Heat Flow Prediction in Friction Stir Welded Aluminium Alloy 2024 Small Diameter Pipes

S. Deivanai[1*], Manoj Soni[2]

[1,2]Indira Gandhi Delhi Technical University for Women, Department of Mechanical & Automation Engineering, Kashmere Gate, New Delhi, India.
Email: s.deivanai2002@gmail.com
*Corresponding Author

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ABSTRACT
Aluminum alloy 2024 is used for a wide variety of items, including electrical conduits, hose reels, sewage pumps, pressure regulators, level indicators, control valves, and many more. The friction stir welding (FSW) method is a new solid state joining technique that combines aluminum, magnesium, zinc, and copper alloys. The welding quality is heavily influenced by the FSW process parameters. Weld speed, shoulder pin diameter, and tool rotational speed were found to influence weld nugget and FSW tool shoulder temperatures, according to the researchers. Research on heat flow is essential because it has a direct impact on the microstructure, joint strength, residual stress, cold cracking, size of the heat affected zone (HAZ), and distortion of welded AA2024 pipes. It was decided to build a mathematical model. To check if the model was sufficient, the ANOVA method was utilized. The graphical depiction of the primary and interaction impacts of the process variables is presented using MINITAB 17.0. The goal of building the model was to make predictions about the flow of heat. In order to assess their relative merits, the mathematical model, the ANN model, and the experimental values were all compared. The findings were satisfactory for the ANN model of the FSW process that used a feed forward strategy. Conducting analyses and computations involving heat flow.

Keywords: Full factorial design, design of experiment, mathematical model, ANN, heat flow

1. INTRODUCTION
The mechanical properties produced by friction stir welding are superior to those of fusion welding. No consumables, gas shield, or filling rod are required. Vertical milling machines, the standard, make quick work of the task. As a result, both the setup cost and the amount of training required are decreased. Thanks to little thickness under- or over-matching and an excellent weld appearance, expensive post-weld machining is not necessary as often. One reason FSW is considered a green method is that it doesn't waste energy, doesn't make any bad smells, and doesn't spatter molten material. Tool design, axial force, pin diameter, weld speed, tool rotational speed, and shoulder diameter are important process parameters in friction stir welding.

2. Identification of important process control variables
Tool rotational speed has been recognized as one of the most critical process factors in friction stir welding based on the literature review. "Various factors such as welding speed, axial force, tool pin form, tool pin diameter, and tool shoulder diameter.

3. Deciding the working range of the process control variables
By manipulating one parameter while holding the others constant, trial runs can be used to determine the process parameters' upper and lower limits. We select the parameter limits so that the joint should not have any obvious flaws. The parameter's upper and lower limits are denoted by HIGH and LOW, respectively. Table 1.1 provides the chosen process parameters, their ranges (both upper and lower), notations, and units.

Table 1. Process Control Parameters And Their Limits

Sl.No	parameters	Units	Notation	-1	+1
1	Tool Rotational speed	RPM	N	550	1460
2	Weld speed	Mm/min	W	22	26
3	Tool pin diameter	mm	D	4	6

4. Developing the design matrix

A 23 factorial design allows for eight possible treatment combinations where three factors—N, W, and D—are of interest, with each factor having two levels.2.

Table 2. Design matrix

Weld no.	Trial no.	Input parameters			labels
		N	W	D	
1	4	-1	-1	-1	(1)
2	7	+1	-1	-1	a
3	1	-1	+1	-1	b
4	6	+1	+1	-1	ab
5	2	-1	-1	+1	c
6	8	+1	-1	+1	ac
7	5	-1	+1	+1	bc
8	3	+1	+1	+1	abc

In the 23 design, there are eight treatment combinations, and each combination has seven degrees of freedom. The primary impacts of N, W, and D are linked to three degrees of freedom. The four degrees of freedom linked to interactions are as follows: one with NWD, one with ND, and one with WD.

5. Conducting the experiments as per the design matrix

At Delhi Skill and Entrepreneurship University's main workshop, the experiments were carried out. Figure 1 shows the standard HMT vertical milling machine that was used for FS welding of small diameter pipes made of aluminum alloy 2024. Milling machine weld speed and tool rotation speed are crucial factors in producing strong FSW joints. The analysis also revealed certain fundamental limits of the milling machine, which were overcome by building an appropriate fixture, when it came to holding circular pipes with small diameters. From what we've seen, the milling machine is the best tool for showing the FSW process on aluminum at low weld speeds, according to our FSW experience.

