clinching (FSC) approach. This approach is thus employed in this paper to join Al and Cu alloys. Recently, Hou *et al.* (2020) revealed that a mechanical interlocking structure with a chaotic interface improved the performance of the friction stir welded 6061/commercially pure Cu joint. Xing *et al.* (2015) also reported that the clinched joint exhibited a promising fatigue performance. Modified friction stir clinching of similar and dissimilar Al alloys has recently been reported in the literature (Paidar *et al.*, 2020a; 2020b; Paidar *et al.*, 2019a; 2019b; Haiyan and

Mehta, 2020). To improve Al/Cu weld performance, this paper employs the friction stir clinching process in joining Al and Cu alloys. The fracture and mechanical performances of the joints are examined with an optical microscope (OM) and scanning electron microscope (SEM).

### Materials and Method

The base materials utilized for this study are 3 mm thick AA5456 Al and oxygen-free (C10100) Cu alloys. The chemical compositions and mechanical properties of these alloys are shown in Table 1. The as-received base materials were cleaned with acetone and cut into the dimensions of 75 × 25 mm on a guillotine machine. The Cu alloy was placed on the Al alloy to create an overlapped geometry having an overlapped area of 25 × 25 mm. This material positioning (Cu as upper plate and Al as lower plate) was employed due to the higher strength and melting point of the Cu alloy. Before the commencement of the friction stir clinching (FSC) process, a predrilled blank hole was produced in the supporting anvil. This is needed to establish the clinching of the two materials (Al and Cu alloys) during the plunging action. The schematic illustration of the FSC process is shown in Figure 1. The welding tool was fabricated from high-speed steel (HSS). A conical shoulder-cylindrical pin tool having a shoulder diameter, pin diameter, and a pin length of 10 mm, 5.5 mm, and 4 mm respectively was used for the FSC process. The welding parameters and their respective levels employed for this study are provided in Table 3. The Taguchi method (TM) was employed in planning and designing the experiment for this study. Based on Table 3, the L9 orthogonal array was chosen for this research.

**Table 1: Chemical Compositions of Base Materials**

| Materials | Mn   | Mg   | Cr   | Ni   | Sb   | Cu  | Zn   | Pb   | Al  |
|-----------|------|------|------|------|------|-----|------|------|-----|
| AA5456    | 0.04 | 5.03 | 0.01 | 0.05 | 0.05 | -   | 0.11 | -    | Bal |
| C10100    | -    | -    | -    | -    | -    | Bal | 0.53 | 0.03 | -   |

**Table 2: Mechanical Properties of Work-piece**

| Materials | Hardness | Tensile Strength (MPa) |
|-----------|----------|------------------------|
| AA5456    | 98       | 341                    |
| C10100    | 65       | 274                    |

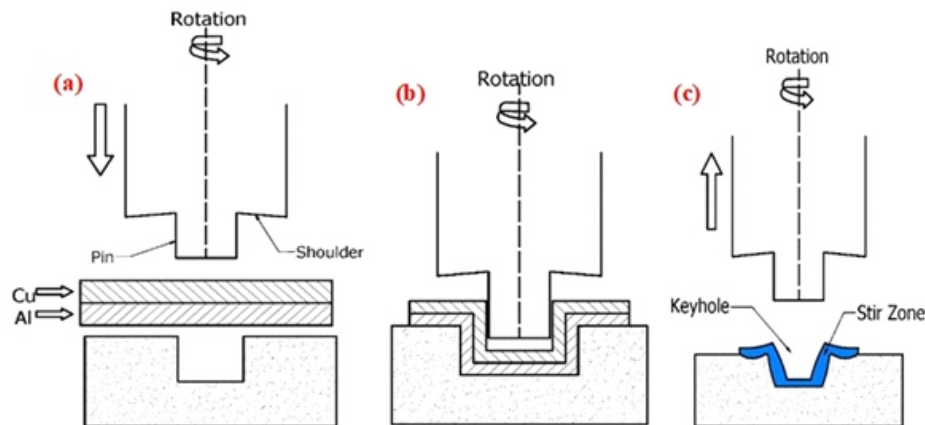


Figure 1: Friction stir clinching process (a) plunging, (b) stirring, (c) retracting processes

**Table 3: Welding Parameters Employed for the FSC Process**

| Welding parameters          | Levels |      |      |
|-----------------------------|--------|------|------|
|                             | 1      | 2    | 3    |
| Tool Rotational Speed (rpm) | 900    | 1120 | 1400 |
| Plunge Depth (mm)           | 0.5    | 1.0  | 1.5  |
| Dwell Time (s)              | 1      | 2    | 3    |

