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Optimization of Friction Welding of Tube-to-Tube Plate Using an External Tool with Filler Plate

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Friction welding of tube-to-tube plate using an external tool (FWTPET) process with filler plate was successfully applied and optimized for joining commercially pure aluminum tube and tube plate. Taguchi approach was applied to determine the most influential control factors which will yield better joint strength. L_9 orthogonal array was used in this study. Through the Taguchi parametric design approach, the optimum levels of process parameters were determined. The percentage of contribution of each process parameter was determined by Analysis of variance. The predicted optimal value of joint strength was found to be 83.26 MPa. The results were confirmed by further experiments.

Keywords FWTPET, Taguchi method, tube to tube plate welding

1. Introduction

Friction welding is a solid-state joining process and one of the most effective processes for joining similar and dissimilar materials with high joint integrity. The unique feature of friction welding process is that the material that is being welded does not melt and recast. Owing to the intensive heat generated at the interface, the material reaches the softened state which interacts with each other and produces good quality weld (Ref 1). The welding process is a multi-input and multi-output process in which joint quality is closely associated with welding parameters. Therefore, identifying the suitable combinations of input process parameters to produce the desired output requires many experiments, making this process time consuming and costly (Ref 2). In order to investigate the effect of process parameters, most researchers follow the conventional experimental techniques wherein one parameter has been varied over a period of time keeping other parameters constant. This kind of conventional parameter-based design of experimental approach consumes a lot of time as well as enormous amounts of resources (Ref 3).

Friction welding of tube to tube plate using an external tool (FWTPET) was invented in the year 2006 and patented by one of the present authors (Ref 4). The prime advantage of this process is to weld similar and dissimilar materials which can be of any dimension. The joint produced by this process exhibits enhanced mechanical properties with lesser energy consumption (Ref 5). The use of backing block in the FWTPET process leads to defect-free weld joint and higher strength (Ref 6). The welding parameters for FWTPET process without filler plate have been optimized, and it is found that tool rotation speed plays a major role in deciding joint strength, followed by shoulder diameter of the tool and pin clearance (Ref 7).

In FWTPET, the temperature and pressure developed at the interface are directly proportional to the volume of metal displaced. In order to increase the volume of metal displaced, an additional plate called filler plate has been employed in the present study. In this case, the volume of metal displaced is in the range of 1625-2851 mm^3. In the conventional FWTPET, the volume of metal displaced for a tube of 19-mm diameter and 6-mm plate thickness is in the range of 354-1581 mm^3. The various process parameters which affect the joint strength are tool rotational speed, shoulder diameter of the tool, pin clearance, plunge depth, and tube projection.

The input parameters considered in this study are tool rotation speed, plunge depth, and tube projection, and the output parameter is joint strength. Three levels of process parameters have been used in this study. Taguchi L_9 orthogonal array has been used to identify the most influential process parameter. This is followed by determining the percentage of contribution of each parameter using Analysis of variance (ANOVA).

2. Materials and Methodology

2.1 Materials

The parent metal employed in this study was commercially pure aluminum. The chemical composition of the parent metal is shown in Table 1.

The experiment was conducted using rolled plates of 6 and 3-mm thicknesses as base and filler plates, respectively, which both are of commercially pure aluminum. The plates were cut into required size (70 mm × 50 mm) using power hacksaw. The tubes of size ∅ 19 mm were cut into required lengths, and holes (∅ 2 mm) were drilled on the peripheral surface. In the base and filler plates, a hole (∅ 19 mm) in the center was drilled. Then, the tubes were fitted to the plates. Heavy alloy

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Table 1 Parent metal composition

	Elements									
	Al	Si	Fe	Cu	Mg	Mn	Ti	Zn	Cr	V
wt.%	99.9947	0.0006	0.0007	0.0013	0.0021	0.0001	0.0001	0.0002	0.0001	0.0001

Table 2 Composition of tool material

	Elements					
	W	Ni	Fe	Mo	Co	O_2
wt.%	90.5623	5.7908	3.2318	0.2228	0.1214	0.0709

Table 3 Factors and levels

	Levels		
Factors	1	2	3
A. Tool rotational speed, TRS, rpm	710	1120	1400
B. Tube projection, TP, mm	1	2	3
C. Plunge Depth, PD, mm	0.5	1.5	2.5

Table 4 Experimental layout of L_9 orthogonal array

	Input parameters		
Experimental run	A. Tool rotational speed, rpm	B. Tube projection, mm	C. Plunge depth, mm
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

tungsten tool was employed to fabricate FWTPET joints, and the chemical composition of the tool is shown in Table 2.