Fig.1 Experimental set up

Fig.2 Friction stir welded samples

5.1 The Base Metal

Pipes made of Aluminium Alloy 2024 with a thickness of 5 mm served as test specimens for the investigation. Its dimensions were 100 mm × 50 OD mm x 5 mm for every pipe. The 2024 aluminum alloy bar and silicon carbide powder are mixed during the melting process of the stir casting method to form the base material. After pouring into the mold, it sets. For the final polish, turning is done after solidification. This is the result of the spectro analysis that was tabulated:

Table 3. Specifications of AA 2024 Silicon carbide embedded pipes (% by weight) sample test conforms to ASTM B 221-13 Alloy 2024

Al	Cu	Mg	Si	Fe	Mn	Cr	Zn	Sic
Remainder	3.81	1.55	0.097	0.008	0.545	0.074	0.086	5

5.2 Tool Material Used

A 70 mm length of mild steel was selected for the tooling, and step turnings with diameters of 12 mm and 20 mm were manufactured. In Figure 3, it can be seen that the tool pins have a diameter between 4 and 6 mm and a depth of 3.5 mm. The frictional heat produced during FS welding oxidises surfaces. Near the shoulder pin, thirty percent of the body's heat is transferred. The weldment receives the leftover heat.

Fig.3 FSW tool

Fig.4 Temperature measurement

6. Recording the Response

Figure 4 shows the results of utilizing a K-Type thermocouple to monitor the temperature at the weld nugget, and Table 4 shows the results for the tool shoulder diameter during friction stir welding.

Table 4. Temperature and heat flow

Run no.	Tool speed (RPM)	Weld speed (mm/min)	Tool pin Diameter (mm)	Temp At nugget (^{0}C)	Heat flow [Q] in (w) In weld nugget	Temp At tool shoulder (^{0}C)	Heat flow [Q] in (w) at tool shoulder
1	550	22	4	240	5217.07	225	4844.43
2	1460	22	4	257	5639.41	236	5117.70
3	550	26	4	270	5962.37	261	5738.78
4	1460	26	4	322	7254.22	304	6807.04
5	550	22	6	275	6086.59	242	5266.76
6	1460	22	6	157	3155.09	140	2732.75
7	1460	26	6	184	3825.85	158	3179.93
8	550	26	6	120	2235.89	103	1813.55

6.1 Heat flow calculations

Once the circular pipes have transferred the majority of the frictional heat, the remaining heat is transferred to the FSW tool. The heat flow that happens during welding has a major influence on phase transitions as well as the microstructure and properties of the weld that follow. It also causes deformation and weld residual stresses. A semi-infinite work piece's thermal flow in three dimensions is analytically solved to determine the thermal input during welding.

$$Q = KA(T_1-T_2)/t$$

Q – Conduction heat transfer($\boldsymbol{W}$); K –Materials thermal conductivity($\boldsymbol{W/mK}$) = 175.73 for AA2024 pipe; A - Cross sectional area($\boldsymbol{m^2}$) = Area of circular pipe having 50 mm outer diameter and thickness 5mm = 706.858mm^2; 0.000706858 m^2; T_1 =Pipe temperature($\boldsymbol{°C}$) at weld nugget; T_2 - Room temperature($\boldsymbol{°C}$); 30($\boldsymbol{°C}$); t - Pipe thickness ($\boldsymbol{m}$)=5 mm; 0.005m

7. Development of Mathematical Model

The Response function can be expressed as: Y = ƒ (N, W, D)

Where, Y = response; N = tool rotational speed; W = weld speed; D= tool pin diameter

A linear regression model with three predictor variables can be expressed with the following equation: $Y = b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23W}WD+b_{123}NWD$

If N=W=D = 0, then the value to predict for Y is b0, the Y-intercept, where b0 is constant and b1, b2, b3, b12, b13, b23, and b123 are model coefficients.

Assuming all other independent variables stay the same, b1 is the difference between the predicted value of Y and N for each one-unit change in N, as N is a continuous variable. If N is different by one unit and W and D are not different, then Y will differ, on average, by b1 units.

7.1 Evaluation of the co-efficient of model

In order to determine the values of the response function's coefficients, regression analysis was employed. We used MINITAB17 and the numbers from Table 5 to do the calculations.

Table 5. Evaluation of the co-efficient of model

Sl.no	Co-efficient	Temperature(^{0}C)	
		At weld	At tool shoulder
1	b_0	-102.1	-69.43
2	b_1	+ 0.2786	+ 0.2204
3	b_2	+ 5.882	+ 3.265
4	b_3	+ 19.39	+ 14.74
5	b_{12}	- 0.008810	- 0.005825
6	b_{13}	- 0.03804	- 0.03185
7	b_{23}	- 0.7690	- 0.4347
8	b_{123}	+ 0.001274	+ 0.000892

7.2 Regression Equations

Temperature at weld nugget (T_N) = $b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b_{123}NWD$

T_N = -102.1 + 0.2786 N + 5.882W + 19.39 D – 0.008810 NW – 0.03804 ND – 0.7690 WD + 0.001274 NWD

Temperature at Tool shoulder = $b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b123NWD$

$T_{tool\ shoulder}$ = -69.43 + 0.2204 N + 3.265 W + 14.74 D – 0.005825 NW – 0.03185 ND – 0.4347 WD + 0.000892 NWD

8. Checking adequacy of the model

To ensure the created models were adequate, analysis of variance (ANOVA) was employed. According to this method:

a. At each given degree of confidence, we compare the created model's F-ratio to the conventional tabulated value of F-ratio.
b. With the accompanying confidence probability, the model may be deemed adequate if the computed F-ratio value does not surpass the tabular value. We used a 95% confidence interval for our analysis.

