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INFLUENCE OF MECHANICAL CHARACTERISTICS OF FRICTION WELDED FERRITE STAINLESS STEEL JOINT THROUGH NOVEL MATHEMATICAL MODEL USING BUCKINGHAM'S PI THEOREM

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ABSTRACT

A suitable mathematical model to optimize the process parameters for continuous drive friction welding of ferrite stainless steel through Buckingham's π theorem is not available. The aim of this work is to develop a mathematical model to predict optimum input process parameters for friction welding based on the method of fundamental dimensions using the Buckingham's π theorem. The developed model helps in identifying the best suitable process parameters for high tensile strength, improved impact toughness and hardness. The experiments were conducted as per L9 orthogonal array by changing the four different parameters namely friction pressure, friction time, forging pressure and rotational spindle speed. A detailed analysis was conducted on mechanical characteristics namely tensile strength, hardness, impact toughness. The experimental results helped in identifying the requirement of a high forging pressure for the production of good tensile strength and impact toughness. The validity of the mathematical model was shown by the consistency of the mapping between the experimental results and the Taguchi method of statistical analysis. In addition, the fracture surface of friction welded sample was analyzed using SEM. Fine dimples and transgranular ductile fracture was observed in the fracture surface.

KEYWORDS: Buckingham's Pi Theorem, Dimensional Analysis, L9 Orthogonal Array, Tensile Strength, Hardness & Impact Toughness

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Original Article

1. INTRODUCTION

Continuous drive friction welding is one of the most effective methods for joining Ferritic stainless steel (AISI 430) considering the difficulty seen in the fusion welding method [1]. In the fusion welding of stainless steel, problems such as micro fissuring, carbide precipitation, knife line attack, stress corrosion cracking occurs. The welding heat affected zone in the base metal is just above a critical temperature and causes a fast grain growth in the ferrite this coarse grain that affects ductility and toughness. These problems can be nullified by the use of the solid state friction welding method [1].This method finds its wide usage in automotive, aerospace, nuclear reactors and chemical industries.

Ferritic stainless steel (AISI 430) is essentially a body centered cubic (BCC) with iron chromium crystal structure. It has magnetic and good ductility. Chromium presence is normally in the range of 20-32% [1]. Even friction welding shows sizeable economic and technical benefits that tend to create metal loss. Optimization technique is carried out for reducing metal losses and maximizing the desired mechanical property. In the optimization of process parameters genetic algorithm, simulated genetic algorithm, particle swam optimization techniques are employed. Among these techniques, genetic algorithm performed well for the continuous drive friction welding process [2]. Normally, there are three methods of quality characteristic in the analysis of the signal to noise ratio, namely the smaller-the-better, larger-the better and the nominal-the-best [3]. In the case of continuous drive friction welding of duplex stainless steel, tensile strength of the joint is richer than that of the base material. The ferrite-to-austenite ratio is 50:50 for the three zones of the weld namely unaffected zone, plastic zone and plastically deformed zone [4]. The joint efficiency increased with a rise in friction time and almost all joints were fractured at the aluminium side. However, 100% joint efficiency was not obtained leading to the softening of aluminium side weld interface [5]. The decrease in Impact toughness with a rise in heat input was due to a drop in the tough austenite phase in microstructure. At room temperature, impact toughness values of the weldment made by the friction welding are more than those of other welding methods [6]. The friction welding process is a solid state fastening process that produces a weld under the upset force contact of one rotating and one stationary work piece. Heat is liberated at the faying surfaces due to the continuous friction of mating surfaces, which in turn causes a temperature rise and following softening of material [7]. Heat is generated by the conversion of kinetic energy into thermal energy at the faying surfaces of the components during rotation under pressure without the need for any energy from the other source [8]. Since the friction welding is a solid state joining process, all defects related with a typical fusion weld are not present in it. During friction welding, heat is highly rigorous at the faying surface. As a result, a friction weld has a very slim heat-affected zone (HAZ), which limits the variations in mechanical characteristics. [9]. In the carreau type fluid constitutive model, material law formulated is in terms of yield stress with the ability to qualitative predictions by means of melt temperature and room temperature [10]. Increase in micro hardness at weld interface may be the reason for the formation of intermetallic components which are brittle in nature and speed of rotation causes the formation of Ti3Al and TiAl at the weldment interface [11]. RSM was applied for the creation of individual regression equations of tensile strength and hardness. Intelligent optimization including as GA were used to for the prediction of pareto optimal solutions [12]. The GA predicted optimized process variables were validated by experimental results subsequently values were within the acceptable deviation [13]. A model of maximum entropy production principle shows speed and friction pressure having the main effect on friction time, hence increase in friction pressure caused a reduction in the friction time in the case of friction welding of GH4169 superalloy [14]. A 3D non-linear finite element model developed using a numerical tool, ANSYS software was validated using experimental outputs that shows the upsetting stage, having a larger impact on axial shortening [15]. Dimensional analysis is helpful for computing dimensionless variables and indicates the group of variables that is affecting the problem [16].

