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INDUSTRIAL APPLICATION

Optimization of friction welding of tube to tube plate using an external tool

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Abstract The field of materials technology has been witnessing tremendous developments. Friction welding is an important solid state joining technique. In this research study, friction welding of tube to tube plate using an external tool has been performed and the process parameters are optimized by Taguchi L_8 orthogonal array. The prioritization of the process parameters has been obtained and ANOVA has been conducted to predict the statistical significance of the process parameters. This is followed by the optimization of welding process parameters using genetic algorithm. The practical feasibility of applying Genetic Algorithm to friction welding process has been ensured by means of studying the deviation between predicted and experimentally obtained welding process parameters.

Keywords Friction welding · Tube to tube plate welding · Taguchi method · Genetic algorithm

1 Introduction

In the past few decades, the field of materials processing technology has been witnessing tremendous improvements. Welding is an important metal joining process that has varied application across several industrial sectors. Friction welding is a solid state welding process that produces weld under the action of compressive forces, contact of rotating work pieces moving relative to one another so as to produce heat by means of controlled rubbing of faying surfaces. Friction welding has gained popularity because of several advantages; one among which is to weld alloys that cannot be welded otherwise. The unique feature of friction welding process is that the material that is being welded does not melt and recast. Due to the intensive heat generated at the interface, the material reaches the softened state which interacts with each other and produces good quality weld (Brien 1991). In order to produce good quality weld joint, it is vital to set proper welding process parameters. Generally, the welding process is a multi-input and multi-output process in which there exists a close relationship between the quality of joints and the welding parameters. This process of identifying the suitable combination of input process parameters so as to produce the desired output parameters necessitates the conduct of several experiments which consumes significant time and cost. Several efforts have been taken to understand the effect of process parameters on material flow behavior, microstructure formation and mechanical properties of friction welded joints (Lakshminarayanan and Balasubramanian 2008). In order to investigate the effect of friction welding 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 experiment approach is time consuming and consumes enormous amount of resources (Sathiya et al. 2009). Friction welding of tube to tube plate using an external tool (FWTPET) was invented in the year 2006 and patented

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was granted in the year 2008 to one of the present author (Muthukumaran 2008). This process is capable of welding tube to tube plate of similar or dissimilar metals. Major advantages of this process include capability to join dissimilar metals and they can be of any dimension (Muthukumaran 2010). However, in the case of friction welding, only smaller work pieces can only be joined. Joints made by FWTPET exhibits enhanced mechanical, metallurgical properties with lesser energy consumption (Muthukumaran 2010). Taguchi's statistical design is a powerful technique which is used to identify the most significant process parameter by the conduct of relatively fewer experiments (Montgomery 2006; Sathiya et al. 2006). However, Taguchi method does not allow interaction among the process parameters. Some research has been reported on the application of Taguchi techniques on casting and fusion welding process. An overview on the friction welding process indicates that commonly rod to rod type of welding has been reported. In this research work, FWTPET process has been carried to achieve leak proof high quality joint. The input parameters considered are tool rotational speed, pin clearance and shoulder diameter and the output parameter is tensile strength. Taguchi L_8 orthogonal array has been used and the most significant process parameter has been identified. This is followed by the conduct of ANOVA for ensuring the statistical significance of the process parameters. Then non-traditional optimization technique namely genetic algorithm (GA) has been used to derive the optimized process parameters of the FWTPET.

2 Experimental details

The FWTPET machine developed in-house is shown in Fig. 1. The external tool consists of a shoulder and pin which is depicted in Fig. 2. The tube to be welded is cleaned

Fig. 1 FWTPET machine (developed in-house)

