# Fracture Location Characterizations of Dissimilar Friction Stir Welds

Esther T. Akinlabi and Stephen A. Akinlabi

***Abstract*—**This paper reports the tensile fracture location characterizations of dissimilar friction stir welds between 5754 aluminium alloy and C11000 copper. The welds were produced using three shoulder diameter tools; namely, 15, 18 and 25 mm by varying the process parameters. The rotational speeds considered were 600, 950 and 1200 rpm while the feed rates employed were 50, 150 and 300 mm/min to represent the low, medium and high settings respectively. The tensile fracture locations were evaluated using the optical microscope to identify the fracture locations and were characterized. It was observed that 70% of the tensile samples failed in the Thermo Mechanically Affected Zone (TMAZ) of copper at the weld joints. Further evaluation of the fracture surfaces of the pulled tensile samples revealed that welds with low Ultimate Tensile Strength either have defects or intermetallics present at their joint interfaces.

***Keywords*—**fracture location, friction stir welding, intermetallics, metallography,

## I. Introduction

FRICTION Stir Welding (FSW) is a solid–state joining technique invented and patented by The Welding Institute (TWI) in 1991 for butt and lap welding of ferrous and non–ferrous metals and plastics [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 schematic diagram of the FSW process is presented in Fig 1.

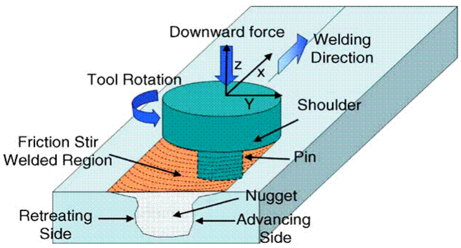


Fig. 1 Schematic diagram of FSW [2]

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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 resulting microstructure of Friction Stir welds are categorized into three distinct regions [3], viz: the Heat-Affected Zone (HAZ), which lies closer to the weld-center, the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties; the Thermo-Mechanically Affected Zone (TMAZ), in this region, the FSW tool has plastically deformed the material, and the heat from the process have exerted some influence on the material and the Weld Nugget (WN) sometimes referred to as the Stir Zone (SZ) is the fully recrystallized area, which refers to the zone previously occupied by the tool pin. The term stir zone is commonly used in friction stir processing, where large volumes of materials are processed. The benefits of this technology include: low distortion, greater weld strength compared to the fusion welding process, no filler metals, no welding fumes or gases, improved corrosion resistance, and lower cost in production applications [4]. Because of the many demonstrated advantages of FSW over fusion welding techniques, the commercialization of FSW is proceeding at a rapid pace and this is brought about by an understanding of the relationship between the process parameters and the resulting weld properties. Yield and tensile strength of Friction Stir welded samples for example are usually assessed to compare the strength and ductility of the welded samples to the base materials. This is often related to the resulting hardness. Many investigators have reported tensile strengths of Friction Stir welded joints as a percentage relative to that of the parent materials; and some have studied its relationship to the process parameters [5-7]. Also, published literature [8-9] of friction stir welding of aluminium and copper are not focused on fracture location characterizations of the tensile samples. The authors found that characterization of the tensile fracture locations which could be an indication to improving the quality of the welds produced has not been well studied. Liu *et al* [10] studied the tensile fracture locations of different aluminium alloys and found that the fracture locations of the joints are dependent on the internal structure of the joints. The aim of this study is to characterize the tensile fracture locations of dissimilar friction stir welds between aluminium and copper.

## II. Experimental Set-Up

The Friction Stir welds between 5754 aluminium alloy and C11000 copper were produced at the Nelson Mandela Metropolitan University (NMMU), Port Elizabeth, South Africa using an Intelligent Stir Welding for Industry and Research Process Development System (I-STIR PDS) platform. The experimental set-up is presented in Fig 2.

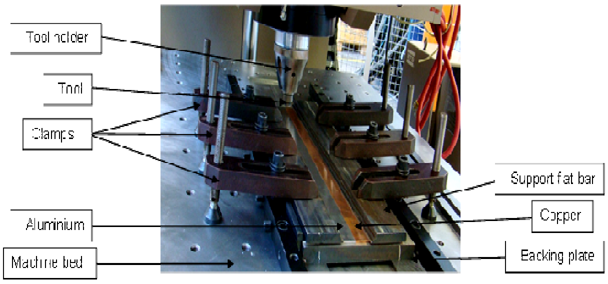


Fig. 2 Experimental set-up for FSW of aluminium and copper

The welds were produced using three different shoulder diameter tools viz: 15, 18 and 25 mm with a constant tool pin diameter of 5 mm. The Copper sheet was placed at the advancing side while the tool pin was plunged in the Aluminium Alloy and made to touch Copper during the welding procedure. The rotational speeds of 600, 950 and 1200 rpm were employed while 50, 150 and 300 mm/min were the feed rates considered representing low, medium and high settings respectively. The fracture locations were identified using the Zeiss microscope. The aluminium alloy side was etched with Keller's reagent and the Cu was etched with modified Poulton's reagent.