This paper deals with the formulation of the equation based on the method of dimensions with π term which contains process parameters. Ferritic stainless steel was joined by friction welding based on L9 orthogonal array for predicting the properties of the joint. After outlining the result, it is compared with mathematical model equations and Taguchi method of statistical analysis.

2. MATERIAL AND METHODS

Friction welding is a solid state joining process. It makes use of frictional heat developed at the contact surface to increase the temperature at the contact surface sufficient to cause the two surfaces joined under forge pressure. In continuous drive friction, welding working is categorized into two phases, presented in Figure 1. In the first phase, one work piece is rotated at a specified speed (N) in position with the second part with friction pressure (F_p). The speed and friction pressure are maintained for mentioned friction time (t_1) to make the required thermal and mechanical conditioning of the joint surfaces. In the second phase, rotary motion is stopped and forging pressure (P) is applied for specified forging time (t_2). The application of forging force keeps the contact between the parts and creates plastic deformation tends to make the weld joint.

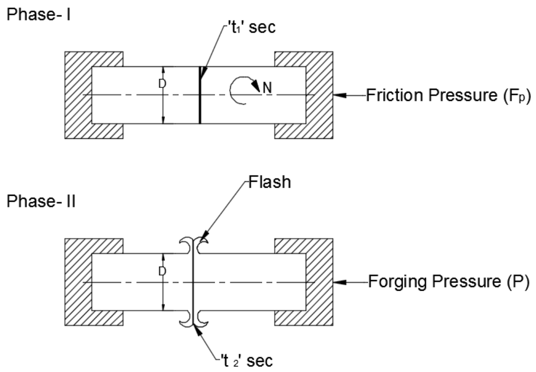

Figure 1: Principle of Friction Welding.

Ferritic stainless steel specimens of 12 mm diameter and 135 mm long were fastened by friction welding. Details of the chemical composition of the AISI 430 are presented in Table 1. The friction welding process variables used in this study are presented in Table 2. The experimental plan based on L9 Orthogonal array is listed in Table 3. A continuous drive FW machine with a maximum load of 150 kN was used for welding. The friction pressure and forging pressure used were in the range of 60–75 MPa and 160–175 MPa respectively. Spindle speed was kept in the range of 1200 rpm to 1800 rpm. The specimen's joint surfaces faced using lathe to maintain perpendicularity. Samples of the friction welded ferritic stainless steel are shown in Figure 2.

Table 1: Chemical Composition of AISI 430

Ingredient	C	Cr	Ni	Mn	Si	S	P	Mo	Fe
Percentage	0.13	16.38	0.46	1.58	0.41	-	0.038	0.21	80.792

Table 2: Process Parameters

Sl. No.	Parameters	Ranges
1	Friction Pressure	65 to 75 (MPa)
2	Friction Time	6 to 8 (sec)
3	Forging Pressure	145 to 155(MPa)
4	Rotational Speed	1200 to 1800 (rpm)

Table 3: Experimental Plan-L9 Orthogonal Array

Sl. No.	Friction Pressure(MPa)	Friction Time (sec)	Forging Pressure (MPa)	Speed of Rotation (rpm)
1	65	8	145	1800
2	65	7	150	1500
3	65	6	155	1200
4	70	8	150	1200
5	70	7	155	1800
6	70	6	145	1500
7	75	8	155	1500
8	75	7	145	1200
9	75	6	150	1800

Figure 2: Friction Welded Samples.