2.2 Taguchi Method

Taguchi method is an efficient problem-solving tool, which can improve the performance of the product, process, design, and system with a significant slash in experimental time and cost (Ref 8). Taguchi method employs a special design of orthogonal arrays to study the entire process parameters, spaced with small number of experiments (Ref 9).

The various process parameters which influence the joint strength are tool rotation speed, shoulder diameter, pin length, plunge depth, and tube projection. In this study, the shoulder diameter of the tool and pin clearance values were chosen as 30 mm and 1 mm, respectively. In this study, L_9 orthogonal array was used, and the process parameters such as tool rotational speed, tube projection, and plunge depth were considered. The factors and their corresponding values are

Fig. 1 FWTPET machine (developed in-house)

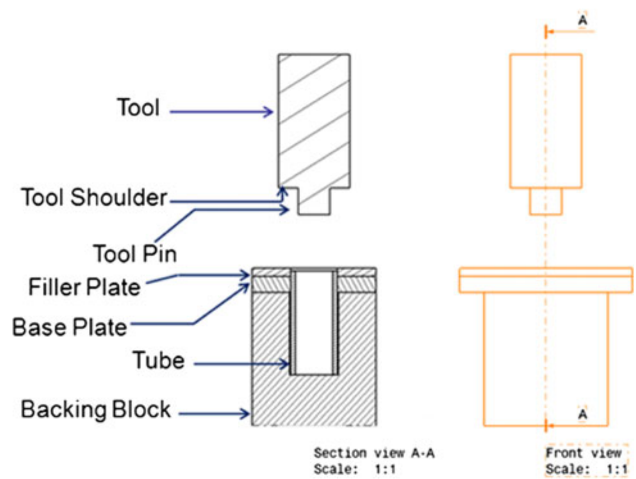

Fig. 2 Experimental setup

shown in Table 3. The format of L_9 orthogonal array is presented in Table 4.

3. Experimental Details

The FWTPET machine developed in-house is shown in Fig. 1. The assembly of tube into the base plate and filler plate is shown in Fig. 2.

The FWTPET machine consists of tool holder, spindle, table, and supporting structure. The tool is lowered during rotation, and heat is generated because of friction when the shoulder touches the filler plate. The tool is lowered till the shoulder touches the base plate so that more heat is generated in the tool. Once the shoulder crosses the filler plate, the filler plate is separated from the assembly.

The metal moved by the shoulder flows toward the centre of the tool axis as shown in Fig. 3, and it occupies the holes drilled on the tube and flows toward the gap between the inner diameter of the tube and pin. The cylindrical pin restricts the metal movement and applies pressure between the tube and plate. The bonding takes place between the surfaces which are at higher pressure and temperature. The tool is withdrawn after achieving necessary plunge depth.

The assembly of the workpiece was placed in the backing block and firmly clamped on the machine vice. The tool was fixed to the spindle of the machine, and the workpieces were welded using different combinations of process parameters. The workpiece samples before and after welding are, respectively, shown in the Fig. 4 and 5.

