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# Effect of Shoulder Size on Weld Properties of Dissimilar Metal Friction Stir Welds

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**This article reports a research study that shows the effect of shoulder diameter size on the resulting weld properties of dissimilar friction stir welds between 5754 aluminum alloy (AA) and C11000 copper (Cu). Welds were produced using three different shoulder diameter tools: 15, 18, and 25 mm by varying the rotational speed between 600 and 1200 rpm and the traverse speed between 50 and 300 mm/min to achieve the best result. Each parameter combination was chosen to represent different heat input conditions (low, intermediates and high). The welds were characterized through microstructural evaluation, tensile testing, microhardness measurements, x-ray diffraction analysis, and electrical resistivity. Microstructural evaluation of the welds revealed that the welds produced consisted of all the friction stir welding (FSW) microstructure zones with organized flow lines comprising mixture layers of aluminum (Al) and copper (Cu) at the Stir Zones. The average Ultimate Tensile Strength (UTS) of the welds considered ranged from 178 to 208 MPa. Higher Vickers microhardness values were measured at the joint interfaces of all the welds because of the presence of intermetallic compounds in these regions. The x-ray diffraction analysis revealed the presence of $Al_4Cu_9$ and $Al_2Cu$ intermetallics at the interfacial regions, and low electrical resistivities were obtained at the joint interfaces. An optimized parameter setting for FSW of Al and Cu was obtained at the weld produced at 950 rpm and 50 mm/min with the 18-mm shoulder diameter tool.**

**Keywords** dissimilar, electrical resistivity, friction stir welding, microstructure, x-ray diffraction

## 1. Introduction

Friction stir welding (FSW) is a solid-state welding technique which allows a range of parts and geometries to be welded. It was invented at The Welding Institute (TWI) in the United Kingdom in 1991 (Ref 1). Since its invention, the process has been continually improved and its scope of application expanded. FSW is a continuous process that involves plunging a portion of a specially shaped rotating tool between the butting faces of the joint. The relative motion between the tool and the substrate generates frictional heat that creates a plasticized region around the immersed portion of the tool. The tool shoulder prevents the plasticized material from being expelled from the weld. The tool is traversed along the joint line, forcing the plasticized material to coalesce behind the tool to form a solid-phase joint. The benefits of FSW include: low distortion, greater weld strength compared to the fusion welding process, absence of filler metals, no welding fumes or gases, little or absence of porosity, and lower cost in production applications (Ref 2). The microstructural evolutions after the FSW process are characterized by three zones (Ref 3),: the Stir Zone (SZ), the Thermo-Mechanically Affected Zone (TMAZ), and the Heat-Affected Zone (HAZ). The SZ is characterized by fine grains, and the TMAZ is known to have elongated grains. The HAZ is a region that has experienced thermal cycle but no plastic deformation has occurred. Although FSW gives high-quality welds, proper implementation of the process and control of a number of parameters are required for a successful outcome (Ref 4). Process parameters, such as the tool design, welding parameters, joint configuration, tool displacement, and the heat input during the process have been studied extensively and established to exert significant effect on the material flow and the resulting weld properties (Ref 4-7), while few studies have been conducted on the effect of shoulder size on the joint properties of friction stir welds (Ref 8, 9). The FSW tool shoulders are usually designed to produce heat through friction and material deformation to the surface and subsurface of the workpiece. Also, the shoulder produces the downward forging action necessary for weld consolidation (Ref 5). Elangovan and Balasubramanian (Ref 8) conducted a research study on the influence of different tool geometries and shoulder diameters on friction stir-processed zone in aluminum; they found that the square pin profiled tool with the 18-mm shoulder diameter tool produced a defect free weld compared to other geometries employed. Also, Zhang et al. (Ref 9) in a research study conducted on the effect of shoulder size on the temperature rise and the material deformation in FSW of aluminum concluded that based on numerical results, the SZ of the welds can be enlarged by an increase of the shoulder size using the same pin diameter. High-quality joints between Al and Cu will promote the use of such joints in industrial applications especially in the field of electrical components. Previous reports showed that brittle intermetallic compounds