3. MATHEMATICAL MODELING

Researchers have developed a model based on regression analysis and carreau fluid constitutive model. However, there has been no research work based on Buckingham's π theorem. Hence this work has created a novel model. Here, dimensional analysis of process parameters involved in friction welded joint is formulated using the Buckingham's π theorem. In any welded joint, tensile strength, hardness, impact toughness are the required basic characteristics.

In this context, Impact toughness (I) of friction welded joint depend on the speed of rotation (N), Forging Pressure (P), Diameter of Specimen (D), Friction Time (t), Heat Flux (Q)

So, I=f (N, P, D, t, Q) and (1)

f_1=I, N, P, D, t, Q = 0. (2)

In this case, number of variables is 6 (six) and number of fundamental dimensions is 3 (three). Hence the number of π terms is 3. Thus, three π terms are formed. Hence the equation are written as

$f_1 (\pi_1 \pi_2 \pi_3) = 0$ that is

π_1= D N P I, (3)

π_2= D N P t, (4)

π_3= D N P Q. (5)

Every π term is solved by the method of dimensional homogeneous. For the 1st π term

$$\pi_1 = \frac{I}{D^3 P}, \quad (6)$$

similarly for the second π term

$$\pi_2 = N.t \quad (7)$$

and third π term

$$\pi_3 = \frac{QN}{D^2 P^2}. \quad (8)$$

Now each π term is substituted in equation

$$f_1 \left(\frac{I}{D^3 P}, N.t, \frac{QN}{D^2 P^2}\right) = 0 \tag{9}$$

therefore

$$I = D^3 P \Phi\left[N.t, \frac{QN}{D^2 P^2}\right]. \tag{10}$$

The experimental result showed a high value of forging pressure and thus providing a high impact resistance to friction welded joint. Mathematical modeling has also confirmed this by the term $I = D^3 P$.

Hardness (H) of friction welded joint depends on speed of rotation (N), Forging Pressure (P), Diameter of Specimen (D), Friction Time (t), Heat Flux (Q) So,

$$H=f (N, P, D, t, Q) \tag{11}$$

and

$$f_1=H, N, P, D, t, Q = 0. \tag{12}$$

In this, the number of variables is 6 (six) and number of fundamental dimensions is 3 (three). Hence, the number of π terms is 3 (three). Thus three π terms are formed, hence equations are written as

$$f_1 (\pi_1\ \pi_2\ \pi_3) = 0$$

that is

$$\pi_1= D\ N\ P\ H, \tag{13}$$

$$\pi_2= D\ N\ P\ t, \tag{14}$$

$$\pi_3= D\ N\ P\ Q. \tag{15}$$

Every π term is solved by the method of dimensional homogeneous. For the 1st π term

$$\pi_1=H \tag{16}$$

similarly for the second π term

$$\pi_2 = N.t \tag{17}$$

and third π term

$$\pi_3 = \frac{QN}{D^2 P^2}. \tag{18}$$

Now each π term is substituted in equation

$$f_1 \left(H, N.t, \frac{QN}{D^2 P^2}\right) = 0 \tag{19}$$

therefore

$$H = \Phi\left[N.t, \frac{QN}{D^2 P^2}\right], \tag{20}$$

from the experimental result increase in the friction time and speed of rotation were seen, causing an increase the hardness which satisfied 'N.t' and $\frac{QN}{D^2P^2}$ of mathematical modeling respectively.