The in-situ temperature-time histories of the FSC C10100/AA5456 joints were recorded at different tool rotational speeds using a data logger (in milliseconds). Three K-type thermocouples (A, B, and D) were inserted into the slotted grooves in the upper plate (C10100 alloy). The distance from the thermocouple D (TD) to the weld center is 15 mm while an equidistance of 6 mm is maintained between thermocouple B (TB) and thermocouple A (TA) respectively. The cross-sections of the as-welded FSC C10100/AA5456 joints were obtained and subjected to the standard metallographic procedure (ASTM E3-11) by grinding with silicon carbide paper (with grits numbers from 200 to 1000), polishing (using diamond pastes), and etching respectively. Keller's reagent and a solution of ethanol + HCL + FeCl<sub>3</sub> were the etchants utilized to etch the AA5456 and the C10100 sides respectively. The resultant microstructures of the FSC C10100/AA5456 joints were viewed under an optical microscope (OM). The tensile shear (failure) load of the FSC C10100/AA5456 joints was investigated on a SANTAM STM250 tensile testing machine according to ASTM E8M-16a and at a strain rate of 0.05 min<sup>-1</sup>. The average of three tensile results was reported as the actual tensile shear load of the FSC C10100/AA5456 joints. The surfaces of the failed joints were viewed in a scanning electron microscope (SEM) to understand the fracture/failure mode of the FSC C10100/AA5456 joints.

## Results and Discussion

### Temperature History and Surface Appearance

Figure 2 shows the in-situ temperature-time history plots of the FSC C10100/AA5456 joints obtained at different speeds (900 - 1400 rpm). AT, RH, TA, TB, and TD represent the local atmospheric temperature, relative humidity, and temperature readings of the thermocouples A, B, and D respectively. The atmospheric temperature (AT) at which the FSC process was carried out slightly varies between 28.85-29.64°C during the welding process while the local relative humidity progressively decreases from the maximum value of 79.12 % to 74.36% (with an uneven or undulation pattern) as the tool rotational speed is increased (900-1400 rpm). The decrease in the local relative humidity is influenced by a rise in the weld heat input during the welding process. The location of the thermocouple (equidistance of 6 mm between the thermocouples) slightly influences the temperature reading (maximum/peak) of the joints as the tool rotational speed is increased. The temperature history shows that a rise in the temperature ensues as soon as the FSC process commences, it reaches a maximum value and then declines (as the welding tool is retracted from the weld nugget). The maximum/peak temperature readings of the FSC C10100/AA5456 joints are 332.4°C, 399.8°C, 577.1°C at 900 rpm, 1120 rpm, and 1400 rpm respectively. This occurrence shows that an increase in the tool rotational speed has a direct relationship with the maximum/peak temperature value of the joint. An increase in the rotational speed generates more friction-aided and plastic deformation-induced heat input in the FSC C10100/AA5456 joints. This phenomenon is reckoned to have increased the peak temperature of the FSC C10100/AA5456 joints as the tool rotational speed is increased. The observed result is in agreement with the reported findings in the literature (Ojo *et al.*, 2015). Meanwhile, the attained temperature at 1400 rpm (577.1°C) is above the eutectic temperature (547.85°C) of the binary Al-Cu phase

diagram. This indicates that a liquid volume fraction (phase) is formed in the weld at 1400 rpm and this occurrence may favor the formation of complex phases

( $\alpha$ -Al, AlCu,  $\theta$ -Al<sub>2</sub>Cu, Al<sub>2</sub>Cu<sub>3</sub>, Al<sub>2</sub>CuMg, and Al<sub>4</sub>Cu<sub>9</sub>) within the stir zone of the FSC C10100/AA5456 joint (Chen *et al.*, 2020; Muhammad and Wu, 2020).