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are formed in the Al/Cu interfacial region which negatively affects the toughness and resistivity of the joint (Ref 10-12). However, there is a gap in knowledge on optimized process parameter to join aluminum and copper. As far as the author know, no literature exists on the effect of shoulder diameter size on weld properties of dissimilar friction stir welds of aluminum and copper. Therefore, this article reports the successful joining of 5754 aluminum alloy (AA) and commercially pure Cu through FSW process, using three different shoulder diameter tools by varying the rotational and traverse speeds. The weld properties were quantified through microstructural evaluation, tensile testing, microhardness measurements, XRD analysis, and electrical resistivities of the joints to achieve the best result. The results of the best weld obtained in each weld group with respect to the tensile strengths of the joints produced are presented and discussed.

## 2. Experimental Set Up

Friction stir welds in butt joint configuration were produced on 600 mm × 120 mm × 3.175 mm thick sheets of 5754 aluminum alloy (AA) and C11000 copper (Cu) with an MTS Intelligent Stir Welding for Industry and Research Process Development System (I-STIR PDS) FSW platform at the Friction Processing Research Institute (FPRI) of Nelson Mandela Metropolitan University, South Africa. The Cu sheet is classified as commercially pure with an average Ultimate Tensile Strength (UTS) of 243 MPa, and the AA had the UTS of 266 MPa. The surfaces of both sheets were cleaned with acetone before the welding process. The Cu sheet was placed at the advancing side (AS) and the AA at the retreating side (RS) during the welding process. The tool pin was plunged in the AA and made to touch Cu during the welding procedure. Three different tools—15-, 18-, and 25-mm shoulder diameter tools with a constant tool pin diameter of 5 mm were employed to produce the welds. The tools were machined from H13 tool steel and hardened to 52 HRC. The features of the tools were threaded pins with concave shoulders. The rotational speeds of 600, 950, and 1200 rpm; and feed rates at 50, 150, and 300 mm/min were chosen to represent low, medium, and high settings, respectively. Other parameters such as the tool tilt angle and the dwell time were kept constant at 2° and 2 s, respectively. Microstructural evaluation of the weld cross section was conducted on Olympus PMG3 Optical microscope. The AA side was etched with flicks reagent, and the Cu was etched with a solution of 25 mL distilled water, 25 mL ammonia water, and 15 mL hydrogen peroxide 3%. The Vickers microhardness profiles were measured 1.5 mm below the weld surface along the cross sections of the welds with a load of 200 gf and a dwell time of 15 s, using an FM-ARS 9000 automatic indenter. The tensile tests were conducted using a servo-hydraulic Instron 8801 tensile machine according to ASTM E8 standard. The x-ray diffraction was conducted using an x-ray diffractometer (Bruker D8 Advance) equipped with standard Bragg-Brentano geometry with Cu (Kα) radiation and a Ni filter at the detector. The 2θ scan range was from 20° to 70° at 0.02° per step. The source and detector slit width were 1 mm and 0.2 mm, respectively. The electrical resistance was measured using a Signatone Four-Point probe meter with 1.6-mm probe spacing, and the sample cross sectional area was 127 $mm^2$.

## 3. Results and Discussion

### 3.1 Weld Matrix at a Glance

Based on the preliminary welds produced, the final weld matrix (3 × 3 × 3) comprising 27 welds (nine welds with each shoulder diameter) were produced. The weld settings were selected to represent the widest range of possible combinations within the limit of the FSW platform. The rotational speeds of 600, 950, and 1200 rpm were chosen to represent low, medium, and high setting, respectively, while 50, 150, and 300 mm/min were the feed rates considered representing, respectively, the low, medium, and high settings. A listing of the parameter combinations, heat input conditions, and their corresponding weld numbers are presented in Table 1. The heat input conditions were defined according to Vilaça et al. (Ref 13). At a constant rotational speed, the high heat input condition is achieved at the lowest feedrate considered, while the weld produced at the highest feed rate is considered to have a low heat input in the setting. The intermediate heat input condition is the weld produced at the medium feed rate within the setting.