## III. Results And Discussion

### A. Fracture location characterization

The fracture locations of all the tensile samples of the weld matrix with respect to the shoulder diameter tools are presented in Appendix A. Table 1 presents the fracture locations and the percentages compared with the overall number of tensile samples produced. Three samples were taken from each weld, indicated as T1, T2 and T3 in the Appendix A, B and C corresponding to the first, second and third tensile sample taken from each weld respectively.

TABLE I
FRACTURE LOCATION CHARACTERIZATIONS

| Shoulder ϕ (mm) | Fracture at the TMAZ Al | % compared to total number of samples | Fracture at the TMAZ Cu | % compared to total number of samples |
|---|---|---|---|---|
| 15 | 8 | 30 | 19 | 70 |
| 18 | 8 | 30 | 19 | 70 |
| 25 | 10 | 37 | 17 | 63 |

From Table 1, it was observed that 70, 70 and 63% of the tensile samples fractured in the region of the TMAZ of copper in welds produced with the 15, 18 and 25 mm shoulder diameter tools respectively. In FSW, it is known that the advancing sides in welds are usually weaker than the retreating side because defects such as voids and wormholes are usually formed on the advancing side [11]. The higher percentage of the fractured samples on the TMAZ of copper placed at the advancing side during the welding process can be attributed to this fact. Other samples that failed in aluminium placed at the retreating side could be due to low clamping force on the work pieces resulting in poor bonding, although all efforts were made to ensure that the plates were properly clamped before the welding process commenced.

### B. Characterization of the fracture surfaces

The fracture surfaces of the welds that had low UTS were further evaluated. The photo montages of these welds are presented in Fig 3 (a) and (b).

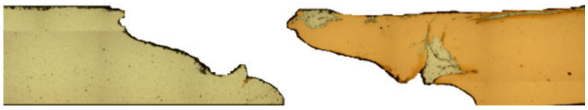

Fig. 3 (a) Fractured surface of weld produced at 950 rpm and 300 mm/min with the 25 mm shoulder diameter tool

Fig. 3 (b) Fractured surface of weld produced at 1200 rpm and 300 mm/min with the 25 mm shoulder diameter tool

It was observed that the fracture locations of these welds all occurred in the TMAZ of Al on the retreating side of the welds. Considering the morphological feature of the joint interfaces, with very little mixing of the two metals achieved; it can be said that the low UTS values obtained in these samples are due to lack of fusion and low metallurgical bonding at the joint interfaces. It should further be noted that most of these welds were produced at high travel speed. This also resulted in limited coalescence and bonding at the joint interface. The fracture locations of samples that failed due to the presence of intermetallic compounds at the joint interfaces are presented in Fig 4 (a) and (b).

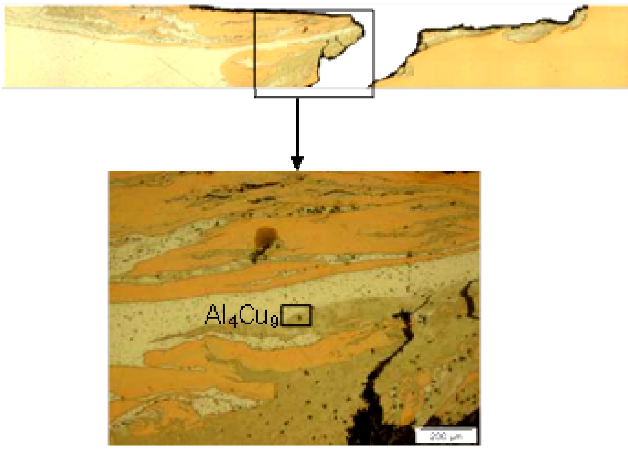


Fig. 4 (a) Fractured surface of weld produced at 950 rpm and 50 mm/min with the 15 mm shoulder diameter tool

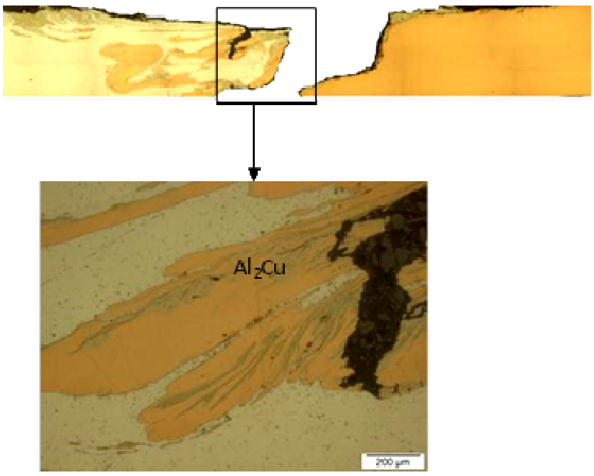


Fig. 4 (b) Fractured surface of weld produced at 600 rpm and 50 mm/min with the 15 mm shoulder diameter tool