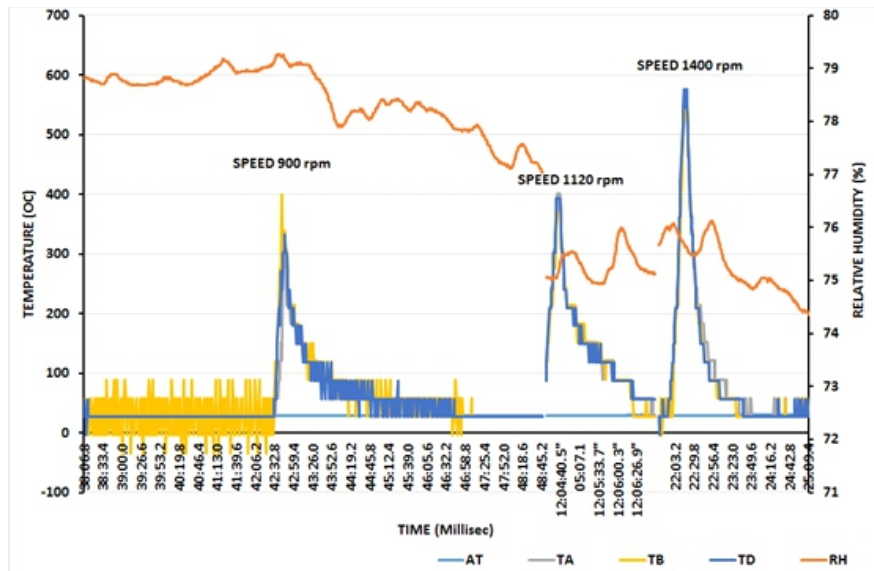


Figure 2: Temperature-time history plots of the FSC joints (AT: local atmospheric temperature; RH: relative humidity; TA: temperature reading of the thermocouple A; TB: temperature reading of the thermocouple B; TD: temperature reading of the thermocouple D)

Figure 3 reveals the top and bottom surfaces of the friction stir clinched C10100/AA5456 joints at different plunge depths (see Figure 3a-c) and rotational speeds (see Figure 3d-f). The top surfaces (C10100 side) of the FSC C10100/AA5456 joints show extruded flashes with different morphologies while the bottom (AA5456) sides reveal flow-induced bulk protrusions in Figure 3a-c. The even circumferential flash (in Figure 3) has been attributed to the occurrence of axisymmetric material flow about the tool rotational axis (Oladimeji *et al.*, 2016). At constant tool rotational speed (900 rpm), the increase in the plunge depth (0.5-1.5 mm) shows that the amount of surface extruded flash increases in Figure 3a-c. The distance from the circumferential boundary of the weld nugget to the tip/end of the extruded flash also increases as the plunge depth is increased. This occurrence is attributed to the fact that more tool pin-induced material shearing ensues as the plunge depth is increased. The downward movement of the welding tool causes the upward extrusion flow of the plasticized dissimilar materials out of the tool pin region towards the shoulder area (Oladimeji *et al.*, 2016). The compressive-shearing attribute of the shoulder surface forces the superfluous plasticized materials (beneath the shoulder surface) out of the weld nugget via a centrifugal drag effect to form surface flash (Oladimeji *et al.*, 2016). Oladimeji *et al.* (2016) corroborated that a direct relationship exists between the plunge depth and the expelled flash volume. It is reported that a percentage of the plasticized materials beneath the shoulder surface is

extruded and squeezed out of the weld nugget zone under a continuous increase in the plunge depth.

A rough and unbroken (extruded) flash profile is observed at a low plunge depth (0.5 mm) in Figure 3a. A serrated or broken flash profile is formed as the plunge depth increases beyond 0.5 mm as shown in Figure 3b and c respectively. The continuous circumferential extrusion or push out of the flash (under an increase in plunge depth) is adjudged to have caused the breakage or serration of the flash tip/end observed in Figure 3b and c. The length of the tool pin-induced protrusion at the AA5456 side (see Figure 3a-c) is constant due to the unchanged depth of the pre-drilled hole employed for this study. Consequently, the effect of plunge depth on the appearance of the inherent protrusion is considered to be insignificant. The tool-aided material flow and the mechanical interlocking attribute are expected to be altered by a change in the plunge depth at the protrusion zone of the FSC joint. Meanwhile, the effect of tool rotational speed on the surface appearance of the FSC joint is revealed in Figure 3d-f. The coloration and overall size of the extruded and expelled flash on the surface of the upper plate (C10100 alloy) change, as the rotational speed is increased from 900 to 1400 rpm (see Figure 3d-f). The rise in the heat input (peak temperature observed in Figure 2) is considered to have changed the color of the expelled flash from brown (at 900 rpm in Figure 3d) to brownish-black coloration (at 1120 and 1400 rpm in Figure 3e and f). At high tool rotational speed, the induced heat input in the FSC joint improves

the flowability of the plasticized materials due to an inevitable reduction in the viscosity of the material. The thermal exposure of the plasticized materials at the

shoulder surface is significantly high at 1400 rpm and this significantly affects the coloration of the extruded flash in Figure 3e and f.