### 3.2 Top Surface Appearances

The crowns of the representative welds, that is, the best weld obtained in each weld group with respect to the tensile strengths of the joints produced using the different shoulder diameters

**Table 1 Weld matrix and the heat input conditions using the (a) 15-mm, (b) 18-mm, and (c) 25-mm shoulder diameter tool**

| Weld no. | Rotational speed, rpm | Feed rate, mm/min | Heat input condition |
|---|---|---|---|
| (a) 15 mm | | | |
| S15_01 | 600 | 50 | High |
| S15_02 | 600 | 150 | Intermediate |
| S15_03 | 600 | 300 | Low |
| S15_04 | 950 | 50 | High |
| S15_05 | 950 | 150 | Intermediate |
| S15_06 | 950 | 300 | Low |
| S15_07 | 1200 | 50 | High |
| S15_08 | 1200 | 150 | Intermediate |
| S15_09 | 1200 | 300 | Low |
| (b) 18 mm | | | |
| S18_01 | 600 | 50 | High |
| S18_02 | 600 | 150 | Intermediate |
| S18_03 | 600 | 300 | Low |
| S18_04 | 950 | 50 | High |
| S18_05 | 950 | 150 | Intermediate |
| S18_06 | 950 | 300 | Low |
| S18_07 | 1200 | 50 | High |
| S18_08 | 1200 | 150 | Intermediate |
| S18_09 | 1200 | 300 | Low |
| (c) 25 mm | | | |
| S25_01 | 600 | 50 | High |
| S25_02 | 600 | 150 | Intermediate |
| S25_03 | 600 | 300 | Low |
| S25_04 | 950 | 50 | High |
| S25_05 | 950 | 150 | Intermediate |
| S25_06 | 950 | 300 | Low |
| S25_07 | 1200 | 50 | High |
| S25_08 | 1200 | 150 | Intermediate |
| S25_09 | 1200 | 300 | Low |

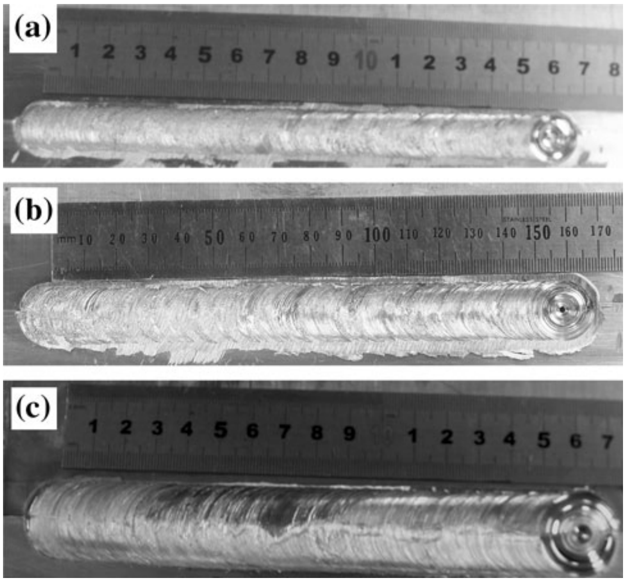


**Fig. 1** (a) Weld produced at 950 rpm and 150 mm/min with the 15-mm shoulder diameter tool. (b) Weld produced at 950 rpm and 50 mm/min with the 18-mm shoulder diameter tool. (c) Weld produced at 950 rpm and 150 mm/min with the 25-mm shoulder diameter tool

employed in this research study are presented in Fig. 1(a)-(c). All the welds were produced with the tool pin plunged in the AA at a distance of 2.5 mm from the weld center line.

The length of the weld produced for each setting was 160 mm as shown in the Fig. 1(a)-(c). The top surface appearances of the welds look similar, the only difference being the width of the stirring zone after the welding procedure which is usually about 2 mm wider than the respective shoulder diameters of the tools. This is typical of all friction stir welds.

### 3.3 Macrographs and Microstructural Evaluation of the Welds

Figure 2(a)-(c) present the macrographs and the corresponding microstructures of the respective SZs of the welds.