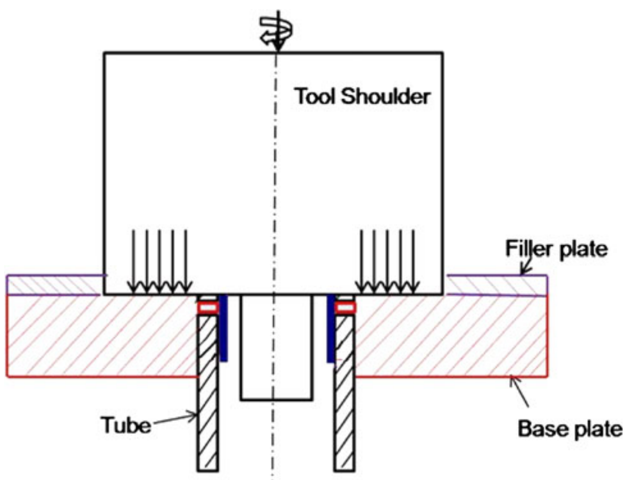

Fig. 3 Metal flow in FWTPET

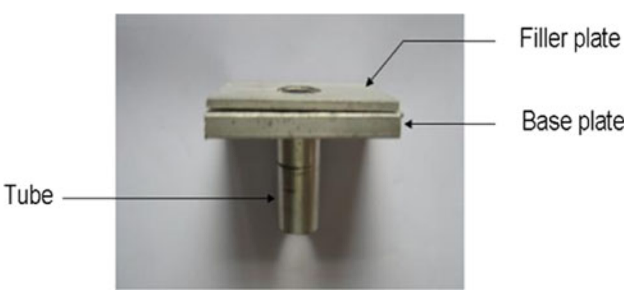

Fig. 4 Sample before welding

Fig. 5 Sample after welding

3.1 Tensile Test

The joint strength of the samples welded by FWTPET process is found by using Hounsfield Tensometer. The test specimen fixed in the Tensometer setup is shown in Fig. 6. Two samples were tested in each combination of process parameters, and the average value is chosen for optimization using Taguchi method and ANOVA.

4. Results and Discussion

4.1 Signal-to-Noise Ratio

Joint strength is the main characteristic considered in this investigation describing the quality of FWTPET joints. In order to assess the influence of factors on the response, the mean and Signal-to-Noise (S/N) ratio for each control factor can be calculated. In this study, the S/N ratio was chosen according to the criterion *Larger the better*, to maximize the response. The various input and output parameters of the FWTPET process are shown in Table 5. MINITAB software (Ref 10) was used for determining the influence of process parameters (factors) on the joint strength (response). Table 6 gives the response table for means, and Table 7 gives response table for S/N ratio.

The means and S/N ratio of the various process parameters when they changed from the lower to higher levels are also

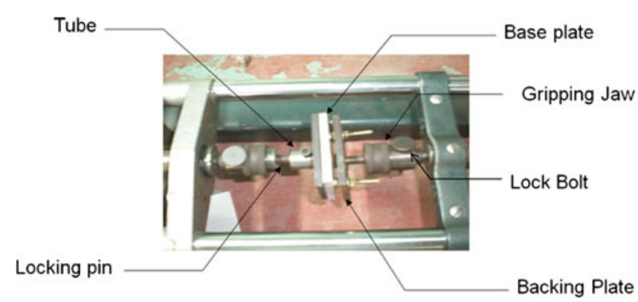

Fig. 6 Hounsfield Tensometer setup

Table 5 Input and output parameters of FWTPET process according to L_9 orthogonal array

Experimental run	Input parameters: Speed, rpm	Tube projection, mm	Plunge depth, mm	Output characteristic Joint strength, MPa
1	710	1	0.5	62.58
2	710	2	1.5	76.02
3	710	3	2.5	73.44
4	1120	1	1.5	71.37
5	1120	2	2.5	63.61
6	1120	3	0.5	70.34
7	1400	1	2.5	49.65
8	1400	2	0.5	51.72
9	1400	3	1.5	69.31

Table 6 Response table for S/N ratio

Level	Speed, rpm	Projection, mm	Plunge depth, mm
1	36.9553	35.6391	35.7153
2	36.6712	35.9636	37.1683
3	35.0025	37.0262	35.7454
Delta	1.9528	1.3871	1.4530
Rank	1	3	2

Table 7 Response table for means

Level	Speed, rpm	Projection, mm	Plunge depth, mm
1	70.6800	61.20	61.5467
2	68.2667	63.61	72.2333
3	56.8933	71.03	62.0600
Delta	13.7867	9.83	10.6867
Rank	1	3	2

given in Tables 6 and 7. It is clear that a larger S/N ratio corresponds to better quality characteristics. The mean effect (Fig. 7) and S/N ratio (Fig. 8) for joint strength were calculated by statistical software, indicating that the joint strength was at its maximum, with tool rotational speed of 710 rpm, tube projection of 3 mm, and plunge depth of 1.5 mm.