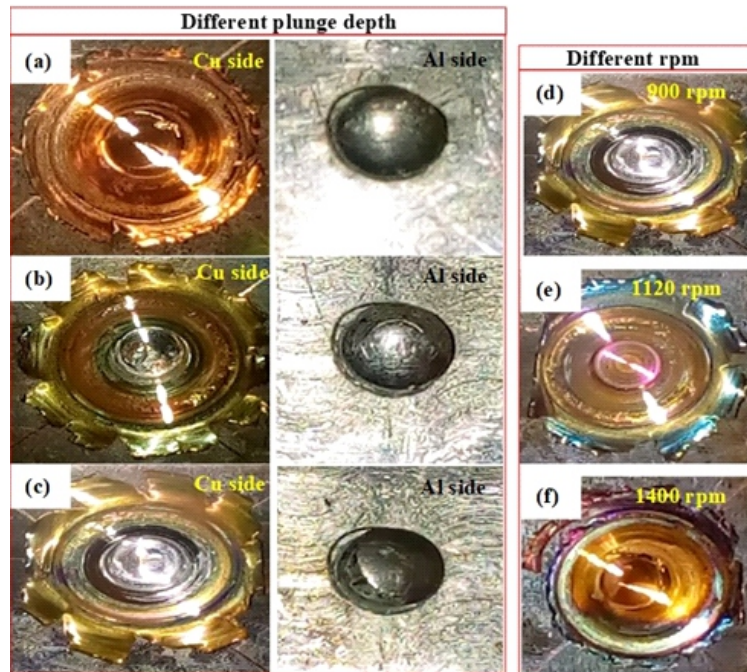


Figure 3: Flash and protrusion appearances of the FSC joint at 900 rpm and different plunge depths of (a) 0.5 mm, (b) 1.0 mm, (c) 1.5 mm, and at different rotational speeds of (d) 900 rpm, (e) 1120 rpm, (f) 1400 rpm

### Microstructure

The microstructure of the FSC C10100/AA5456 joints is similar to that of the conventional friction stir welded joints except for the presence of an interlocked protrusion section in the joint. Different imaging of the FSC joint is employed to effectively reveal the interlocking attribute of the FSC process. The mechanical interlocking of the dissimilar materials of the FSC C10100/AA5456 joint is shown in Figure4.

The C10100 Cu alloy is plastically interlocked in the matrix of the AA5456 Al alloy. This phenomenon is expected to offer some resistance to axial/tensile loading in conjunction with the metallurgical bonding between C10100 and AA5456 alloys. The different or multi-stack colors in the interlocked zone indicate that intermixing or material intermingling occurs at this zone (see the color mapping in Figure4).

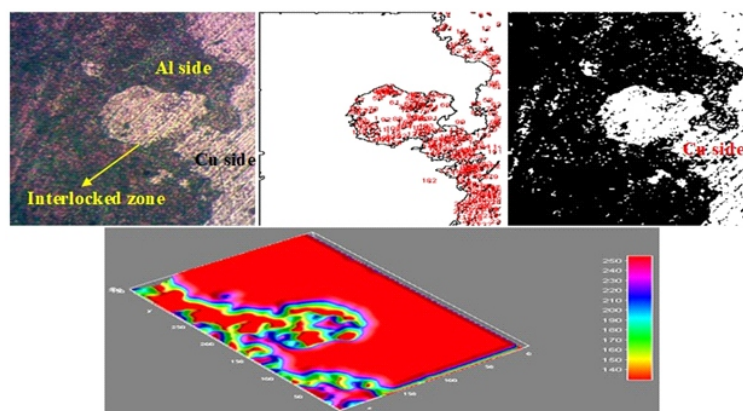


Figure 4: The interlocking of Cu and Al in the FSC C10100/AA5456 joint

The visual observations (microstructures) of the FSC C10100/AA5456 joints are somewhat similar in appearance as the processing parameters are varied, as a result, the different zones across the joint are presented in Figure 5. The weld zones are the stir zone, thermo-mechanically affected zone, heat affected zone, base metal, and thermally affected interfacial/faying zone. These zones have been well reported in the literature and the observed findings in these zones corroborate with existing reports (Ojo *et al.*, 2018; Fan *et al.*, 2022). The tool-aided severe plastic deformation and dynamic recrystallization attributes at the stir zone of the joint promoted the formation of fine equiaxed grains in Figure 5a (Paidar *et al.*, 2021; 2022; Fan *et al.*, 2020b; Bai *et al.*, 2022). Homogeneously dispersed fine equiaxed grains, as revealed by the grain counts in Figure 5a, are present at