Tensile strength (σ) of FW joint is a function of the speed of rotation (N), Axial thrust (P), Diameter of Specimen (D), Friction Time (t), Heat Flux (Q) So,

$\sigma = f(N, P, D, t, Q)$ (21)

and

$f_1 = \sigma, N, P, D, t, Q = 0.$ (22)

In this, number of variables is 6 and number of fundamental dimensions is 3 (three). Hence number of π terms is 3 (three).Thus, three π terms are formed. Hence, equations are written as

$f_1 (\pi_1 \pi_2 \pi_3) = 0$

that is

$\pi_1 = D\ N\ P\ \sigma,$ (23)

$\pi_2 = D\ N\ P\ t,$ (24)

$\pi_3 = D\ N\ P\ Q.$ (25)

Each π term is solved by the principle of dimensional homogeneity. For the first π term

$\pi_1 = \frac{\sigma D^2}{P}$ (26)

similarly for the second π term

$\pi_2 = N.t$ (27)

and third π term

$\pi_3 = \frac{Q}{DNP}.$ (28)

Now each π term is substituted in equation

$f_1 (\frac{\sigma D^2}{P}, N.t, \frac{Q}{DNP}) = 0$ (29)

therefore

$\sigma = \frac{P}{D^2}\Phi[N.t, \frac{Q}{DNP}].$ (30)

4. RESULTS AND DISCUSSIONS

In this, investigation friction welded AISI 430 Ferritic stainless steel revealed the formation of flash is a typical characteristics of friction welded joints due to the forging action of the process. AISI 430 was subjected to high deformation compared to AISI 304L due to low strength. The mechanical characteristics of friction welded joints were evaluated using tensile tests, impact tests and hardness tests.

4.1 Tensile Test

All joint tensile test specimens were prepared as per the ASTM standard. The specimen length of 240mm and diameter 12mm at middle diameter were machined to 9mm for 75mm length. The flash (burr) which was formed at the interface of the weld during the friction welding was removed by machining for tensile testing specimens. Tensile test results are presented in Table 4, which confirms the absence of achievement of parental strength, even when high strength was achieved in all the samples. When joints were made with forging pressure 155MPa and rotational speed 1200 rpm, tensile strength 550.1MPa with joint efficiency of 98.23% was seen. For the same forging pressure, the increase in speed of 1500 rpm which provided tensile strength of 534.42MPa with joint efficiency of 95.43% , ie a reduction of nearly 2.85%. The increase in the speed of 1800 rpm, the tensile strength 526.56MPa with joint efficiency of 94.02% with 4.27% reduction in tensile strength. From equ.no:28 confirmed that experimental findings with the developed model.

The increase in speed caused a marginal decrease in the tensile strength of the joint. The cause for decrease in the strength of increase in speed is the softened area on the nearer to the weld joint. The tensile strength was comparable to that each of the other samples. Fracture was established at joints in all the samples. The maximum tensile strength of the welded specimen obtained was 550.1MPa, as shown in Figure 3. This could be achieved under the conditions of forging pressure 155MPa, friction pressure 65MPa, friction time 6 Sec, and rotational speed 1200rpm.The high tensile strength was the result of an increase in the bond between the material near the weld junction caused by high forging pressure. The minimum tensile strength of the welded specimen obtained was 471.55MPa. This could be achieved under conditions of forging pressure 150MPa, friction pressure 70MPa, friction time of 8 (eight) Sec, and rotational speed 1200rpm.The reason for the low tensile strength is due to reduction in forging pressure, which is causing a decrease in the bond between the material at the joint surface. The experiment showed an increase in forging pressure providing high tensile strength which satisfies equ.no:26, ie tensile strength is the function of forging pressure. The SN ratio plot in Figure 4 shows high intensity of forging pressure attaining high tensile strength while an increase in the speed of 'N' caused a reduction in the tensile strength. This confirmed the good agreement of the experimental findings with developed mathematical model and statistical analysis.