The resulting microstructure and subsequent property distribution during FSW are dependent on several factors which include the welding parameters and the tool geometry employed (Ref 6). In this research study, it was observed that the microstructure of the SZs of the welds (Fig. 2aii-cii) did not have the onion ring feature typical to FSW macrograph usually found in butt joints of aluminum and its alloys. The SZs were characterized by organized flow lines resulting from the mechanical stirring of the tool during the process. Flow lines are mixture layers of both materials joined, showing the pattern of material flow during the FSW process. Good material flow is synonymous to good weld (Ref 5). It was observed that the mixture layers are more pronounced in the welds produced with the 15- and 18-mm shoulder diameter tools. The microstructure of the weld produced with the 25-mm shoulder diameter tool (Fig. 2cii) is characterized by an opening in Al occupied by Cu fragments during the welding procedure. This can be attributed to the size of the shoulder diameter employed (25 mm) compared to the two others considered in this research study. It is known that increasing the tool shoulder diameter has practical limitations (Ref 8); in this case, the 25-mm shoulder diameter tool did not achieve good material flow around the pin as shown the weld microstructure in Fig. 2(cii).

Table 2 presents the sizes of the SZs of the three welds discussed; it was observed that the widths of the SZs of all the welds produced in this research study are almost the same irrespective of the size of the shoulder diameter employed.

This is contrary to the report of Zhang et al. (Ref 9): the numerical results indicated that the stirring zone of welds on aluminum can be enlarged by increasing the shoulder size using the same pin diameter. It should be noted that the weld produced with the 25-mm shoulder diameter tool has the least width of SZ.

### 3.4 Tensile Properties

Table 3 presents the average UTS and the Weld Joint Efficiency ($\eta$) of the FSWs produced at 950 rpm and 150 mm/min, 950 rpm and 50 mm/min, and 950 rpm and 150 mm/min with the 15-, 18-, and 25-mm shoulder diameter tools, respectively.

The Weld Joint Efficiency ($\eta$) that is, the ratio of the joint strength compared to the strength of the parent material usually expressed in percentage varies from 100% for a perfect weld down to 75-85% for an acceptable weld (Ref 14). Notably, the weld produced at 950 rpm and 50 mm/min with the 18-mm shoulder diameter tool has the highest Weld Joint Efficiency. The tensile behaviors of the welds are presented in Fig. 3.

It was observed that the welds produced at 950 rpm and 50 mm/min with the 18-mm shoulder diameter tool have more ductile behavior compared with the other welds. With respect to the tensile results, there is an indication that the 18-mm shoulder diameter tool is suitable for achieving good joints between Al and Cu, and it can be referred to as the optimized parameter setting in this regard.

### 3.5 Microhardness Distribution

The microhardness profiles of the friction stir welds produced at 950 rpm and 150 mm/min, 950 rpm and 50 mm/min, and 950 rpm and 150 mm/min with the 15-, 18-, and 25-mm shoulder diameter tools, respectively are presented in Fig. 4. The average Vickers microhardness values of the base metals AA was HV 60 and that of copper (Cu) was HV 95.

It was observed that in all the welds, higher Vickers microhardness values were measured at the interfacial regions, which were the positions previously occupied by the tool pin and the shoulder during the welding process. The increase in the microhardness values in these regions can be attributed to dynamic recrystallization which has occurred during the welding process or because of the presence of intermetallic compounds. It is worthy to note that the Vickers microhardness measured at the joint interface of the weld produced with the 25-mm shoulder diameter tool is not as high, as in the cases of 15 mm and 18 mm, which can be attributed to the fact that the level of deformation experienced in this weld is low compared with the other two presented.

### 3.6 X-Ray Diffraction Analysis

X-ray diffraction (XRD) analysis was conducted on the joint interfaces of the joints produced to identify the phases present at the interfacial regions where high Vickers microhardness values were measured. The diffractograms of the welds considered are presented in Fig. 5(a)-(c).