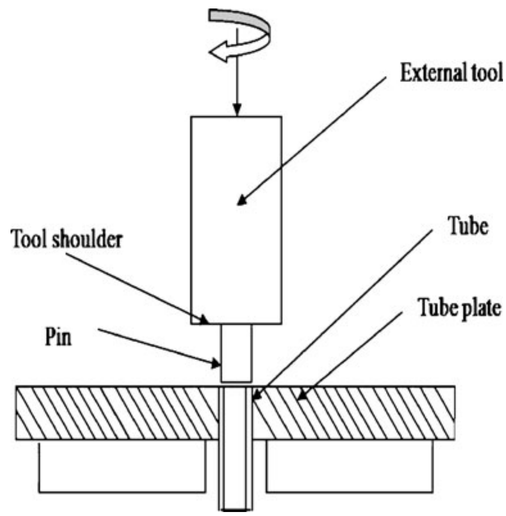


Fig. 2 Tube to tube plate welding set up

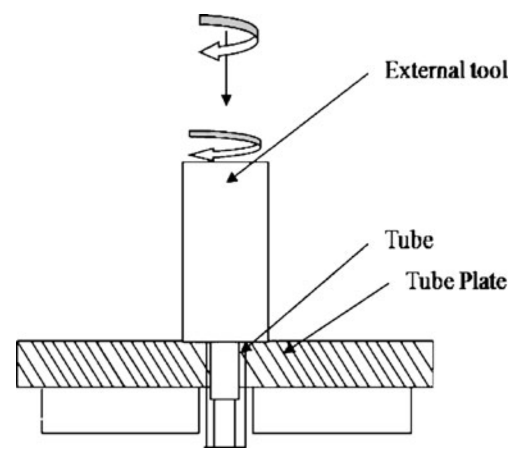


Fig. 3 Tube to tube plate welding setup when the shoulder touches the plate surface

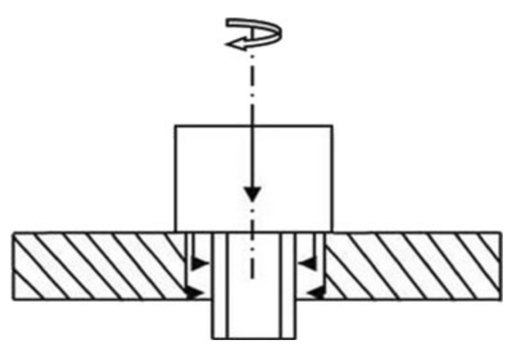


Fig. 4 Plasticized metal flows towards the tube axis due to downward force exerted by the shoulder

Table 1 Parent material chemical composition

	Element									
	V	Si	Fe	Cu	Mg	Mn	Ti	Zn	Cr	Al
Wt%	0.0001	0.0006	0.0007	0.0013	0.0021	0.0001	0.0001	0.0002	0.0001	Bal

and holes or slots are prepared along the faying surface of the tube (Muthukumaran et al. 2010). A suitable hole is drilled in a plate and the tube is fitted to the assembly in FWTPET machine table as shown in Fig. 3. The FWTPET machine consists of tool holder, spindle, table and supporting structure. The tool is lowered during rotation and heat is generated due to friction when the shoulder touches the plate.

The plastic flow of metal takes place towards the center of the tool axis as shown in Fig. 4. The metal flows through the holes in the tube and occupies the gap between pin and inner diameter of the tube. The tool is withdrawn after a predetermined time.

The cylindrical pin restricts the material movement and applies pressure between the tube and plate. The bonding takes place between surfaces which are at high pressure and temperature (Muthukumaran 2008). The process variables considered in the present study are tool rotational speed, pin clearance and shoulder diameter. The parent metal employed in this study is commercial pure aluminium. The chemical composition of the parent metal is shown in Table 1.

The experiment has been conducted using 6 mm rolled plates of commercially pure aluminium and cut into the required sizes (50 mm × 70 mm) by means of a power hacksaw. Similarly, tubes of 19 mm external diameters have been cut into required size (35 mm height). This is followed by drilling of 19 mm diameter holes in the rolled plate. Then the tubes are fixed in their respective hole position. Tools made of tool steel have been used to fabricate FWTPET joints in the present study and the chemical composition of tool material is shown in Table 2.

The assembly of the work piece is clamped on the machine table and the tool has been fixed to the spindle of the machine. Friction weld joint before and after performing friction welding process are shown in Figs. 5 and 6.