4.2 Analysis of Variance

Analysis of variance (ANOVA) test was performed with a purpose of identifying the process parameters that are statistically significant and investigating the significance of the process parameters which affect the joint strength of FWTPET joints. In this study, MINITAB software is employed to calculate the percentage contribution of each process parameter to the overall joint strength. The results of ANOVA is presented in Table 8.

Based on the results shown in Table 8, tool rotational speed is found to be the most influential process parameter with 46.98% contribution, followed by plunge depth (30.71%), and tube projection (22.29%), and the respective percentage contributions are also graphically represented in Fig. 9.

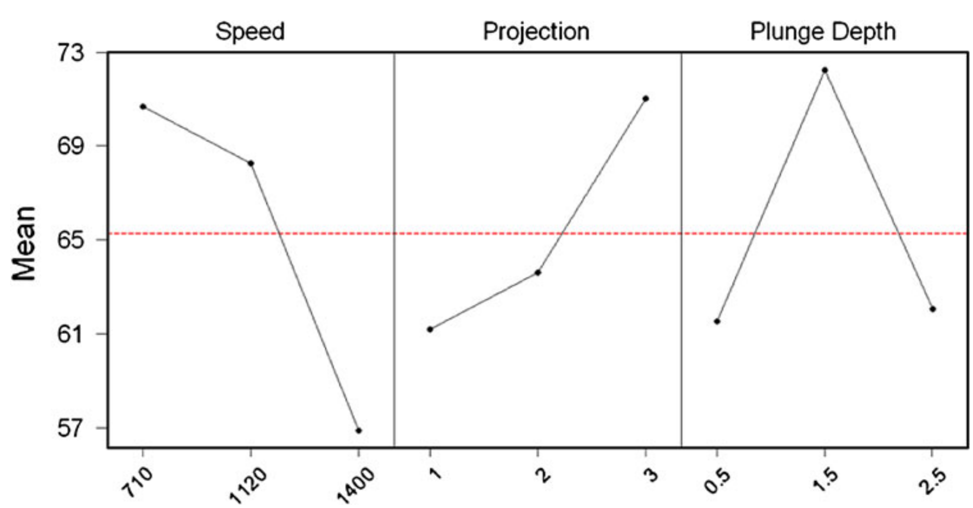

Fig. 7 Main effect plot for means

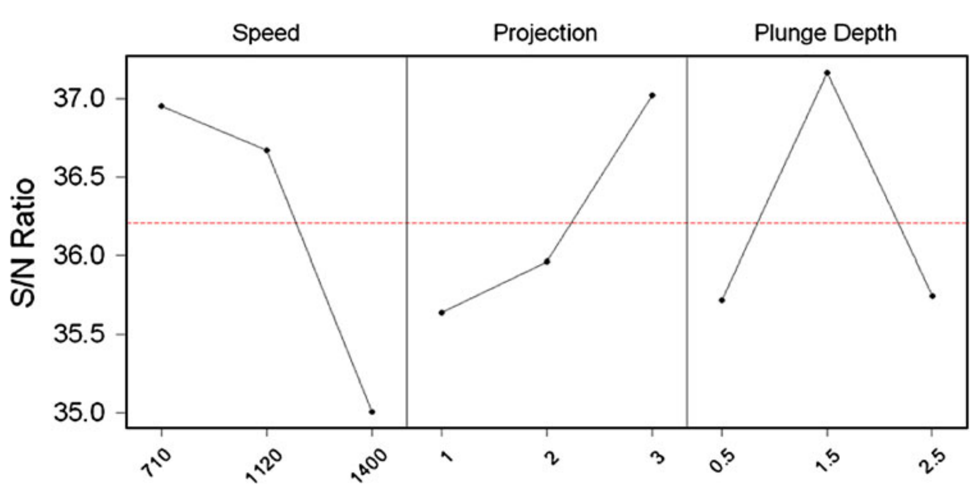

Fig. 8 Main effect plot for S/N ratios

Table 8 Results obtained from ANOVA

Source	DF	Seq. SS	Adj. SS	Adj. MS	*F*	*P*	Percentage of contribution
Speed, rpm	2	328.42	328.42	164.21	1857.32	0.001	46.98
Tube projection, mm	2	155.82	155.82	77.91	881.21	0.001	22.29
Plunge depth, mm	2	214.68	214.68	107.34	1214.08	0.001	30.71
Error	2	0.18	0.18	0.09			0.02
Total	8	699.09					100.00

Seq. SS, sequential sum of squares; Adj. SS, adjusted sum of squares; Adj. MS, adjusted mean squares; *F*, statistical test; *P*, statistical value

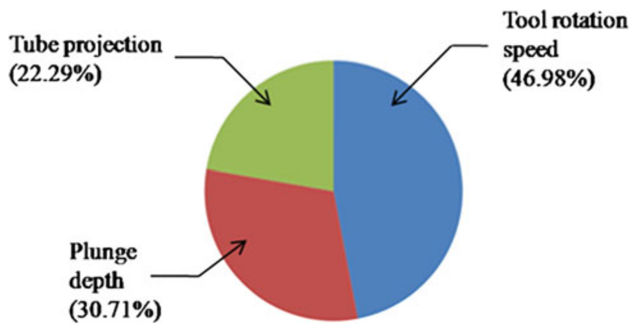

Fig. 9 Influence of input parameters on output parameter

4.3 Estimation of Optimal Joint Strength

Once an experiment is conducted and the optimum treatment condition within the experiment is determined, either of the following two possibilities exists:

(1) The prescribed combination of factors level is identical to one of those in the experiment;
(2) The prescribed combination of factors level is not included in the experiment.

