Friction Stir Welding of Dissimilar Materials – Statistical Analysis of the Weld Data

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***Abstract*—This paper reports the results of statistical analysis conducted on the weld data obtained from friction stir welding of aluminium and copper. The welds were produced by varying the process parameters; the rotational speed was varied between 600 to 1200 rpm and the welding speed varied between 50 and 300 mm/min. The Statistica (version 9.0) statistical analysis software package was used to generate the scatter and surface plots relative to the experimental results obtained from the tensile testing and the FSW data. Regression analysis was also done on the weld data. It was found that the downward vertical force has a significant effect on the Ultimate Tensile Strength of the weld and a strong relationship exist between the heat input into the welds and the measured electrical resistivities of the welds.**

***Keywords*—** friction stir welding, dissimilar materials, statistical analysis.

I. INTRODUCTION

Solid-state welding is the process whereby coalescence is produced at temperatures below the melting point of the base metal without the use of any filler metal. Examples of solid-state welding processes include friction welding, Friction Stir Welding (FSW), ultrasonic welding, resistance welding, explosive welding and diffusion welding. There are fewer defects in solid-state welding because the metals do not reach their melting temperatures during the welding process. However, the base metals being joined retain their original properties, and the Heat Affected Zone (HAZ) is small when compared with the fusion welding techniques [1]. Friction Stir Welding is a variant of friction welding that produces a weld between two or more work pieces by the heating and plastic material displacement caused by a rapidly rotating tool that traverses the weld joint [2]. The schematic diagram of the process is presented in Fig 1. [3] In FSW, the inter-relationship between the process parameters is complex; the two most important welding parameters being the tool rotational speed in a clockwise or anti-clockwise direction, and the tool traverse speed along the joint line [4]. The rotation of the tool results in the stirring and mixing of material around the rotating pin during the welding process which in turn affect the evolving properties of the weld. As such, understanding the relationship between the process parameters and the resulting properties of the welds is important.

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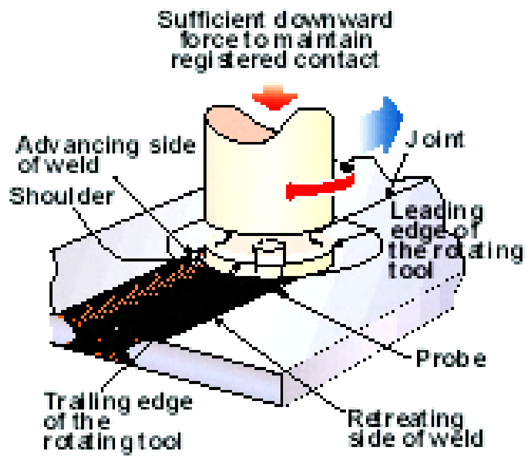

Fig. 1: Schematic diagram of friction stir welding process [3]

Research studies on process-property relationship [4-7] reported that the input process parameters are found to exert significant effect on the resulting joint integrities. In attempting to further understand the process-property relationship in FSW, statistical analyses of the weld data have been conducted on similar joints of aluminium alloys. Rajamanickam and Balusamy [8] conducted statistical analysis on the weld data obtained in FSW of 2014 aluminium alloy and concluded that the weld speed has the highest statistical influence on the mechanical properties of the welds produced. Also, Benyounis and Olabi [9] conducted a literature survey on optimization of different welding processes using statistical and numerical approaches and concluded that modeling; control of the process parameters and optimization of different welding processes can be achieved using different statistical tools. The aim of this study is to conduct statistical analysis on the weld data obtained from dissimilar FSW of aluminium and copper in other to gain insight and understanding into the interaction between the process-properties of the resulting welds.

