CHAPTER 4: ENGINEERING MATERIALS AND APPLICATIONS

Effect of Travel speed on Joint properties of Dissimilar Metal Friction Stir Welds.

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ABSTRACT
This paper reports the effect of traverse speed on joint properties of dissimilar metal friction stir welds between aluminium and copper sheets. Welds in butt joint configurations were produced between 5754 Aluminium Alloy (AA) and C11000 Copper (Cu). The welds were produced at a constant rotational speed of 950 rpm and the traverse speed was varied between 50 and 300 mm/min while all other parameters were kept constant. Microstructural evaluation of the welds revealed that at a constant rotational speed and varying the traverse speed, better mixing of both metals and metallurgical bonding were improved at the lowest traverse speed. The average Ultimate Tensile Strength of the welds decreased as the welding speed increased. Higher Vickers microhardness values were measured at the Thermo-Mechanically Affected Zones (TMAZ) and Stir Zones (SZ) of the welds due to dynamic recrystallization and also due to the presence of intermetallic compounds formed in the joint regions. Unlike with similar metal welds which showed a smooth force feedback curve, it was found that a significant variation in force feedback data was obtained for dissimilar metal welds.

KEYWORDS: Dissimilar metal; Friction Stir Welding; Macrostructure; Process parameters.

1.0 INTRODUCTION
Friction Stir Welding (FSW) is a solid-state joining technique invented and patented by The Welding Institute (TWI) UK in 1991 for butt and lap welding of ferrous and non-ferrous metals and plastics (Thomas *et al*. 1991). Although FSW gives high quality welds, proper use of the process and control of a number of process parameters is needed to achieve this (Kumar and Kailas, 2008). Process parameters such as tool design, input welding parameters, joint configuration, tool displacement, forces acting on the tool during the welding process and the heat input into the weld during the process, are found to exert significant effect on the material flow and temperature distribution (Record *et al*. 2004; Akinlabi *et al*. 2010), thereby influencing the microstructural evolution and mechanical properties of the joints.

Most research work reported on process-property relationship in FSW is carried out on aluminium alloys (Reynolds *et al*. 2000; Shukla and Baeslack, 2005). However, there have been recent reports on FSW of aluminium and copper (Elrefaey *et al*. 2005; Liu *et al*. 2008); although, the focus has been on microstructural evaluation. In this report, defect-free welds of dissimilar friction stir welds of aluminium and copper were produced and characterised through microstructural evaluation, tensile testing and microhardness profiling. As part of our effort to relate the process parameters to the resulting properties of the welds, the effect of the traverse speed on the joint properties of the welds were studied. The force feedback obtained was also compared to that of a butt weld using similar materials.

2.0 EXPERIMENTAL PROCEDURE

The parent materials used in the research study were 5754 Aluminium Alloy (AA) and C11000 Copper (Cu). The Ultimate Tensile Strength of the AA was 266 MPa and that of Cu was 244 MPa. The dimensions of the test samples were 600 mm x 120 mm x 3.175 mm. The surfaces of both sheets were cleaned with acetone before the welding procedure. Cu was placed at the advancing side and the tool pin was plunged in the AA. Friction Stir welds were produced using position control on an Intelligent Stir Welding for Industry and Research Process Development System (I-STIR PDS) platform at a constant rotational speed of 950 rpm and the welding speed at 50, 150 and 300 mm/min. The tool was machined from H13 tool steel and hardened to 52 HRC having a shoulder diameter of 18 mm, pin diameter 5 mm, and a pin length of 2.6 mm. The features on the tool were cylindrical threaded pin and a concave shoulder. For microstructural evaluation, samples were cut at 50 mm length from the start of the weld in a transverse direction. The aluminium 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% in order to reveal the microstructure. The Vickers microhardness profiles were measured using an FM-ARS 9000 automatic indenter according to ASTM 384. The measurements were made along the cross-sections of the welds at 1.5 mm below the surface with a load of 200g and a dwell time of 15 seconds. The tensile samples were cut perpendicularly to the weld direction and the tests were conducted using a servo-hydraulic Instron 8801 tensile machine according to ASTM E8 standard.

