

# 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

**F**RICITION 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.

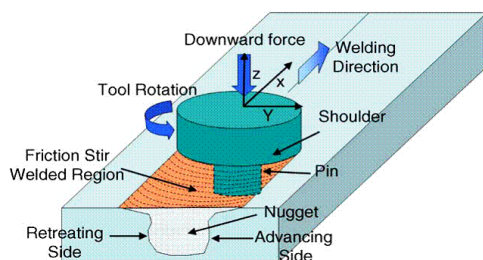


Fig. 1 Schematic diagram of FSW [2]

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.

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## 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.

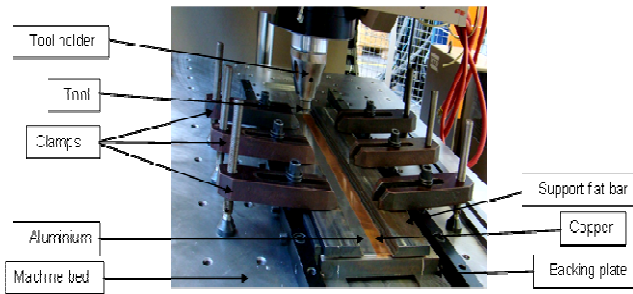


Fig. 2 Experimental set-up for FSW of aluminium and copper

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 $\phi$ (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).

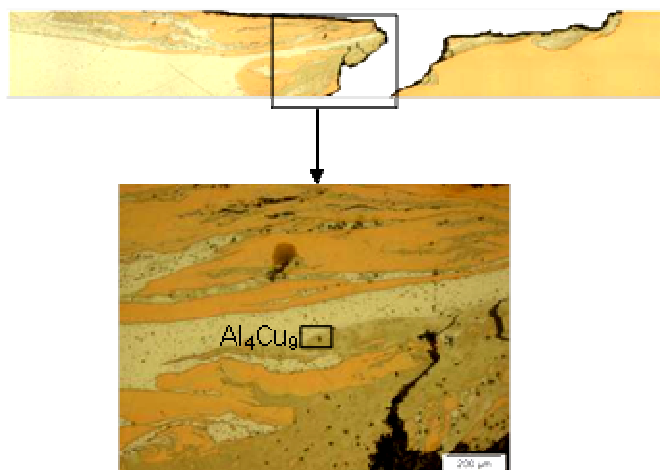


Fig. 4 (a) Fractured surface of weld produced at 950 rpm and 50 mm/min with the 15 mm shoulder diameter tool

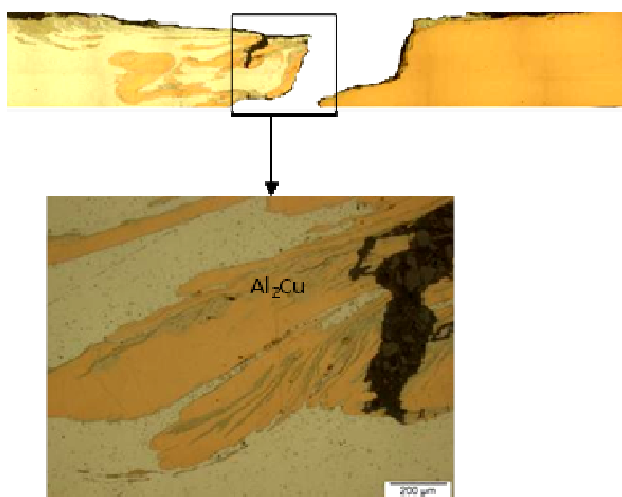


Fig. 4 (b) Fractured surface of weld produced at 600 rpm and 50 mm/min with the 15 mm shoulder diameter tool

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 ( $\text{Al}_4\text{Cu}_9$  and  $\text{Al}_2\text{Cu}$ ). 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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#### REFERENCES

- [1] W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Templesmith and C. J. Dawes. "Improvements relating to Friction Welding". International Patent Application, PCT/GB92/02203 (Patent) December 1991.
- [2] R. S. Mishra and Z. Y. Ma. "Friction stir welding and processing". Materials Science and Engineering R. 2005; 50: pp1-78.
- [3] P. L. Threadgill. "Terminology in friction stir welding". Science and Technology of Welding and Joining. 2007; 12(4): p. 357- 360.
- [4] A. P. Reynolds. "Friction stir welding of aluminium alloys". In: Totten GE, MacKenzie DS (eds.) Handbook of Aluminium, Volume 2 Alloy Production and Materials Manufacturing. New York, Marcel Dekker; 2003. pp. 579-700.
- [5] S. Lim, S. Kim, C. Lee and S. Kim. "Tensile behaviour of friction stir welded Al 6061-T651". Metallurgical and Materials Transactions A 2004; 35: pp. 2829-2835.
- [6] S. Lim, S. Kim, C. Lee and S. Kim. "Tensile behaviour of friction stir welded A356-T6/Al 6061T651 bi-alloy plate". Metallurgical and Materials Transactions A. 2004; 35: pp. 2837-2843.
- [7] L. Ceschini, I. Boromei, G. Minak, A. Morri and F. Tarterini. "Effect of friction stir welding on microstructure, tensile and fatigue properties of the AA7005/10% vol. %Al<sub>2</sub>O<sub>3</sub>P composite". Composites Science and Technology 2007; 67: pp. 605-615.
- [8] J. Ouyang, E. Yarrapareddy and R. Kovacevic. "Microstructural evolution in the friction stir welded 6061 aluminium alloy (T6- temper condition) to copper". Journal of Materials Processing technology 2006; 172: pp. 110-122.
- [9] A. Abdollah – Zadeh, T. Saeid and B. Sazgari. "Microstructural and mechanical properties of friction stir welded aluminium/copper lap Joints". Journal of Alloys and Compounds 2008; 460: pp. 535-538.
- [10] H. Liu, H. Fujii, M. Maeda and K. Nogi. "Tensile fracture location characterizations of friction stir joints of different alloys". Journal of Material Science Technology, 2004; 20: pp. 103-105.
- [11] R. Nandan, T. DebRoy and H. K. D. H. Bhadeshia. "Recent advances in friction stir welding- Process, weldment structure and properties". Progress in Material Science 2008; 53: pp. 980-1023.

## 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