Table 4: Tensile Test Results

Sample Number	Yield Load (kN)	Ultimate Load (kN)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Joint Efficiency (%)
1	12	31	188.61	487.26	87.01
2	16	33	251.49	518.70	92.62
3	17	35	267.21	550.14	98.23
4	13	30	204.33	471.55	84.20
5	16.5	33.5	259.35	526.56	94.02
6	15.5	32.5	243.63	510.84	91.22
7	17	34	267.21	534.42	95.43
8	18	34.5	282.92	542.28	96.83
9	14.5	31.5	227.91	495.13	88.41
Parent Metal	20	35.63	314.37	560	-

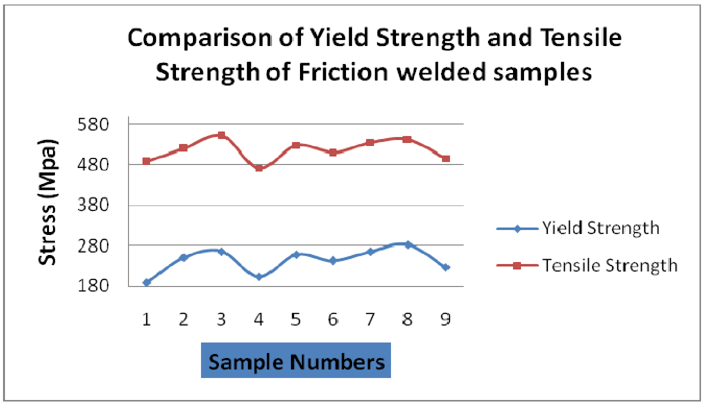

Figure 3: Comparison of Yield Strength and Tensile Strength of Friction Welded Samples.

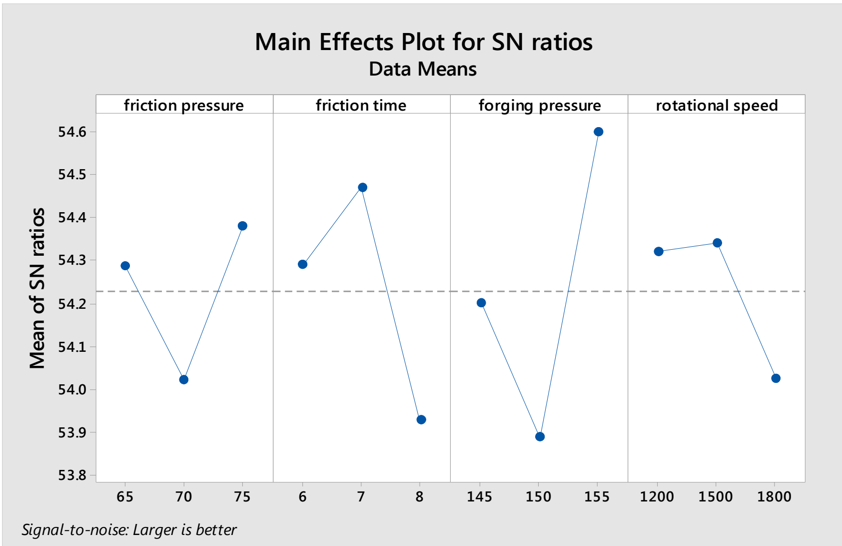

Figure 4: SN ratio for Main Effects of Ultimate Tensile Strength.

4.2 Hardness

The Vickers hardness test is carried out based on ASTM E-18. The flash formed during the welding was removed to facilitate penetration of the diamond intender. The test was carried out at room temperature with the total test force100g for 10 s. The readings for the maximum load are shown in Table 5. The hardness of the welded pieces decrease from the plastic zone to plastically deformed zone, as shown in Figure 6. There was an increase in the hardness of the plastic zone to 130.25% of the parent metal. This is a very low variation compared to other joining methods. In the plastic zone (PZ), the maximum value of hardness was obtained for all the samples. The maximum value of hardness 184 HV was obtained for the operating condition of friction time in 8 Sec. The long duration of rubbing action of two contact surfaces and high amount of heat involved in the joint interface was the reason for high hardness. The hardness value in the Plastically Deformed Zone (PDZ) and Unaffected Zone (UZ) were small. Heat transferred in the PDZ and UZ was small. This was the cause of the low hardness. The various zones of friction welded joint are shown in Figure 5.