3.0 RESULTS AND DISCUSSION

3.1 FSW data and force feedback

The weld data captured during the welding process are presented in Table 1. The output process parameters viz; the advancing force (F_x), the vertical downward force (F_z) and the torque (T) presented are average values obtained between 30 mm and 130 mm of weld length. The heat input was calculated using equation (1), where Q (J/mm) is the heat input, η the efficiency factor (0.9 for Al and Cu), ω (rpm) the rotational speed, T (Nm) is the response torque and f (mm/min) the feed rate (traverse speed).

$$Q = \eta \frac{2\pi\omega T}{f} \tag{1}$$

Table 1: FSW data

Weld No.	Rotational speed, ω (rpm)	Feed rate, f (mm/min)	Advancing force, F_x (kN)	Vertical downward force, Fz (kN)	Torque (Nm)	Resultant Heat input, Q (J/mm)
W01	950	50	2.85	11.6	12.8	1375
W02	950	150	3.12	14.5	15.2	543
W03	950	300	3.47	16.7	17.4	293

It was observed that the advancing force F_x, the torque T and consequently the heat input to the welds, Q, decreased as the vertical downward force F_z increases. Analysis of forces acting during the FSW process was conducted by Vilaça *et al.* (2007); in which the downward vertical force was related to the mechanical power delivered by the tool into the plates. It was reported that both the advancing force and torque, and consequently, the total mechanical power delivered by the tool into the parts being welded, increase with an increase in the vertical downward force. Further observation of the force feedback showed a significant variation of the forces during the welding process compared to those obtained for butt welds of single alloys. Figure 1(a) and (b) illustrate the force feedback plots for Al-Cu produced at

950 rpm and 50 mm/min; and a butt weld of Titanium (Ti-6Al-4V) produced at 950 rpm and 55 mm/min by Mashinini (2010).

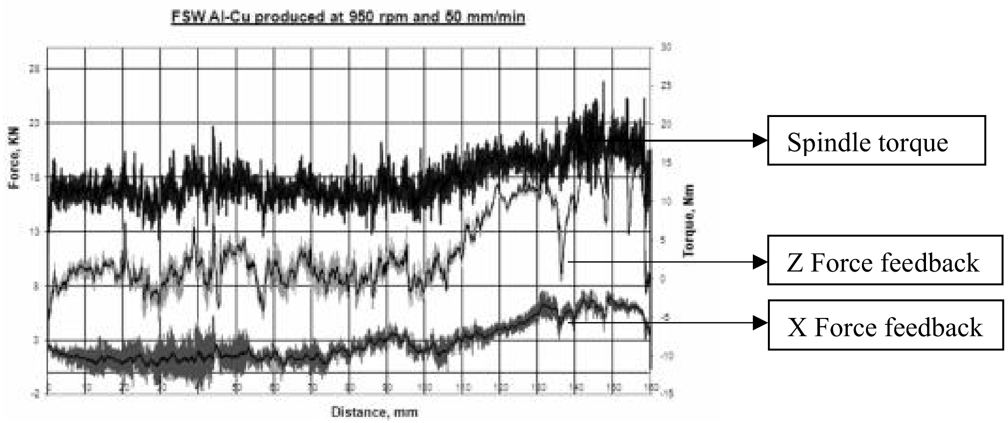

Figure 1(a): Force feedback of FSW Al-Cu produced at 950 rpm and 50 mm/min.