9. Modelling Using Artificial Neural Network

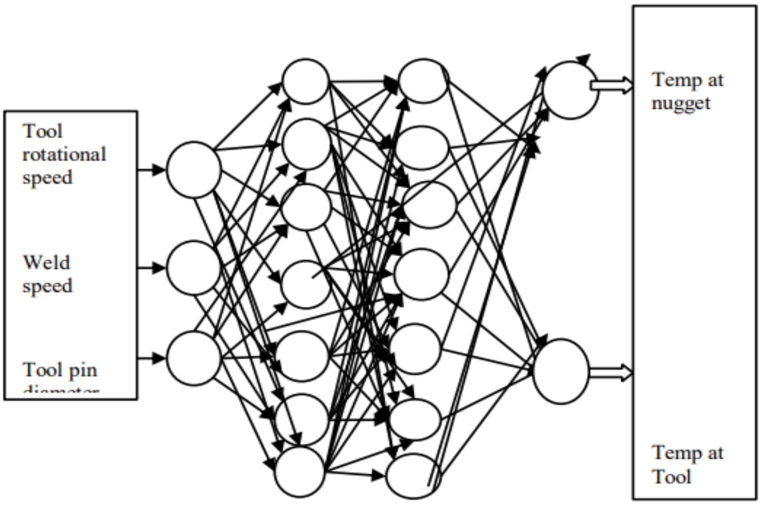

Fig 5. FFNN to predict temperature

Shown in Figure 5 is a typical feed forward network. This network is used to model the process in the current study. We used a three-neuneuron input layer and a seven-neuneuron output layer to mimic the process. Weld speed, tool pin diameter, and tool rotational speed were the three input factors studied. We also looked at how these factors affected the friction stir welding temperature. We kept the target at 0.01.

10. Comparison of ANN, Math. Model and Experiment values

Table 9. Comparison of predicted temperature values

	Weld Run	ANN	%ERROR	MATH. MODEL	%ERROR	EXPERIMENT VALUE
Temp T_N	7	169.43	-7.91%	175.75	-4.48%	184
	8	109.12	-9.06%	117.25	-2.29%	120
Temp at tool shoulder ^0C	7	161.00	+1.89%	164.00	+3.79%	158
	8	105.61	+2.53%	104.75	+1.69%	103

The experimental data is compared to the projected temperatures and heat flows on the weldment and tool shoulder using the ANN and mathematical models, as shown in Table 9". Inaccuracy is less than 10%. Thus, the model being discussed is the best one.

11.RESULTS AND DISCUSSIONS

Effect of process variables

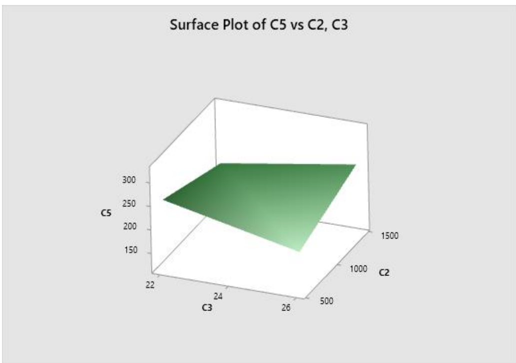

Fig 6. surface plot of C5 vs C2, C3

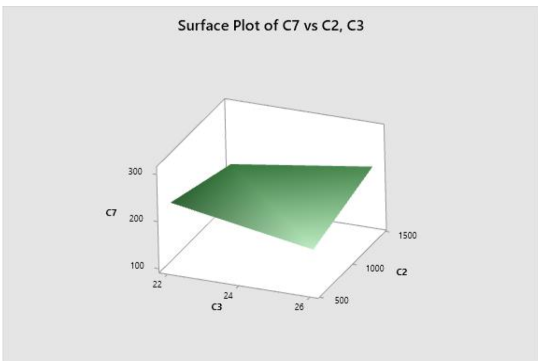

Fig 7. surface plot of C7 vs C2, C3

C2- Tool Rotational Speed; C3-Weld Speed; C5-Temperature at weld nugget;
C7-Temperature at Tool shoulder

It is learned from Figures 6 and 7 that the weldment area increases with higher heat input, tool pin diameter, and weld speed. Good stirring and increased joint efficiency are guaranteed by the enhanced heat input. Improved joint efficiency is a direct result of these FS Welding settings.

12. CONCLUSIONS

1. A high rotational speed for the tool causes an increase in temperature at the weld nugget and tool shoulder. Both temperature and heat input are reduced when the tool's rotating speed is reduced. The reason for this is that the tool pin's shoulder has reduced friction with the surface of the Aluminium alloy 2024 pipe.
2. The temperature at the weld nugget and tool shoulder is reduced with an increase in weld speed. The low temperature could be due to a lack of stirring time. It is greater at slow welding speeds. The efficient joint in FS welding is caused by axial force and frictional heat.
3. The heat flow at the pipe welding area is 5217.07 watts, while it is 4844.43 watts at the tool pin shoulder.

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