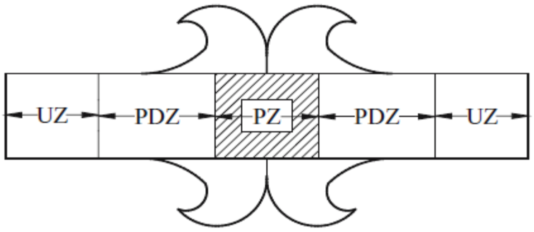

Figure 5: Cross Section of Weldzone [1].

Table 5: Hardness Test Results

Specimen Number	Unaffected Zone	Plastically Deformed Zone	Plastic Zone	Plastically Deformed Zone	Unaffected Zone
1	163	171	182	172	164
2	164	169	184	175	162
3	163	170	177	172	166
4	166	174	180	170	167
5	164	171	178	172	166
6	166	175	180	172	166
7	170	176	182	177	174
8	161	171	176	170	167
9	164	166	179	170	167

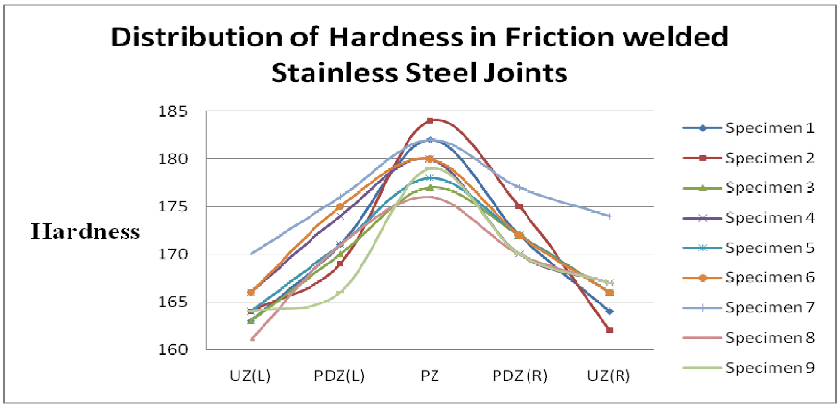

Figure 6: Hardness Distribution in Friction Welded Samples.

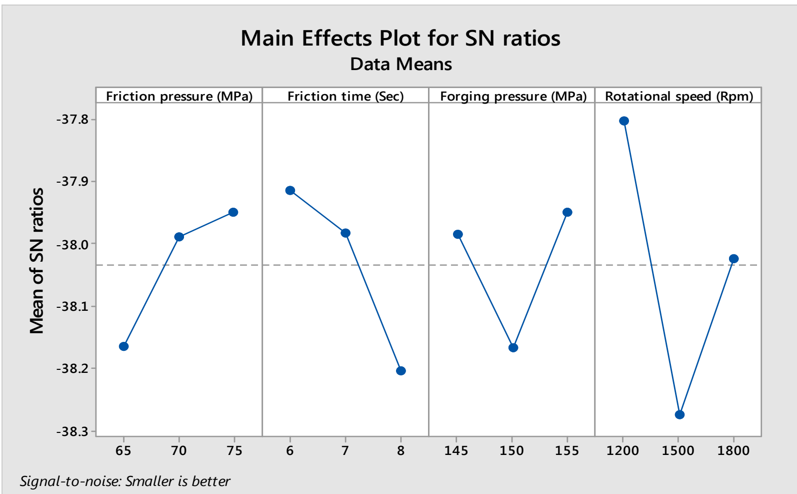

Figure 7: SN Ratio for Main Effects of Hardness.

The experimental result shows the value of friction time and speed of rotation is the deciding factor that causes intensity of hardness. The statistical analysis (Figure 7) shows the process parameters, the friction time and the rotational speed, which influences the hardness of the joint. This confirmed the good agreement of the experimental findings with equ.no:17 and equ.no:18 of the developed mathematical model.