The microstructures of the regions indicated with square boxes are shown at higher magnifications. It was observed that most of the samples failed in the region of the TMAZ / SZ of Cu on the advancing side. An Energy Dispersive Spectroscopy (EDS) of the various phases in the samples as shown in the microstructures of the Stir Zones revealed the presence of intermetallic compounds ($Al_4Cu_9$ and $Al_2Cu$). These intermetallic phases are hard and brittle in nature and would therefore rather fracture than be plastically deformed, hence, the presence of secondary cracks running parallel to the main fracture surface as shown in Fig 4 (a) and (b).

## IV. Conclusion

The tensile fracture locations of the welds produced in this research work were evaluated and characterized. It was found that majority of the welds fractured in the advancing side of the weld. Most of the welds with low Ultimate Tensile Strength either have defects or the presence of intermetallic compounds at their joint interfaces. It can be concluded that the evaluation of the tensile fracture locations of the dissimilar Friction Stir welds of aluminium and copper revealed that the fracture locations are dependent on the internal structures of the weld regions, either due to the presence of weld defects or the presence of intermetallic compounds in the joints. Hence, characterizing the fracture locations is important in understanding the joint integrities of the welds.

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APPENDIX

(A) FRACTURE LOCATIONS OF TENSILE SAMPLES OF WELDS PRODUCED WITH THE 15 MM SHOULDER DIAMETER TOOL

| Weld No. | Rotational speed (rpm) | Traverse speed (mm/min) | Tensile sample | Fracture location | Ultimate Tensile Strength (MPa) |
|---|---|---|---|---|---|
| S15_01 | 600 | 50 | T1 | TMAZ Cu | 156 |
| S15_01 | 600 | 50 | T2 | TMAZ Cu | 100 |
| S15_01 | 600 | 50 | T3 | TMAZ Cu | 146 |
| S15_02 | 600 | 150 | T1 | TMAZ Cu | 194 |
| S15_02 | 600 | 150 | T2 | TMAZ Cu | 168 |
| S15_02 | 600 | 150 | T3 | TMAZ Cu | 170 |
| S15_03 | 600 | 300 | T1 | TMAZ Al | 195 |
| S15_03 | 600 | 300 | T2 | TMAZ Al | 215 |
| S15_03 | 600 | 300 | T3 | TMAZ Cu | 166 |
| S15_04 | 950 | 50 | T1 | TMAZ Al | 186 |
| S15_04 | 950 | 50 | T2 | TMAZ Cu | 103 |
| S15_04 | 950 | 50 | T3 | TMAZ Cu | 192 |
| S15_05 | 950 | 150 | T1 | TMAZ Al | 153 |
| S15_05 | 950 | 150 | T2 | TMAZ Al | 219 |
| S15_05 | 950 | 150 | T3 | TMAZ Cu | 201 |
| S15_06 | 950 | 300 | T1 | TMAZ Al | 168 |
| S15_06 | 950 | 300 | T2 | TMAZ Cu | 112 |
| S15_06 | 950 | 300 | T3 | TMAZ Cu | 118 |
| S15_07 | 1200 | 50 | T1 | TMAZ Cu | 155 |
| S15_07 | 1200 | 50 | T2 | TMAZ Cu | 86 |
| S15_07 | 1200 | 50 | T3 | TMAZ Cu | 192 |
| S15_08 | 1200 | 150 | T1 | TMAZ Al | 160 |
| S15_08 | 1200 | 150 | T2 | TMAZ Cu | 170 |
| S15_08 | 1200 | 150 | T3 | TMAZ Cu | 217 |
| S15_09 | 1200 | 300 | T1 | TMAZ Cu | 135 |
| S15_09 | 1200 | 300 | T2 | TMAZ Al | 115 |
| S15_09 | 1200 | 300 | T3 | TMAZ Cu | 165 |