After the completion of welding, the tube to tube plate joints are sliced for macro-structural studies. The rough scratches on the surfaces have been removed using a belt grinder and the fine scratches have been removed using emery sheet of different grades. Further polishing has been done using alumina and diamond paste by using a disc polishing machine. This is followed by etching the macro-structure using tucker's reagent (composition: 4.5 ml HNO_3, 2.5 ml H_2O, 1.5 ml HCl, 1.5 ml HF). Then the sample has been washed, dried and observed using a macroscope. The macrostructures of the weld obtained with tool rotational speed, pin clearance and shoulder diameter of 1,030 rpm, 1 mm and 30 mm respectively is shown in Fig. 7a. The macrostructure observation reveals a better weld interface between the tube and the tube plate.

The microstructures of the weld joint obtained with the process parameters (1,030 rpm speed, 1 mm pin clearance and 30 mm shoulder diameter) have been analyzed at different weld zones. The keller's etchant has been used for microstructural studies (composition: 2 ml HF, 3 ml HCl, 5 ml HNO_3, 190 ml distilled water) and typical micrographs at different zones in the joint are shown in Fig. 7b.

Compared to the base metal, the changes in microstructure are observed at the weld zone interface. The grains at base metal (plate and tube) are coarser and a fine grain structure has been observed in the weld zone interface as shown in Fig. 7b. When more quantity of plate material (which is in plastic condition) is forced through small holes, a metallurgical bond is achieved at the joint interface.

2.1 Tensile test

Joints have been produced by FWTPET machine and tensile test has been conducted using a tensometer. Tensile

Table 2 Tool material chemical composition

	Element							
	C	Mn	Si	Cr	Ni	Mo	W	V
Wt%	0.87	0.36	0.30	3.71	0.31	4.31	0.95	2.05

Fig. 5 Arrangement of tube to tube plate before FWTPET

Fig. 6 Tube to tube plate weld joints after FWTPET

Fig. 8 Tensile test set up conducted using a tensometer

test specimen fixed in the tensometer is shown in Fig. 8. Three joints have been tested for each set of process parameters and the average value is obtained. The best input and output parameters obtained through Taguchi technique and Genetic Algorithm were used to process the friction joints experimentally.

3 Taguchi method

Taguchi method is an efficient tool which enables the upgradation of the performance of the product, process, and design with significant prediction of cost and time (Lakshminarayanan and Balasubramanian 2009; Benyounis

Fig. 7 **a** Macrostructure of joint obtained by FWTPET process, **b** microstructure of joint obtained by FWTPET process