II. EXPERIMENTAL SET-UP

Friction Stir Welds of 5754 aluminium alloy (AA) and C11000 copper in butt joint configurations were produced on 600 mm x 120 mm x 3.175 mm thick sheets 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 (NMMU), Port Elizabeth

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South Africa. The surfaces of both sheets were cleaned with acetone before the welding procedure. The Cu sheet was placed at the advancing side (AS) and the AA at the retreating side (RS) during the welding process. Optimized tool displacement setting according to Akinlabi et al [10] was used in which the tool pin was plunged in the AA and made to touch Cu during the welding procedure. Three different shoulder diameter tools – 15, 18 and 25 mm with a constant tool pin diameter of 5 mm were used to produce the welds. The weld matrixes and the process parameters employed are presented in Table 1.

TABLE I
WELD MATRIX

Weld No	Spindle speed (rpm)	Feed rate (mm/min)
S15_01	600	50
S15_02	600	150
S15_03	600	300
S15_04	950	50
S15_05	950	150
S15_06	950	300
S15_07	1200	50
S15_08	1200	150
S15_09	1200	300
S18_01	600	50
S18_02	600	150
S18_03	600	300
S18_04	950	50
S18_05	950	150
S18_06	950	300
S18_07	1200	50
S18_08	1200	150
S18_09	1200	300
S25_01	600	50
S25_02	600	150
S25_03	600	300
S25_04	950	50
S25_05	950	150
S25_06	950	300
S25_07	1200	50
S25_08	1200	150
S25_09	1200	300

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 process parameters like the tool tilt angle and the dwell time were kept constant at 2^o and 2 seconds respectively. 160 mm weld length per setting was produced. 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 tensile tests were conducted using a servo-hydraulic Instron 8801 tensile machine according to ASTM E8. 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. The FSW output parameters i.e. Forces in the x, y and z directions, the Torque and the calculated heat input taken from an average of the recorded values of the data obtained during the welding procedure from 25 to 135 mm (stable region) of the weld length are presented in Table 2.

TABLE II
FSW OUTPUT DATA OBTAINED

Weld No	Fx (kN)	Fy (kN)	Fz (kN)	Torque (kNm)	Q_{input} (J/mm)
S15_01	2.11	-1.17	10.14	16.50	1119.92
S15_02	2.60	-0.04	13.87	19.97	451.69
S15_03	3.02	-0.90	17.94	23.63	289.86
S15_04	1.63	-1.04	6.97	8.59	923.18
S15_05	2.02	-0.27	10.67	12.09	432.83
S15_06	2.63	-0.67	12.25	13.12	219.31
S15_07	1.52	-0.76	7.45	8.01	1087.67
S15_08	3.14	-0.65	11.59	12.67	524.30
S15_09	3.54	-0.77	13.07	15.24	299.59
S18_01	2.87	-0.93	10.47	17.47	1185.71
S18_02	3.42	-0.60	14.27	20.96	474.02
S18_03	4.06	-0.09	18.53	26.20	296.37
S18_04	2.85	-0.72	11.56	12.80	1374.86
S18_05	3.12	-0.75	14.47	15.15	542.63
S18_06	3.47	-0.12	16.69	17.37	293.06
S18_07	2.26	-0.18	10.60	12.95	1765
S18_08	2.68	-0.23	12.51	15.12	683
S18_09	3.16	-0.01	14.91	17.44	405
S25_01	3.26	-0.08	20.94	25.51	1731.02
S25_02	3.90	-0.64	22.49	26.12	590.92
S25_03	3.99	-0.75	24.28	28.91	326.91
S25_04	2.33	-0.09	12.14	14.74	1583.49
S25_05	4.43	0.12	26.08	29.26	934.11
S25_06	5.20	0.26	32.24	36.74	577.29
S25_07	3.34	0.17	15.23	20.51	2067.58
S25_08	4.54	0.48	21.00	33.02	950.15
S25_09	5.91	-0.07	24.64	35.81	557.24

The torque values reported are measured response values and the heat input was calculated using (1).

$$Q = \eta \frac{2\pi\omega T}{f} \qquad (1)$$

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).