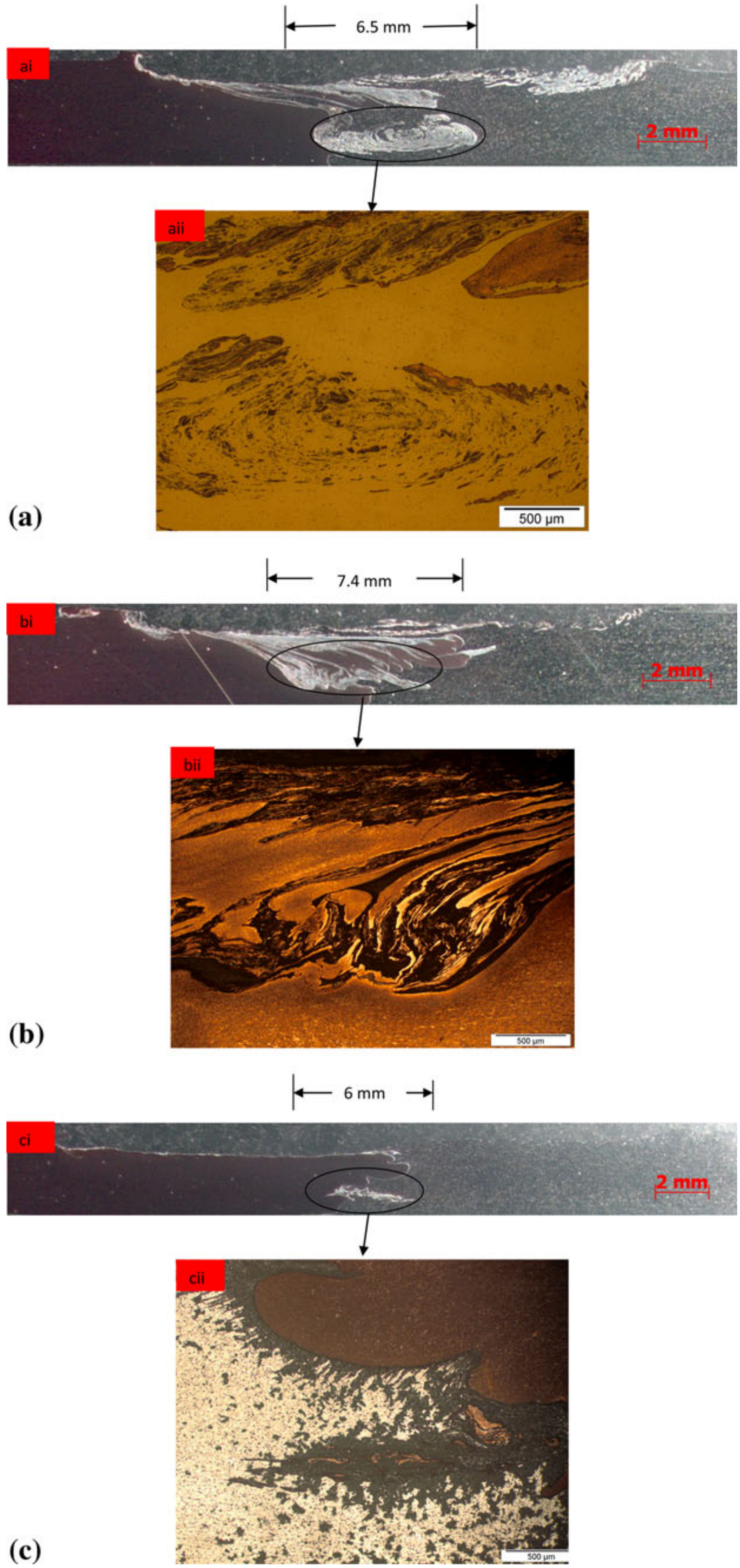


**Fig. 2** (i) Macrographs and (ii) microstructures of etched Stir Zones of the welds produced at (a) 950 rpm and 150 mm/min with the 15-mm shoulder diameter tool, (b) 950 rpm and 50 mm/min with the 18-mm shoulder diameter tool, and (c) 950 rpm and 150 mm/min with the 25-mm shoulder diameter tool

**Table 2 Data obtained for size of Stir Zones**

| Sample | Rotational speed, rpm | Feed rate, mm/min | Size of Stir Zone, mm |
|---|---|---|---|
| S15_05 | 950 | 150 | 6.5 |
| S18_04 | 950 | 50 | 7.4 |
| S25_05 | 950 | 150 | 6.0 |