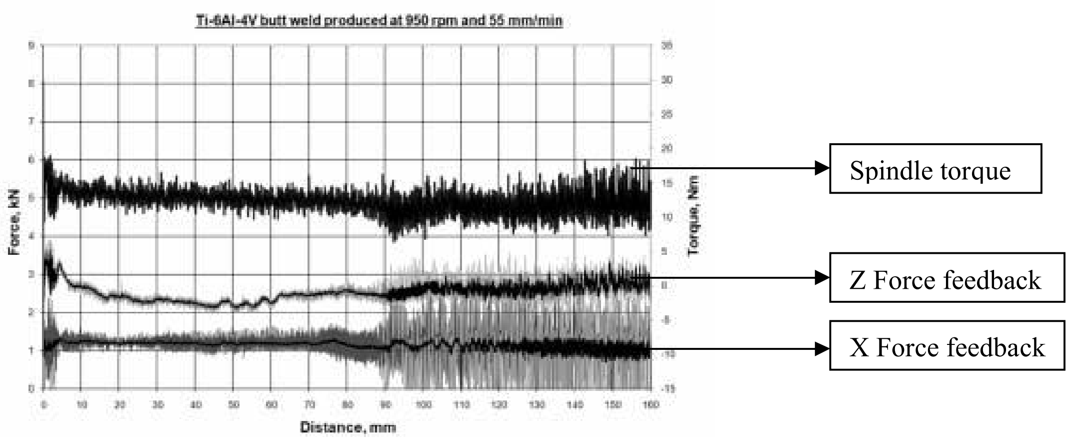

Figure 1(b): Force feedback of FSW Ti-6Al-4V produced at 950 rpm and 55 mm/min (Mashinini, 2010).

Further work is ongoing to attempt to quantify the amount of the variation of forces during the welding process and also to identify possible means to achieve a smooth curve (preferred).

3.2 Optical macrographs

Figures 2(a), (b) and (c) present macrostructures (through the cross-section) of the welds produced at 950 rpm and at 50, 150 and 300 mm/min respectively.

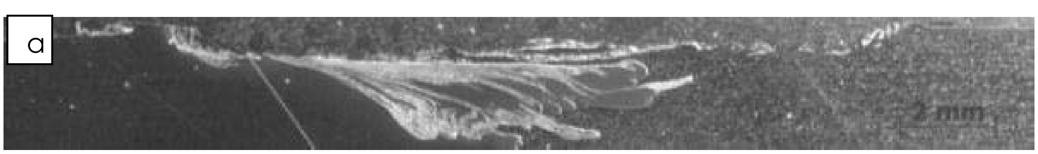

Figure 2(a): FSW produced at 950 rpm and 50 mm/min

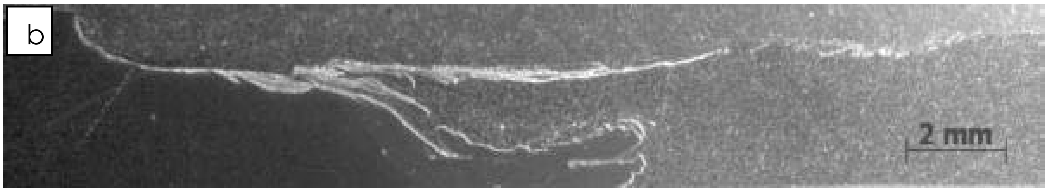

Figure 2(b): FSW produced at 950 rpm and 150 mm/min

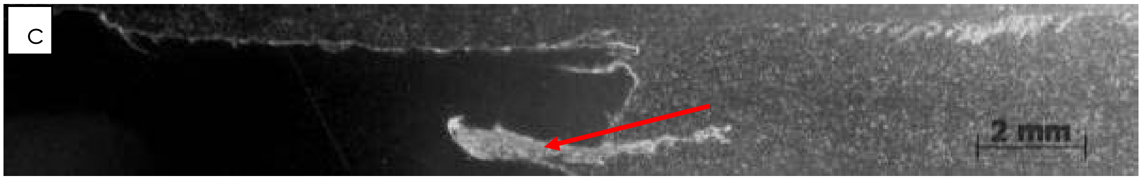

Figure 2(c): FSW produced at 950 rpm and 300 mm/min

It was observed that improved mixing of both metals was achieved at the lowest travel speed of 50 mm/min (Figure 2a), which was produced at a low downward force, (F_z) and high heat input compared to the remaining welds produced. The Stir Zone (SZ) of the welds produced at 50 mm/min and 150 mm/min are characterised by mixture layers of aluminium and copper. This observation agrees with Liu *et al*. (2008) on macro appearance of welds produced between aluminium and copper. At a high transverse speed of 300 mm/min (Figure 2c), the vertical downward force is high but the heat input to the weld was low as shown in Table 1; the macrostructure was characterized by 'openings' in the Copper, which were filled with the Aluminium Alloy during the welding process as indicated by the arrow. This can be attributed to the fast movement of the tool at this speed; and as a result, the frictional heat generated was not high enough to achieve coalescence and proper mixing of both metals during the welding process.