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III RESULTS AND DISCUSSION

3.1 Regression analysis

Multiple regression analysis was conducted on the data obtained from the FSW process in order to derive linear equations relating the dependent to the independent variables. The equations derived from the multiple regression analysis are stated in equations 3.1 to 3.5. The parameters are represented as follows: Torque – T, Feed rate – F, Spindle speed – S, and Interaction – I.

$$\text{Torque (Nm)} = 25.63624 - 0.01334 * S + 0.03330 * F - 0.00001 * I \qquad 3.1$$

$$\text{Heat input (KJ/mm)} = 1.13653501 - 0.00346301 * F + 0.00033264 * S - 0.00000053 * I \qquad 3.2$$

$$\text{UTS (MPa)} = 146.9909 + 0.275 * S + 0.0511 * F - 0.0001 * I \qquad 3.3$$

$$\text{Electrical resistivity } (\mu\Omega) = 0.10151956 - 0.00002725 * F + 0.00000081 * S - 0.0000001 * I \qquad 3.4$$

$$\text{UTS (MPa)} = 194.6103 + 10.8737 * Fx + 24.9234 * Fy - 3.0675 * Fz - 0.4985 * T \qquad 3.5$$

The linear equations outlined above can be used to predict dependent variables (weld properties) when the independent variables are known. It was observed that statistically, (Fy) and (Fz) could contribute significantly to changes in the Ultimate Tensile Strength (UTS) of the welds. This can be explained further because the forces acting on the tool during the welding process dictate the forging force, the amount of heat input into the welds and the resulting weld defects that may form, all of these can be related to the UTS of the welds.

3.2 Analysis of Variance (ANOVA)

The results of the analysis of variance of the data obtained for Ultimate Tensile Strength of the weld samples are presented in Table III. Marked effects are significant at $P < 0.05000$.

TABLE III
UNIVARIATE TEST OF SIGNIFICANCE FOR UTS AND FSW PARAMETERS

	All Groups Univariate Tests of Significance for UTS Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	2045536	1	2045536	1837.593	0.000000
Spindle speed	2447	2	1223	1.099	0.338689
Feed rate	6727	2	3363	3.021	0.054951
Spindle speed*Feed rate	10113	4	2528	2.271	0.069819
Error	80148	72	1113		

A noticeable effect observed where the p-value is not less than 0.05 but only marginally bigger is found in the effect of feed rate on the UTS of the welds produced in this research study. It can be interpreted that the feed rate influences the UTS of the welds produced.

3.2 Analysis of scatter plots

The scatter plot of the results of the electrical resistivity and heat input to the welds is presented in Fig 2.

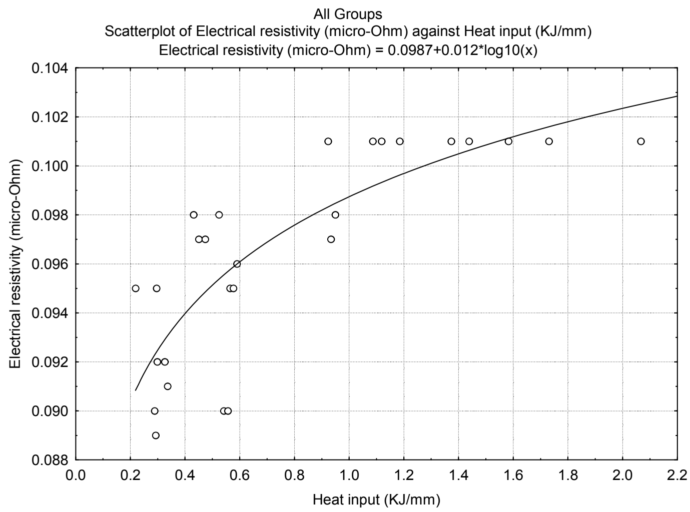

Fig 2: Scatter plot of electrical resistivity versus heat input for all the welds produced.

The scatter plot of electrical resistivity versus heat input shows that a fairly strong relationship exists between them. It can be interpreted that the electrical resistivity increases as the heat input increases, but is limited at a certain point when the electrical resistivity becomes constant.