the stir zone of the FSC C10100/AA5456 joint. A progression to the thermo-mechanically affected zone (see Figure 5b) also reveals the presence of fine grain structure due to the combined impact of the tool-induced deformational and frictional assisted thermal effects at the transition zone between the stir zone and the heat-affected zone. The appearances of the heat-affected zone and the base metal of the joints are shown in Figure 5c and d respectively. The examined base metal has a relatively coarse grain structure. However, the interfacial/faying region of the joint beneath and outside of the tool shoulder's circumferential zone (see Figure 5e) is affected by the frictionally induced heat input. The heat input and the tool-induced pressure at this region (faying region) are not sufficient to establish metallurgical bonding in Figure 5e as inter-material mixing is absent.

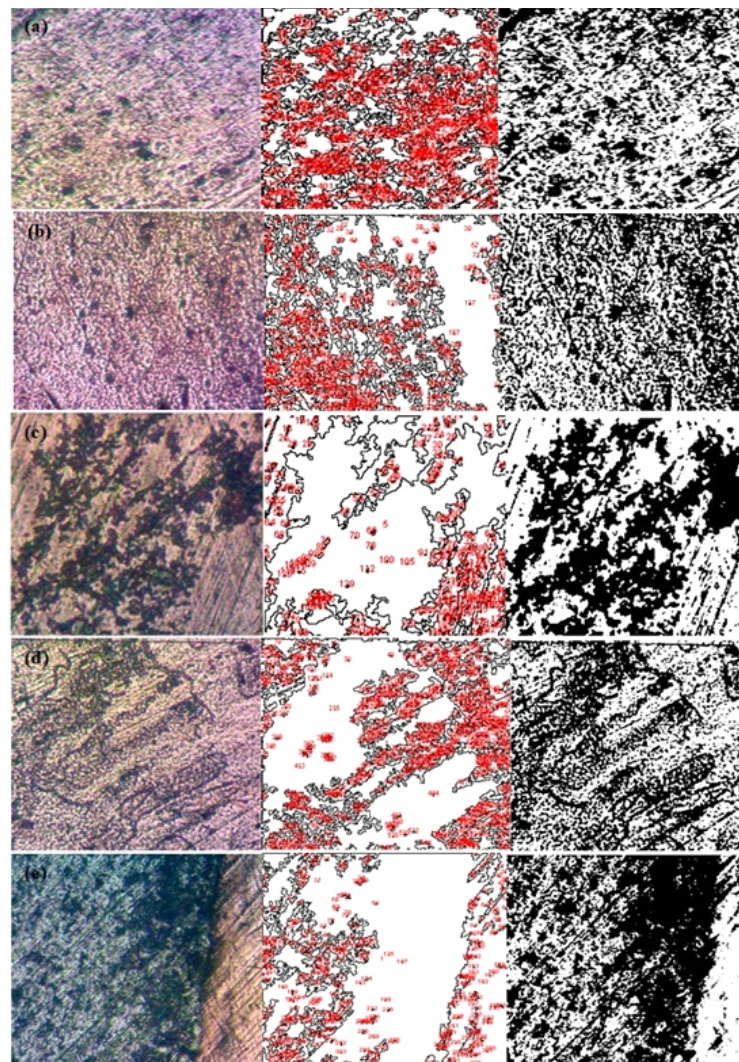


Figure 5: Microstructure of the different weld zones of the FSC C10100/AA5456 joints (a) stir zone, (b) thermo-mechanically affected zone, (c) heat-affected zone, (d) base metal, (e) thermally affected faying region