3.3 Microhardness profiling

The microhardness profiles of the three welds are shown in Figure 3. The measurements were taken at 1.5 mm below the top surface. The average Vickers microhardness values of the parent materials – Aluminium Alloy (AA) and Copper (Cu) are HV 60 and HV 95 respectively.

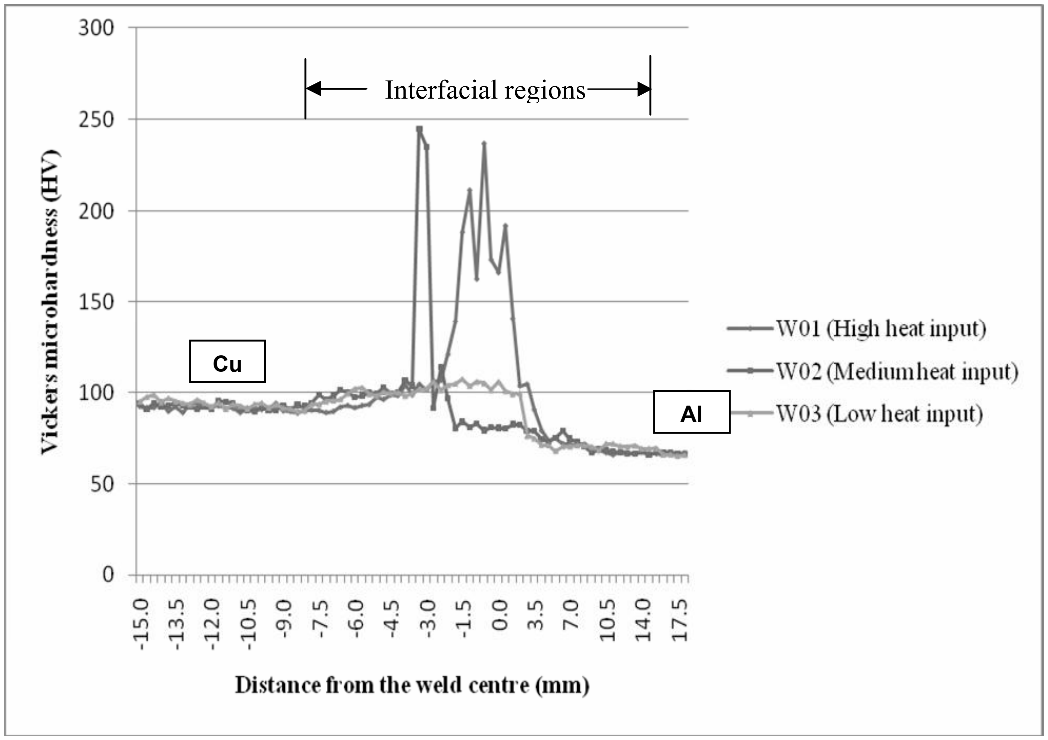

Figure 3: Microhardness profiles of welds produced at a constant rotational speed of 950 rpm with varied traverse speeds.

It was observed that higher Vickers microhardness values were measured in the Thermo-Mechanically Affected Zones (TMAZ) and the Stir Zones (SZ) of both metals which are regions previously occupied by the tool pin and the shoulder during the welding process. These regions are referred to as interfacial regions. The increase in the microhardness values at the interfacial regions can be attributed to dynamic recrystallization that has occurred during the welding process and also due to the presence of intermetallic compounds. Due to the variations in the macrostructures as presented in Figure 2(a) to (c), it was observed that the peaks in Figure 3 are distributed according to the positions of the intermetallics in the welds.