3.2 Analysis of surface plots

Surface plots were created from the weld data to aid visualization of the interrelationship that could exist between a dependent variable and two independent variables. The surface plot of the horizontal force, Fx against the spindle speed and the feed rate is presented in Fig 3.

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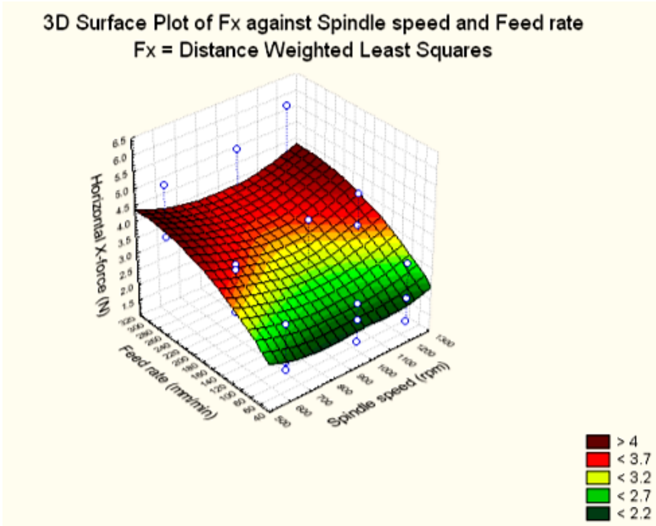

Fig 3: Surface plot relating horizontal force (Fx), spindle speed and feed rate for all the welds.

It was observed from Figure 3 that the horizontal force (Fx) increases as the feed rate increases, while the spindle speed does not seem to have any significant effect on the horizontal force acting during the welding process. This is important information for design purposes when considering the forces acting on the tool during the welding process.

The surface plot of the horizontal force (Fy) acting perpendicular to the (Fx) compared with the spindle speed and the feed rate is presented in Fig 4.

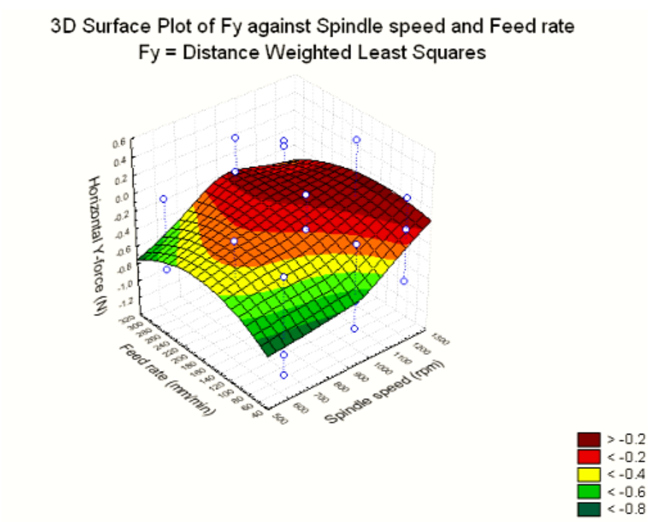

Fig 4: Surface plot relating horizontal force Fy, spindle speed and feed rate for all the welds.

The surface plot revealed that the (Fy) increases as the spindle speed increases, while the feed rate does not seem to have much effect on the (Fy) acting on the tool. It stands to reason that the side force (Fy) would increase slightly, because the material is pushed faster in the X and Y directions, as a result of increasing the spindle speed.

The surface plot relating vertical force (Fz), spindle speed and feed rate for all the welds is presented in Fig 5.