### Tensile and Fracture Results

Table 4 shows the tensile results of the FSC C10100/AA5456 joints based on the designed L9 orthogonal array. It is revealed that a change in the process parameter combination alters the average failure load of the joints. The highest and the least failure loads of the joints are 2282 N (900 rpm/1.5 mm/3 s) and 1060 N (1120 rpm/0.5 mm/2 s) respectively. This occurrence indicates that the least tool rotational speed (900 rpm) and high plunge depth are favorable for improving the weld failure load of the joint. The synergy of the protrusion-induced mechanical interlocking and metallurgical bonding is adjudged to have improved the weld failure load of the joint at 900 rpm/1.5 mm/3 s while the metallurgical bonding has been impaired as the tool rotational speed is increased owing to the formation of intermetallic compounds. However, the Taguchi design of experiment is employed to ascertain the influence of the process parameters on the weld failure load (Ojo and Ulkana, 2021). The Larger-the-Better signal-to-noise (SN) ratio is selected since the weld failure load

is to be maximized. The main effects plots (mean of the SN ratios) of the weld failure load are shown in Figure 6. It is observed that the increase in the plunge depth has a linear effect on the failure load of the joint whereas the effect of an increase in the other process parameters (tool rotational speed and dwell time) does not have a direct/linear impact on the weld failure load of the FSC C10100/AA5456 joint. An increase in the tool rotational speed could have favored complex interaction between the intermixed dissimilar alloys to form undesirable intermetallic compounds and consequently caused a nonlinear effect on the weld failure load of the FSC C10100/AA5456 joints. A liquid volume fraction phase is formed in the joint welded at 1400 rpm (based on the peak temperature above the eutectic point). This attribute favors the formation of complex undesirable phases in the joint and this hampers the weld failure load at high tool rotational speed as against the joint obtained at 900 rpm. The maximum mean of SN ratios (shown as red points in Figure 6) represents the optimum parameters for the FSC C10100/AA5456.

Table 4: Tensile Results Based on the L9 Orthogonal Array

| Exp. No. | Tool Rotational Speed(rpm) | Plunge Depth (mm) | Dwell Time (s) | Failure Load (N) |
|----------|----------------------------|-------------------|----------------|------------------|
| 1        | 900                        | 0.5               | 1              | 1278.32          |
| 2        | 900                        | 1.0               | 2              | 1713.76          |
| 3        | 900                        | 1.5               | 3              | 2281.64          |
| 4        | 1120                       | 0.5               | 2              | 1060.36          |
| 5        | 1120                       | 1.0               | 3              | 1539.70          |
| 6        | 1120                       | 1.5               | 1              | 2194.20          |
| 7        | 1400                       | 0.5               | 3              | 1632.52          |
| 8        | 1400                       | 1.0               | 1              | 1699.55          |
| 9        | 1400                       | 1.5               | 2              | 1628.32          |

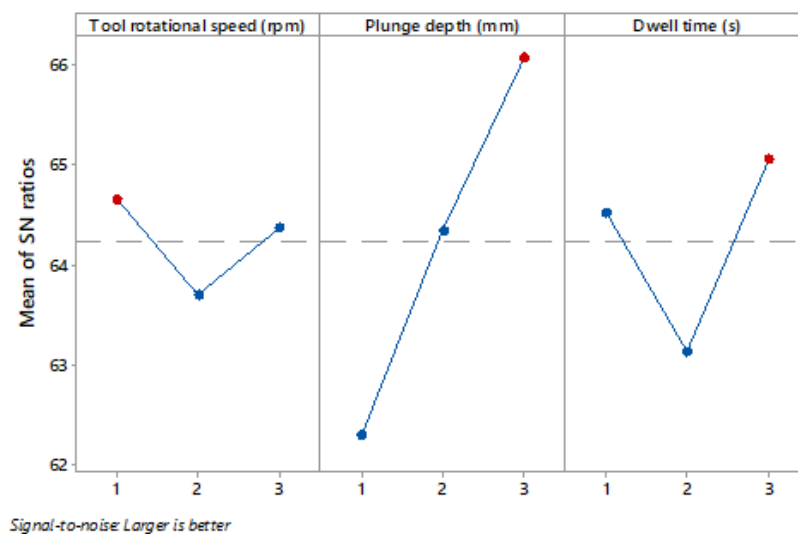
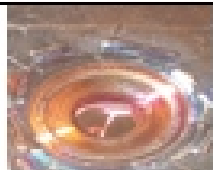
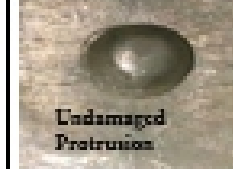
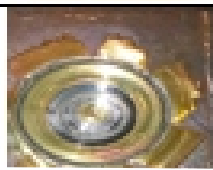