4.3 Impact Toughness

Impact specimens for the Charpy's test, with measurement of 10mm x 10mm x 55mm, a groove angle of 45^{o} with 2mm depth V notch were prepared. Ferritic stainless steels high in Cr and C (16–39%), (0.13%) respectively tend to create chromium carbides at grain boundaries in the weld HAZ. Due to this, friction welded joints of Ferritic stainless steel showed lowest impact toughness. Charpy 'v' notch tests were carried out for getting the toughness of the friction welded joints. The results of 'v' notch impact tests carried out at atmospheric temperature is tabulated. Normally, the welding heat causes coarsened grain structure at the welded portions, which can be the cause for a reduction in the toughness of the joints. [1]

The impact toughness results are provided in Table 6. The maximum impact toughness of the welded specimen obtained was 23 Joules. This could be achieved under conditions of forging pressure 155MPa, friction pressure 75MPa, friction time 8 Sec, and rotational speed 1500rpm, as shown in Figure 8. The cause for high impact toughness is the increase in cohesiveness between the materials near the weld interface that is caused by an increase in high forging pressure. The experimental result revealed the high value of forging pressure providing high impact resistance of the friction welded joint. The developed mathematical model was also confirmed by the term I = D^3P (equation 10). The minimum impact toughness of the welded specimen was 14 joules achieved under conditions of forging pressure 145MPa, friction pressure 65MPa, friction time 8 Seconds, and speed 1800rpm. The reason for the low impact toughness was the low forging pressure and friction pressure softened the surface near the weld interface. The statistical analysis shown in Figure 9 also supports the high value forging pressure maximizing the value of impact toughness of the friction welded joint.

Table 6: Impact Toughness Test Results

Sample Number	Impact Toughness (Joules)
1	14
2	16
3	20
4	18
5	21
6	18
7	23
8	15
9	19
Parent Metal	28

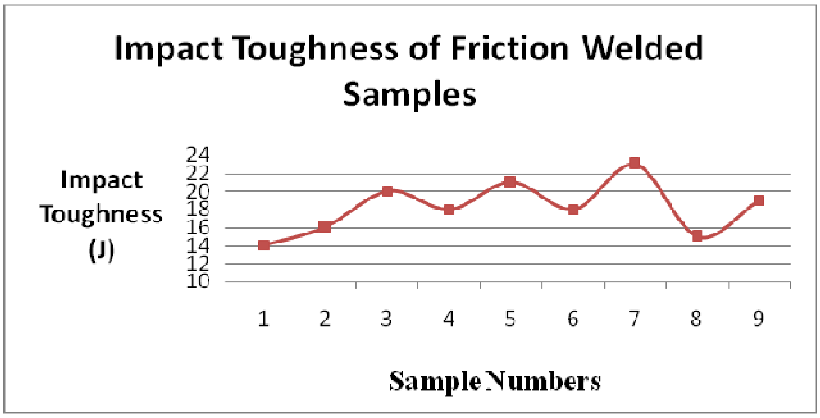

Figure 8: Comparison of Impact Toughness of Friction welded Samples.

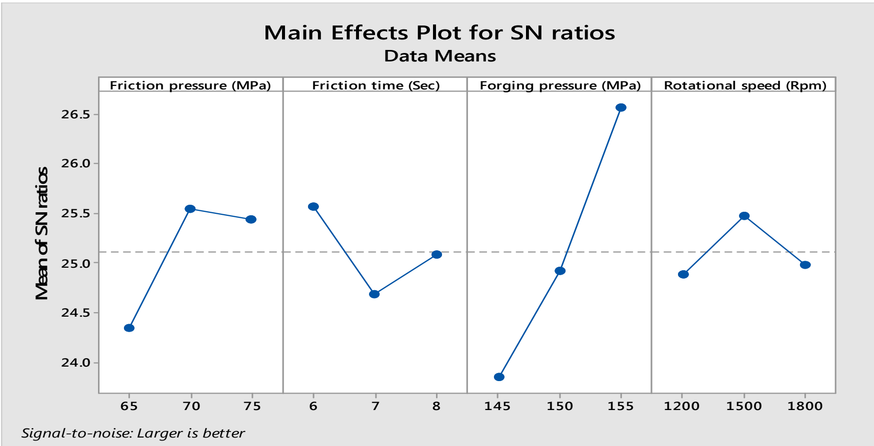

Figure 9: SN Ratio for Main Effects of Impact Toughness.