Energy Dispersive Spectroscopy (EDS) was conducted on the joint interface region of the weld produced at 950 rpm and 50 mm/min to investigate the presence of intermetallic compounds. It was observed that the high peaks correspond to AlCu intermetallic compound as shown in Figure 4.

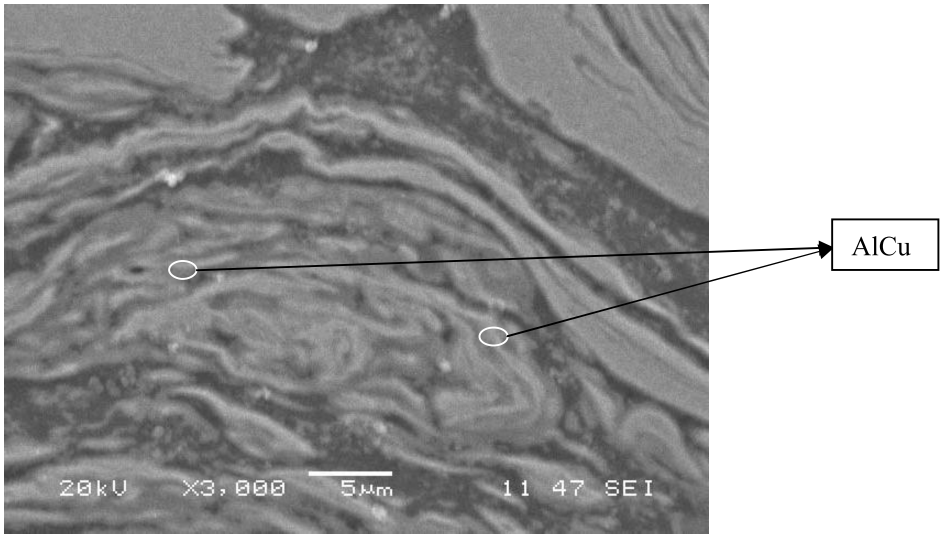

Figure 4: Joint interface of W01 (high heat input) produced at 950 rpm and 50 mm/min.

3.4 Tensile results

The average Ultimate Tensile Strength of the parent materials and the welds are presented in Table 2. The tensile samples were taken from different positions along the welds and are designated as T1, T2 and T3 corresponding to the first, second and third samples respectively. The trend observed was that at a constant rotational speed, the tensile strengths of the welds decreased as the traverse speed increased from 50 to 300 mm/min respectively. This observation can be related to the heat input into the weld which is higher at low traverse speed as presented in Table 1.

Table 2: UTS of the parent materials and the welds

Samples	T1	T2	T3	Average UTS
PM AL	266	266.1	266.4	266
PM CU	243	246	243	244
W01	229	187	209	208
W02	195	190	210	198
W03	141	182	105	143

The highest tensile strength was obtained from the joint produced at low travel speed and can be attributed to the observations on the macrostructures of the welds. It was observed that coalescence and bonding of both metals are better achieved at the lowest travel speed. This trend observed in the tensile results agrees with the explanation given by Cederqvist and Reynolds (2000). It was reported that colder welds produced at high travel speed has less vertical transport of material during the FSW process and therefore influences the mixing of both metals during welding and consequently influences the tensile strength of the welds.

4.0 CONCLUSION

Dissimilar friction stir welds between 5754 Aluminium Alloy and C11000 Copper were successfully produced. Material characterisation of the welds revealed that good process-property relationship exists in FSW of Al and Cu (based on the UTS). Microstructural evaluation revealed that at a constant rotational speed, improved metallurgical bonding and mixing of both metals were achieved at the lowest traverse speed due to low downward vertical force and high heat input. Higher Vickers microhardness were measured at the interfacial regions due to dynamic recrystallization and the presence of intermetallics. The average Ultimate Tensile Strength of the welds decreased as the welding speed increased. Analysis of the FSW forces acting during the welding procedure revealed that the advancing force (F_x) the torque (T) and consequently the heat input to the welds (Q) increased as the vertical downward force increased.

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