Figure 6: Main effects plot of the FSC C10100/AA5456 joint

The fracture mode and path of the FSC C10100/AA5456 joints are examined to correlate the weld failure load with the fracture mode of the joints. The fracture surfaces of the FSC C10100/AA5456 joints after the tensile loading processes are shown in Table 6. From the assessment of the C10100 side in Table 6, the fracture modes of the joint are grouped into three namely, the sheared Cu protrusion with unbuttoning fracture mode (the sheared sections are indicated with the dotted black enclosures in Table 6), the unbuttoning/protrusion pullout (Exp. 7), and the completely sheared protrusion fracture modes (see Exp 4 and 9). Similarly, the assessment of the AA5456 side in Table 6 also shows three forms of fracture based on the post-fracture protrusion appearance. They include partially sheared protrusion, completely sheared protrusion, and undamaged protrusion fracture modes. Based on this observation, the cross-sections of the three different fracture modes are obtained to further understand the fracture paths of the joint. Figure 7a-b shows the sheared protrusion with unbuttoning, unbuttoning/protrusion pullout, and completely sheared protrusion fracture modes respectively. The unbuttoning/protrusion produced the least failure load followed by the sheared protrusion with unbuttoning

and the completely sheared protrusion modes respectively. The red dotted lines are the fracture paths in Figure 7a and 7b while the dotted green lines are the sheared parts within the interlocked Cu protrusion side. However, the red dotted enclosure represents the completely sheared (Al/Cu interlocked) protrusion section in Figure 7c. The completely sheared protrusion (fracture mode) is attributed to the inhibited bond-delamination effect and fracture resilience of the joint obtained in the sample fabricated at 900 rpm (during the tensile loading process) owing to the synergy of the protrusion-induced mechanical interlocking and metallurgical bonding effects. The plasticized and interlocked Cu and Al alloy at the protrusion zones of the joints shear off and consequently improves the load-bearing resistance of the samples with completely sheared protrusions (during the tensile loading process). The effective inter-material mixing and bonding prevented protrusion pullout and this offered more resistance to failure load in the joint (with completely sheared protrusion). Meanwhile, the joints with unbuttoning or protrusion pullout are adjudged to have been mainly supported by the protrusion-induced interlocking while it suffered from adequate metallurgical bonding.

Table 6: Fractured FSC C10100/AA5456 joints

| Exp. | Top view of Cu alloy                                                                | Back view of Cu alloy                                                               | Top view of Al alloy                                                                 | Back view of Al alloy                                                                 |
|------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| 1.   |    |    |    |    |
| 2.   |    |    |    |    |
| 3.   |    |    |    |    |
| 4.   |   |   |   |   |
| 5.   |  |  |  |  |
| 6.   |  |  |  |  |
| 7.   |  |  |  |  |
| 8.   |  |  |  |  |
| 9.   |  |  |  |  |

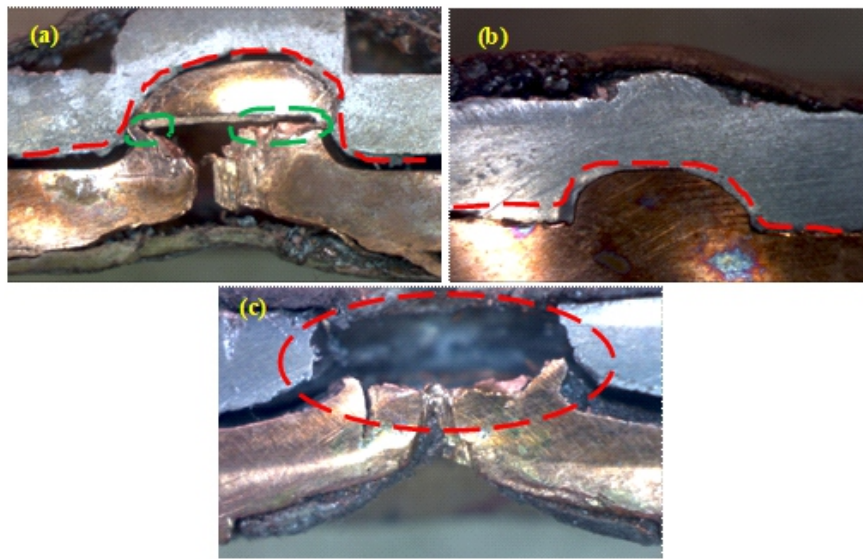


Figure 7: Cross-sections of fractured FSC joints (a) sheared protrusion with unbuttoning, (b) unbuttoning/protrusion pullout, and (c) complete sheared protrusion