4.4 Metallurgical Analysis

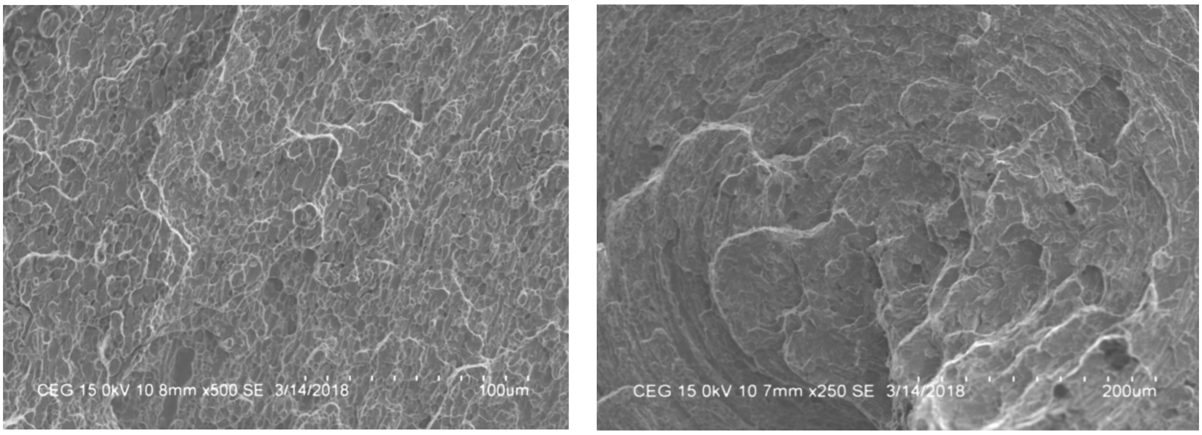

Figure 10: SEM Photograph of the Tensile Fracture Surface.

The fracture morphology of friction welded joints was studied using SEM. Fine dimples observed in the fracture surface represented transgranular ductile fracture. The grains were stretched in the fracture zone along the direction of load, showing the high resistance to fracture offered by the grains.

5. CONCLUSIONS

In this paper, a mathematical model based on a dimensional analysis for continuous drive friction welding is presented. The significant feature of the proposed model is the easy derivation of equations in terms of process parameters. The current model has the ability to provide qualitative predictions through use of process parameters that include speed of rotation, forging pressure, friction pressure and friction time.

The influence of the process parameters on the mechanical properties of Ferritic stainless steel were studied and comparisons were made with mathematical models based on the Buckingham's π theorem and following conclusions are drawn. The forging pressure should be 155 MPa for getting better tensile strength and impact toughness due to better adherence to friction surface.

- Tensile strength 550.1MPa with joint efficiency of 98.23% is seen when joints are made with forging pressure 155Mpa and rotational speed 1200 rpm. Increase in forging pressure and reduction in rotational speed provide a high tensile strength which satisfies the term $\sigma = \frac{P}{D^2}$ and $\frac{Q}{DNP}$ in the mathematical modeling.
- The experimental results exhibit higher friction pressure and forging pressure gives better toughness and high value of forging pressure providing high impact resistance of friction welded joint. This is confirmed by mathematical modeling by the term $I = D^3 P$.
- The experimental results show the high value of friction time and speed of rotation providing high hardness. This is confirmed by 'N.t' and $\frac{QN}{D^2P^2}$ of mathematical modeling based on Buckingham's π theorem.

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