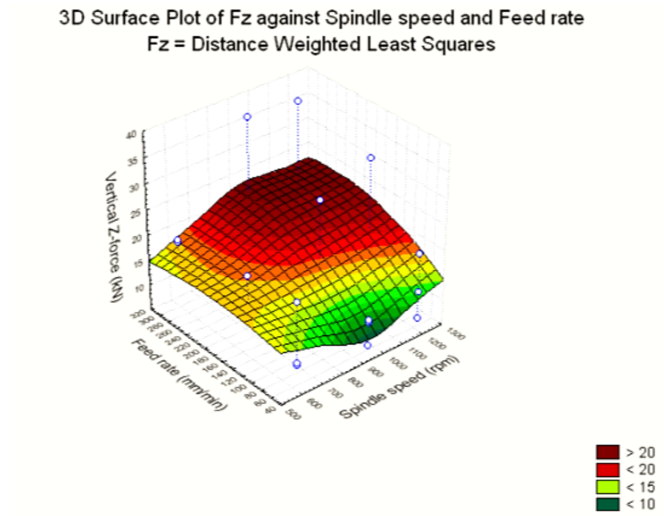

Fig 5: Surface plot relating vertical force (Fz), spindle speed and feed rate for all the welds.

From Fig 5, it was observed that the downward vertical force Fz increases as the feed rate and spindle speed increase. This is expected because at high feed rates and high spindle speeds, the tool moves relatively fast; hence, less heat input is generated. As such, a high vertical force is practically required to ensure forging during the welding process.

The surface plot relating torque (T), spindle speed and feed rate for all the welds produced is presented in Fig 6.

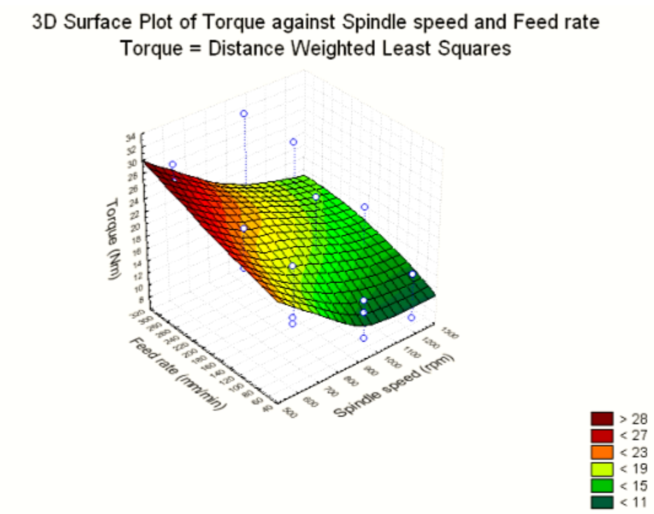

Fig 6: Surface plot relating torque (T), spindle speed and feed rate for all the welds.

The trend observed in the torque values shown in the surface plot (Fig 6) was that the torque increases as the feed rate increases, but it decreases as the spindle speed increases. The explanation given earlier on the relationship between vertical force, spindle speed and feed rate is also related to this case, since a linear relationship exists between vertical force and torque; that is to say, an increase in the downward vertical force gives an increase in torque values. Hence, it is revealed in this plot, that the feed rate plays a significant role in the resulting torque values compared to the spindle speed.

The surface plot relating heat input, spindle speed and feed rate for all the welds produced are presented in Fig 7.

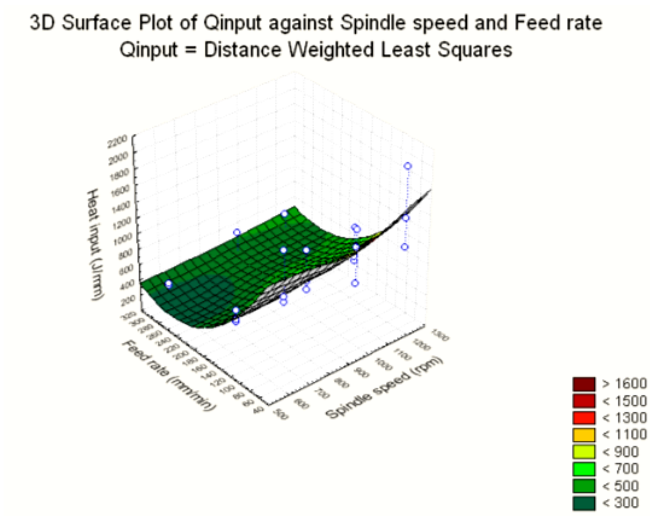

Fig 7: Surface plot relating heat input, spindle speed and feed rate for all the welds.