(B) FRACTURE LOCATIONS OF TENSILE SAMPLES OF WELDS PRODUCED WITH THE 18 MM SHOULDER DIAMETER TOOL

| Weld No. | Rotational speed (rpm) | Traverse speed (mm/min) | Tensile sample | Fracture location | Ultimate Tensile Strength (MPa) |
|---|---|---|---|---|---|
| S18_01 | 600 | 50 | T1 | TMAZ Cu | 155 |
| S18_01 | 600 | 50 | T2 | TMAZ Cu | 174 |
| S18_01 | 600 | 50 | T3 | TMAZ Cu | 195 |
| S18_02 | 600 | 150 | T1 | TMAZ Al | 168 |
| S18_02 | 600 | 150 | T2 | TMAZ Cu | 152 |
| S18_02 | 600 | 150 | T3 | TMAZ Cu | 132 |
| S18_03 | 600 | 300 | T1 | TMAZ Cu | 131 |
| S18_03 | 600 | 300 | T2 | TMAZ Al | 160 |
| S18_03 | 600 | 300 | T3 | TMAZ Cu | 151 |
| S18_04 | 950 | 50 | T1 | TMAZ Cu | 229 |
| S18_04 | 950 | 50 | T2 | TMAZ Cu | 187 |
| S18_04 | 950 | 50 | T3 | TMAZ Cu | 209 |
| S18_05 | 950 | 150 | T1 | TMAZ Cu | 195 |
| S18_05 | 950 | 150 | T2 | TMAZ Cu | 190 |
| S18_05 | 950 | 150 | T3 | TMAZ Cu | 210 |
| S18_06 | 950 | 300 | T1 | TMAZ Al | 141 |
| S18_06 | 950 | 300 | T2 | TMAZ Cu | 182 |
| S18_06 | 950 | 300 | T3 | TMAZ Al | 105 |
| S18_07 | 1200 | 50 | T1 | TMAZ Al | 214 |
| S18_07 | 1200 | 50 | T2 | TMAZ Al | 202 |
| S18_07 | 1200 | 50 | T3 | TMAZ Cu | 197 |
| S18_08 | 1200 | 150 | T1 | TMAZ Al | 131 |
| S18_08 | 1200 | 150 | T2 | TMAZ Cu | 190 |
| S18_08 | 1200 | 150 | T3 | TMAZ Cu | 198 |
| S18_09 | 1200 | 300 | T1 | TMAZ Cu | 134 |
| S18_09 | 1200 | 300 | T2 | TMAZ Al | 166 |
| S18_09 | 1200 | 300 | T3 | TMAZ Cu | 198 |

(C) FRACTURE LOCATIONS OF TENSILE SAMPLES OF WELDS PRODUCED WITH THE 25 MM SHOULDER DIAMETER TOOL

| Weld No. | Rotational speed rpm | Traverse speed (mm/min) | Tensile sample | Fracture location | Ultimate Tensile Strength (MPa) |
|---|---|---|---|---|---|
| S25_01 | 600 | 50 | T1 | TMAZ Al | 156 |
| S25_01 | 600 | 50 | T2 | TMAZ Cu | 170 |
| S25_01 | 600 | 50 | T3 | TMAZ Cu | 158 |
| S25_02 | 600 | 150 | T1 | TMAZ Al | 127 |
| S25_02 | 600 | 150 | T2 | TMAZ Al | 126 |
| S25_02 | 600 | 150 | T3 | TMAZ Cu | 105 |
| S25_03 | 600 | 300 | T1 | TMAZ Cu | 126 |
| S25_03 | 600 | 300 | T2 | TMAZ Al | 154 |
| S25_03 | 600 | 300 | T3 | TMAZ Cu | 123 |
| S25_04 | 950 | 50 | T1 | TMAZ Al | 132 |
| S25_04 | 950 | 50 | T2 | TMAZ Cu | 174 |
| S25_04 | 950 | 50 | T3 | TMAZ Cu | 183 |
| S25_05 | 950 | 150 | T1 | TMAZ Al | 159 |
| S25_05 | 950 | 150 | T2 | TMAZ Al | 195 |
| S25_05 | 950 | 150 | T3 | TMAZ Cu | 180 |
| S25_06 | 950 | 300 | T1 | TMAZ Al | 92 |
| S25_06 | 950 | 300 | T2 | TMAZ Cu | 135 |
| S25_06 | 950 | 300 | T3 | TMAZ Cu | 150 |
| S25_07 | 1200 | 50 | T1 | TMAZ Cu | 165 |
| S25_07 | 1200 | 50 | T2 | TMAZ Cu | 141 |
| S25_07 | 1200 | 50 | T3 | TMAZ Cu | 95 |
| S25_08 | 1200 | 150 | T1 | TMAZ Cu | 101 |
| S25_08 | 1200 | 150 | T2 | TMAZ Cu | 120 |
| S25_08 | 1200 | 150 | T3 | TMAZ Cu | 146 |
| S25_09 | 1200 | 300 | T1 | TMAZ Al | 92 |
| S25_09 | 1200 | 300 | T2 | TMAZ Al | 132 |
| S25_09 | 1200 | 300 | T3 | TMAZ Cu | 182 |