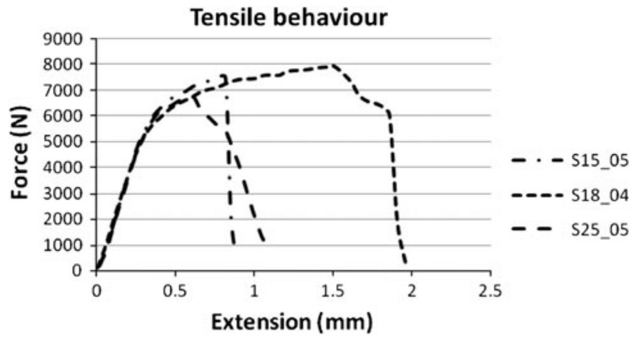


**Fig. 3** Tensile behaviors of welds produced at 950 rpm and 150 mm/min with the 15-mm shoulder diameter tool (S15_05), 950 rpm and 50 mm/min with 18-mm shoulder diameter tool (S18_04), and 950 rpm and 150 mm/min with the 25-mm shoulder diameter tool (S25_05)

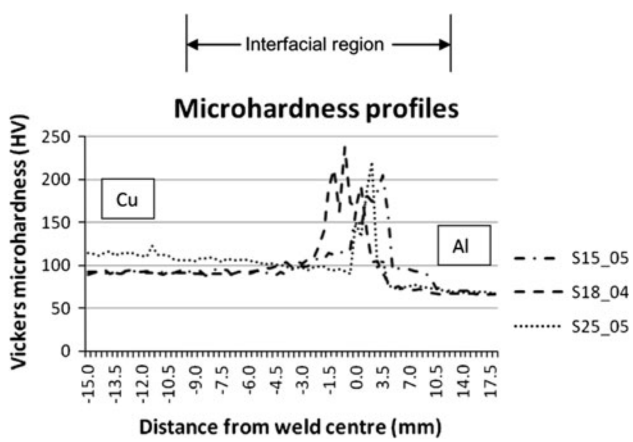


**Fig. 4** Microhardness profiles of welds produced at 950 rpm and 150 mm/min with the 15-mm shoulder diameter tool (S15_05), 950 rpm and 50 mm/min with 18-mm shoulder diameter tool (S18_04), and 950 rpm and 150 mm/min with the 25-mm shoulder diameter tool (S25_05)