It must be noted that the above combination of factor levels A1, B3, C2 are not among the nine combinations tested for the experiment. This is expected because of the multifactor nature of the experimental design employed (9 from $3^3 = 27$ possible combinations). The optimum value of tensile strength is predicted at the selected levels of significant levels of significant parameters. The estimated mean of the response characteristics (tensile strength) can be computed as

$$\text{Joint strength (JS)} = \text{TRS}_1 + \text{TP}_3 + \text{PD}_2 - 2J \qquad \text{(Eq 1)}$$

where J is the overall mean of joint strength, MPa (Table 2); TRS_1 is the joint strength at first level of rotational speed, TP_3 is the average joint strength at third level of tube projection, and PD_2 is the average joint strength at second level of plunge depth.

Substituting the values of various terms in the Eq 1, then

$$\begin{aligned}\text{Joint strength} &= 70.68 + 71.03 + 72.23 - (2 \times 65.34)\\ &= 83.26\,\text{MPa}\end{aligned}$$

4.4 Confirmation Test

The final step is verifying the improvement in joint strength by conducting experiments using optimal conditions. Three confirmation experiments were conducted at the optimum setting of process parameters. The average joint strength of commercially pure aluminium welded by FWTPET process with filler plate was found to be 83.24 MPa, which was within the confidence interval of the predicted optimal of joint strength.

5. Conclusion

(1) The tube-to-tube plate samples were successfully welded by FWTPET process with filler plate, which has wider industrial applications. This process produced a high-quality and defect-free weld joint.
(2) Taguchi L_9 orthogonal array was used in this study, and the tool rotational speed is found to be the most influential process parameter in deciding the joint strength.
(3) The optimal values of process parameters, namely, tool rotational speed, tube projection, and plunge depth are found to be 710 rpm, 3 mm, and 1.5 mm respectively.
(4) The percentage of contribution of each process parameter has been found by ANOVA, with the tool rotational speed leading with the highest contribution (46.98%), followed by plunge depth (30.71%) and tube projection (22.29%).

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