Figure 8 reveals the SEM images of the fractured FSC C10100/AA5456 joints. The fracture surfaces of the sample with sheared protrusion with unbuttoning are shown in Figure8a and b. The sheared protrusion section reveals the presence of some ductile dimples (see Figure8b) and a brittle-like appearance at the unbuttoned section (see Figure8a). Figure8c shows the fracture surface of the sample with an

unbuttoning/protrusion pullout mode. Brittle and delaminated fracture is predominant in Figure8c while fine ductile dimples are present on the fracture surface of the sample with completely sheared protrusion (see Figure8d). Conclusively, the dominant presence of fine ductile dimples in the sample with completely sheared protrusion confirms the occurrence of more loadbearing resistance as compared with the sample with sheared protrusion with unbuttoning.

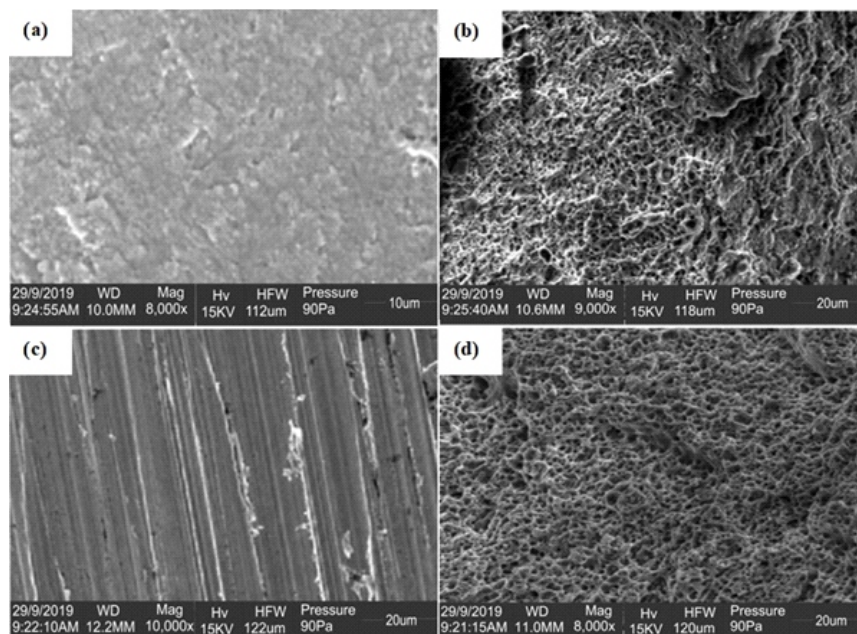


Figure 8: SEM images of the fractured FSC joints (a) and (b) sheared protrusion with unbuttoning, (c) unbuttoning/protrusion pullout, and (d) completely sheared protrusion

## Conclusion

The friction stir clinching (FSC) of the C10100 and AA5456 alloys is investigated by examining the microstructure, weld failure load, and fracture modes of the FSC C10100/AA5456 joints. The findings of the study are summarized as follow:

- i. Protrusion-induced mechanical interlocking is established by the friction stir clinching (FSC) process. The combined effect of mechanical interlocking and metallurgical bonding offers better resistance to tensile loading.
- ii. A direct relationship exists between the tool rotational speed and the maximum/peak temperature readings of the FSC C10100/AA5456 joints. Peak temperatures of 332.4°C, 399.8°C, and 577.1°C were obtained at 900 rpm, 1120 rpm, and 1400 rpm respectively.
- iii. The amount of extruded surface flash increases with the level of the plunge depth. The distance between the weld nugget and the tip/end of the extruded flash increases with plunge depth.
- iv. The weld zones of the joint typically include the stir zone, thermo-mechanically affected zone, heat affected zone, base metal, and thermally affected interfacial/faying zone.
- v. An increase in the tool rotational speed (900 - 1400 rpm) hampers the weld failure load while an improved failure load is obtained by increasing the plunge depth (0.5 -1.5 mm). The highest and the least failure loads of the joints are 2282 N and 1060 N respectively.
- vi. Three forms of fracture modes are obtained namely partially sheared protrusion, completely sheared protrusion, and undamaged protrusion/protrusion pullout. The completely sheared protrusion fracture mode produced the maximum failure load due to the synergetic benefit of protrusion-induced interlocking and metallurgical bonding.

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