From the surface plot relating the heat input to the process parameters (Fig 7), it was observed that the heat input into the welds increases as the feed rate decreases, but not linearly. The spindle speed does not have a significant effect on the heat input. The explanation for this is based on the fact that the tool moves slowly at low feed rates; hence most of the heat generated is contained in the welds leading to high heat input.

The surface plot relating UTS, spindle speed and feed rate for all the welds is presented in Fig 8.

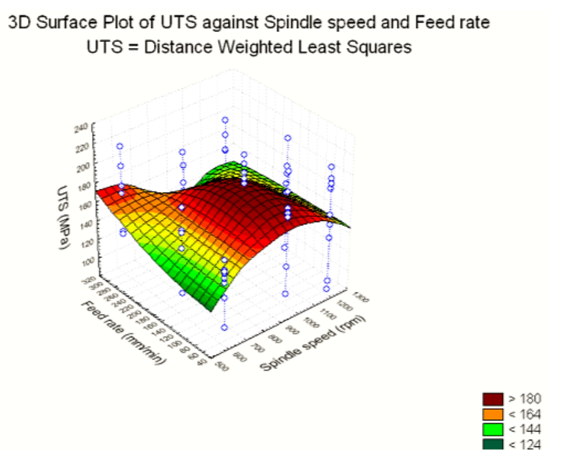

Fig 8: surface plot relating UTS, spindle speed and feed rate for all the welds

The surface plot relating the UTS, spindle speed and feed rate of the entire weld data (Fig 8) revealed that the UTS increases as the feed rate decreases, but decreases slightly at high spindle speeds. This can be due to the fact that good weld consolidation can be better achieved at low feed rates. With respect to the entire weld matrix considered in this research, it can be said that the optimum weld setting with respect to the UTS, is 950 rpm and 150 mm/min based on the statistical analysis.

Fig 9 presents the surface plot relating percentage elongation, spindle speed and feed rate for all the welds.

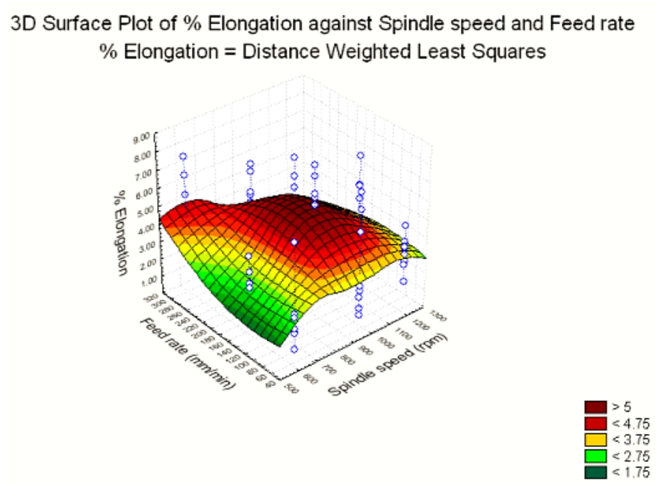

Fig 9: Surface plot relating percentage elongation, spindle speed and feed rate for all the welds.

The red region of the surface plot relating the percentage elongation and the process parameters (Fig 9) considered statistically significant; looked similar to that of the UTS earlier discussed. Hence, the trends observed in both properties are similar.

IV CONCLUSION

The statistical analysis of the weld data obtained in this study have been reported and discussed. Linear equations relating the dependent and independent variables in FSW process were achieved. The Analysis of Variance revealed that the downward vertical force, (Fz) has a significant effect on the UTS of the welds. There is also an indication of a strong relationship between the electrical resistivity and the heat input into the welds. Based on the statistical analysis, the optimal weld setting with respect to the UTS is weld produced at 950 rpm and 150 mm/min. It can be concluded that the input process parameters in FSW play a very significant role in determining the joint integrity of the resulting weld.

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