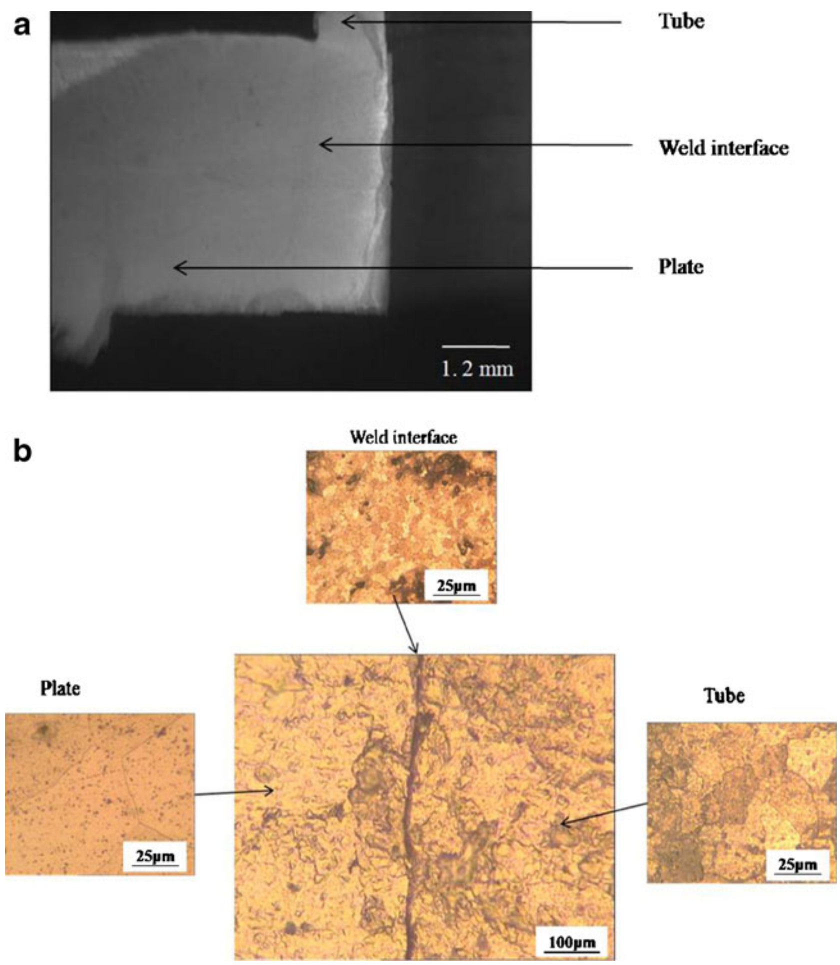


Table 3 Factors and levels

Factors	Levels	
	1	2
A (tool rotational speed, rpm)	1,030	1,500
B (pin clearance, mm)	1	2
C (shoulder diameter, mm)	25	30

and Olabi 2008; Kim et al. 2003). It is a systematic approach for enabling the design optimization thereby ensuring both quality and performance by means of Taguchi's parameter design concept. The system performance could be optimized by means of systematic setting of design parameters and reducing the fluctuations. Taguchi method employs a special design of orthogonal arrays to study entire process parameters space with small number of experiments (Sharma et al. 2005; Anawa and Olabi 2008a, b; Vijian and Arunachalam 2006). The optimal result could be generated out of Taguchi method by means of systematic analysis of data and the dominant factor involved in optimization. In this study, L_8 orthogonal array has been used and three process parameters are considered in this study; tool rotational speed (revolutions per minute), pin clearance (millimeters) and shoulder diameter (millimeters). The factors and their corresponding values are presented in Table 3. The format of L_8 orthogonal array is presented in Table 4.

Table 5 shows the various input parameters and output parameters of FWTPET process. The ranking of process parameters generated by the conduct of Taguchi method is shown in Table 6. As inferred from Table 6, speed has been ranked as the highly prioritized process parameter followed by the shoulder diameter and pin clearance.

Table 4 Experiment layout using an L_8 orthogonal array

Experiment number	FWTPET parameters level		
	A (tool rotational speed, rpm)	B (pin clearance, mm)	C (Shoulder diameter, mm)
1	1	1	1
2	1	1	2
3	1	2	1
4	1	2	2
5	2	1	1
6	2	1	2
7	2	2	1
8	2	2	2

Table 5 Input parameters of orthogonal array and the output characteristics

Experiment	Input parameters			Output characteristics
run	Speed (rpm)	Pin clearance (mm)	Shoulder diameter (mm)	Tensile strength (MPa)
1	1,030	1	25	60.31
2	1,030	1	30	70.87
3	1,030	2	25	55.72
4	1,030	2	30	63.37
5	1,500	1	25	44.69
6	1,500	1	30	48.52
7	1,500	2	25	38.57
8	1,500	2	30	42.55

3.1 Analysis of variance (ANOVA)

The statistical analysis of variance (ANOVA) has been performed to predict the statistical significance of the process parameters (Casalino et al. 2005). It helps to determine the effect of individual input parameter on output parameters. The results of ANOVA are presented in Table 7.

Based on the results presented in Table 7, tool rotational speed is found to be the most influencing process parameter with 80.61% contribution followed by shoulder diameter (9.46%) and pin clearance (8.17%) and this apportionment shown in Fig.9. The main effects plot generated by MINITAB software pertaining to ANOVA is shown in Fig. 10 (MINITAB 2008). It can be inferred that higher tensile strength could be obtained when the speed and pin clearance are low and shoulder diameter is large. However at very low speeds, heat generation and joint strength is found to be poor.