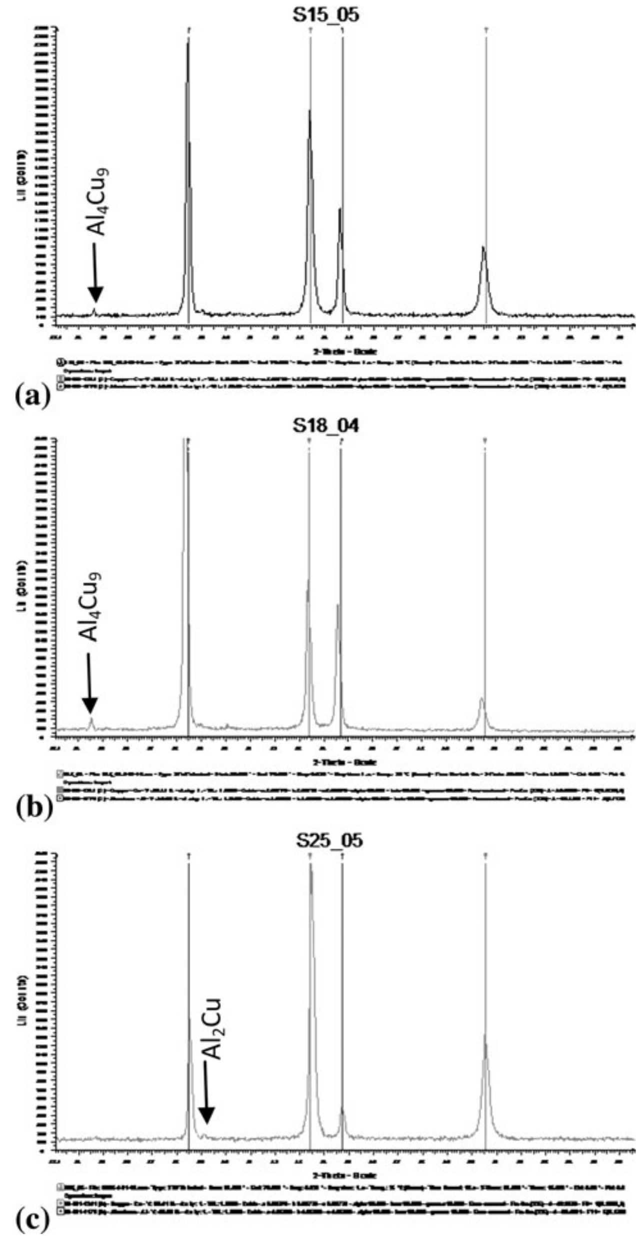


**Fig. 5** (a) Diffractogram of a weld produced with the 15-mm shoulder diameter tool at 950 rpm and 150 mm/min, (b) Diffractogram of a weld produced with the 18-mm shoulder diameter tool at 950 rpm and 50 mm/min, and (c) Diffractogram of a weld produced with the 25-mm shoulder diameter tool at 950 rpm and 150 mm/min

**Table 3 Average Ultimate Tensile Strength (UTS) and the Weld Joint Efficiency (η) of the welds**

| Weld no. | Shoulder diameter, mm | Rotational speed, rpm | Feed rate, mm/min | Heat input condition | Mean UTS, MPa | η compared to Cu parent material, % |
|---|---|---|---|---|---|---|
| S15_04 | 15 | 950 | 150 | Intermediate | 191 | 79 |
| S18_04 | 18 | 950 | 50 | Hot | 208 | 86 |
| S25_05 | 25 | 950 | 150 | Intermediate | 178 | 73 |

The slight shifts in the main Al and Cu peak positions observed in the diffraction patterns are possibly due to sample displacement and preparation on the diffractometer. It was observed that the most common intermetallic compounds formed at the joint interfaces of the welds are $Al_4Cu_9$ and $Al_2Cu$. These intermetallic compounds are hard and brittle in nature, and are thermally activated (Ref 12). Hence, high Vickers microhardness values are measured at the joint

**Table 4 Electrical resistivities of the parent materials and the joints**

| Weld No. | Rotational speed, rpm | Traverse speed, mm/min | Electrical resistivity, μΩ | Percentage increase in electrical resistivity (%) compared to the joint resistance |
|---|---|---|---|---|
| S15_05 | 950 | 150 | 0.098 | 6.5 |
| S18_04 | 950 | 50 | 0.101 | 9.7 |
| S25_05 | 950 | 150 | 0.097 | 5.4 |
| Aluminum parent material | | | 0.088 | |
| Copper parent material | | | 0.096 | |
| Average joint resistance of the parent materials | | | 0.092 | |

interfaces. It is notable that the peaks are weak in the welds because of low concentration of the intermetallics formed.

### *3.7 Electrical Resistivities of the Joints*

The electrical resistivities of the joint interfaces of the welds were determined from the measurements of the electrical resistances. The data obtained are presented in Table 4.

It was found that the percentage increases in the electrical resistivities of the welds compared to the parent materials are low. This is an indication that these welds were successful welds with excellent joint integrities.

## 4. Conclusion

Friction stir welds between 5754 aluminum alloy and C11000 copper were successfully produced using three different shoulder diameter tools—15, 18, and 25 mm by varying the rotational and the traverse speeds. The best weld in each weld group was found to be produced with either intermediate or hot welding condition at a constant rotational speed of 950 rpm. The material flow pattern observed at the SZs of the welds indicated that the 15- and 18-mm shoulder diameter tools are more appropriate than the 25-mm shoulder diameter tool. The higher Vickers microhardness measured at the joint interfaces was attributed to recrystallized grains and the presence of intermetallics in these areas as a result of heat input during the welding process. Tensile test results showed that the welds under discussion have Weld Joint Efficiencies of between 73 and 86%, and can be acceptable for design process. Also, the welds considered have low percentage increase in electrical resistivities; hence, the settings can be recommended for successful joints between Al and Cu.


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