Table 6 Ranking of influential process parameters by Taguchi's method

Level	Speed (rpm)	Pin clearance (mm)	Shoulder diameter (mm)
1	62.57	56.10	49.82
2	43.58	50.05	56.33
Delta	18.98	6.05	6.51
Rank	1	3	2

Table 7 Analysis of variance for tensile strength, using adjusted SS for tests

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	Percentage of contribution
Tool rotational speed	1	720.86	720.86	720.86	184.33	0.000	80.61
Pin clearance	1	73.08	73.08	73.08	18.69	0.012	8.17
Shoulder diameter	1	84.63	84.63	84.63	21.64	0.010	9.46
Error	4	15.64	15.64	3.91			1.75
Total	7	894.22					100

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

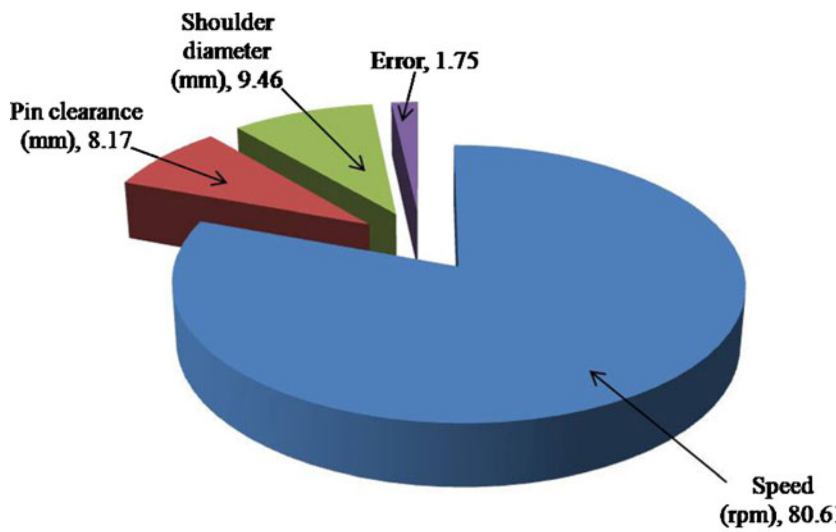


Fig. 9 Contribution in percentage of FWTPET process parameters

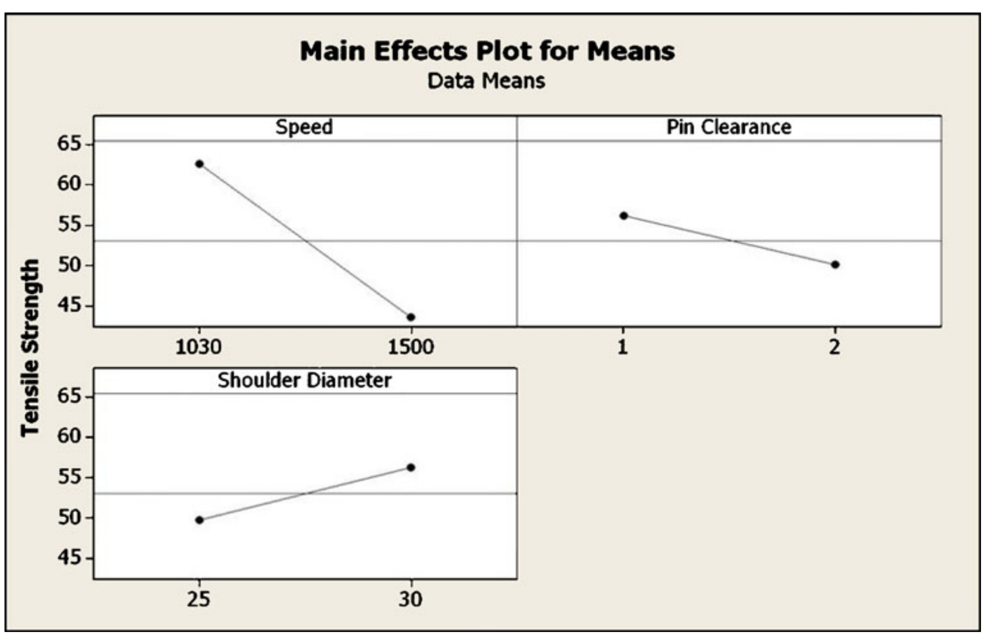


Fig. 10 Main effects plot generated by MINITAB software

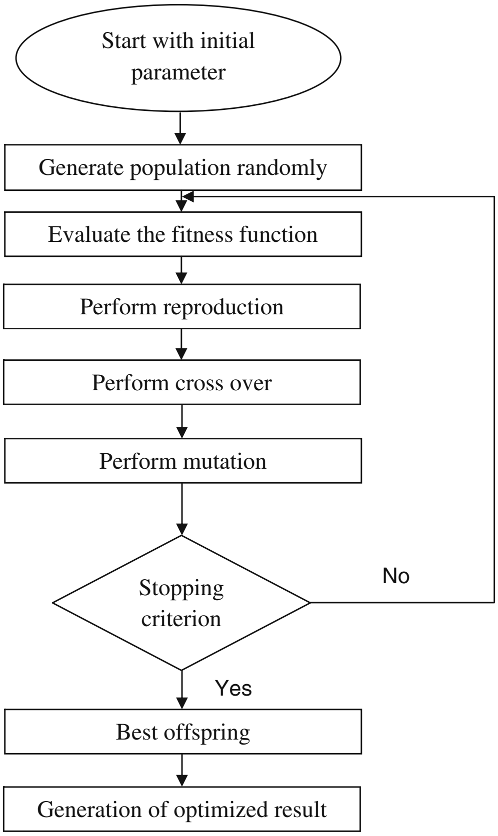


Fig. 11 General structure of genetic algorithm

4 Optimization by genetic algorithm

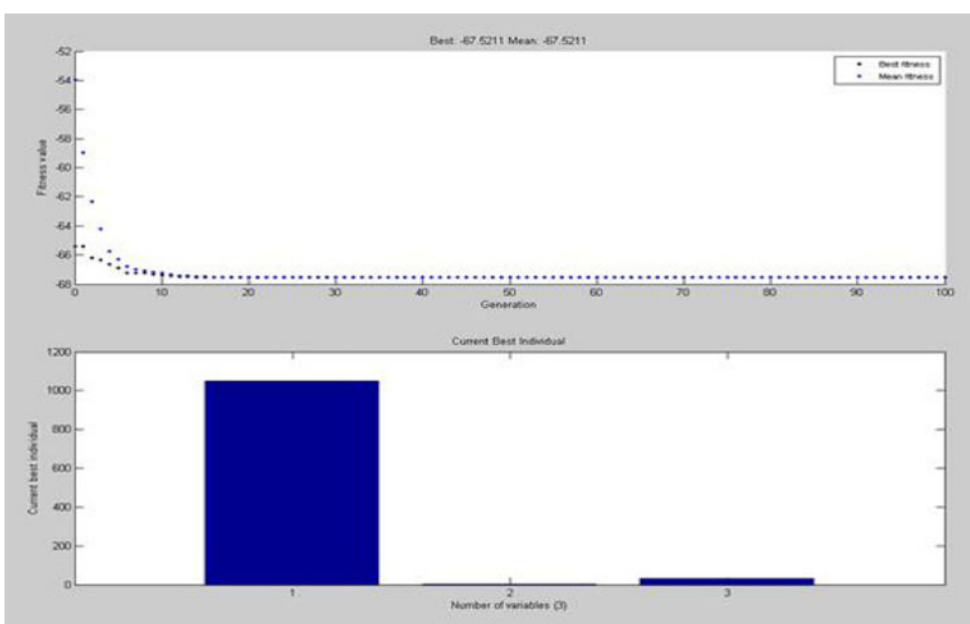
Genetic algorithm (GA) is a nontraditional optimization algorithm based on the principles of natural genetics (Paneerselvam et al. 2009). The principle of natural genetics is that 'Fit parents would yield fit offspring'. GA has wide variety of applications in engineering problems because of simplicity and ease of operation (Kim and Rhee 2001). The minimum or maximum of a function is found based on the variation of $X_1, X_2, X_3 \ldots X_n$ beginning with one or more starting point. GA evaluates a set of points, and the basic element of GA consists of a chromosome and fitness value. The fitness value describes how well an individual can adapt to survival and mating (Aydın and Ayvaz 2010). In our study, the basic elements of GA consists of a value of speed, pin clearance, shoulder diameter and tensile strength = f (S, PC, SD). GA works on the basis of binary code in the form of 0 and 1. An individual in GA is denoted by I = {S, PC, SD, f (S, PC, SD)}. A set of search individual is called a population and general structure of GA is shown in Fig. 11 and convergence GA result depicting in Fig. 12. The parameters used in GA are; population size = 100, length of chromosome = 20, selection operator = stochastic uniform, crossover probability = 0.8, mutation probability = 0.2, fitness parameter = tensile strength. The objective function is given by

$$\text{Tensile strength} = f\ (S, PC, SD)\,.$$

Table 8 Optimized results

	Tool rotational speed (rpm)	Pin clearance (mm)	Shoulder diameter (mm)	Tensile strength (MPa)
GA	1,049	1.08	29.98	67.52
Experimental value	1,030	1	30	70.87

Fig. 12 Screenshot depicting the convergence result obtained using GA



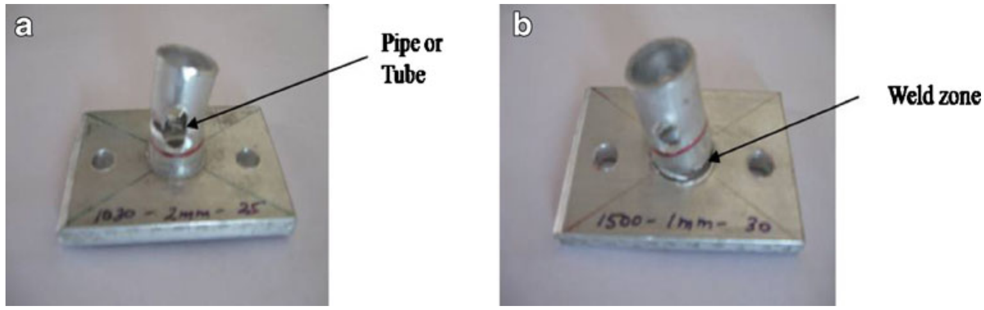


Fig. 13 Tensile test samples showing different fracture locations. **a** Fracture occurrence at the base material (pipe side). **b** Fracture occurrence at the weld zone

4.1 Welding constraints

The practical constraints imposed during welding process are stated as follows:

Parameter bounds:

Bounds on tool rotational speed (S)

$S_L \leq S \leq S_H$

Where $S_L = 1{,}030$ rpm $S_H = 1{,}500$ rpm are lowest and highest speed respectively.

Bounds on pin clearance (PC)

$PC_L \leq PC \leq PCH$

Where $PC_L = 1$ mm $PCH = 2$ mm are lowest and highest pin clearance respectively.

Bounds on shoulder diameter (SD)

$SD_L \leq SD \leq SD_H$

Where $SD_L = 25$ mm $SD_H = 30$ mm are lowest and highest shoulder diameter respectively.

Table 8 presents the optimized parameters for obtaining maximum tensile strength. Based on the optimum value, validation experiment has been conducted using the feasible input parameters. There has been a narrow deviation between the theoretically predicted and experimentally obtained values for tensile strength which conforms the practical applicability of GA to FWTPET process.

The weld has been performed with optimized process parameters; the fracture occurs away from the joint which is shown in Fig. 13a and majority of the instances; the fractures have been occurred in the weld zone as shown in Fig. 13b. The strength achieved using optimized process parameters is 70.87 MPa (1030 rpm, 1 mm pin clearance and 30 mm shoulder diameter).

5 Conclusions

In this study, FWTPET process has been used to join tube to tube plate which is an innovative process having wider applications. This process is capable of producing high quality and defect free weld joints. Also, this process is capable of producing joints with enhanced mechanical and metallurgical properties with lesser energy consumption. Taguchi L_8 orthogonal array has been used in this study and the statistical significance of the welding process parameters has been determined by the conduct of ANOVA. Percentage contributions of the process parameters have been found and the speeds possess highest contribution (80.61%) followed by the shoulder diameter (9.46%) and the pin clearance (8.17%). The optimization of the process parameters has been carried out using GA. The optimized value of tool rotational speed, shoulder diameter, pin clearance and ultimate tensile strength are 1030 rpm, 1 mm, 30 mm and 70.87 MPa respectively. The coherence between the theoretically optimized values and the experimentally obtained values of the process parameters ensures the high potential of applying GA to the FWTPET process.

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