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Friction welding Optimization of tube-to-tube plate using an internal tool by genetic algorithm and Taguchi method

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ABSTRACT: *In this research project, friction welding of tube-to-tube plate using an external tool (FWTPET) has been performed, and the process parameters have been prioritized using Taguchi's L_{27} orthog-onal array. Numerous advancements have been occurring in the field of materials processing. Friction welding is an important solid-state joining technique. Genetic algorithm (GA) is used to optimize the welding process parameters. The practical significance of applying GA to FWTPET process has been validated by means of computing the deviation between predicted and experimentally obtained welding process parameters.*
Keywords: *Tube-to-tube plate welding, Taguchi method Genetic algorithm*

I. INTRODUCTION

During the past few decades, the field of materials processing technology witnessed numerous developments. Welding is an important metal fabrication process that has several industrial applications. Friction welding is a solid-state welding process that produces weld due to combined work pieces moving relative to one another so as to generate heat by means of controlled rubbing of faying surfaces. Friction welding process has high potential for several applications because of its ability to produce good quality weld as the material being welded does not melt and recast [1].

Proper setting of welding process parameters is essential to produce good quality weld. The process of identification of 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. Researchers have concentrated on under-standing and studying the effect of process parameters on material flow behavior, microstructure formation, and mechanical properties of friction welded joints. Researchers have applied conventional experimental techniques in which single parameter will be varied, keeping other parameters constant [2]. Conventional parameter-based design of experiment approach is time-consuming and consumes enormous amount of resources [3]. FWTPET was innovated in the year 2006 by one of the present authors and patent was granted in the year 2008 [4]. This process is capable of welding tube-to-tube plate of similar or dissimilar metals. Major advantages of this process include ability to join dissimilar metals and can be of any dimension [5]. However, in the case of friction welding, only shorter work pieces can be joined. Joints made by FWTPET exhibits enhanced mechanical and metallurgical properties with lesser energy consumption [6–8]. The concept of identifying most significant process parameters by the conduct of relatively fewer experiments has been emphasized by Taguchi [2]. Some research has been reported on the application of Taguchi techniques on casting and fusion welding process [2]. The input parameters considered in the present research project are tool rotational speed, pin clearance, and shoulder diameter, and the output parameter is tensile strength. Taguchi L_{27} orthogonal array has been used to identify the most significant process parameter. Nontradi-tional optimization technique, genetic algorithm (GA) has been used to obtain the optimized process parameters of the FWTPET process.

II. FWTPET PROCESS

The FWTPET machine developed in-house is shown in Fig. 1. The external tool consists of a shoulder and pin which is shown in Fig. 2, and dimensions of the workpiece and tool used in FWTPET process are shown in Fig. 3. The tube-to-tube weld is cleaned, and holes or slots are prepared along the faying surfaces of the tube. A suitable hole is drilled in a plate and the tube is fitted, and the assembly in FWTPET machine table is shown in Fig. 4. 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 toward the center of the tool axis as shown in Fig. 5. 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 the predetermined time. The cylindrical pin restricts the material movement, and pressure is applied between the tube and plate. The bonding takes place between surfaces which are at higher pressure and temperature. The process variables consid-ered in this research study are tool rotational speed, pin clearance, and shoulder diameter. Both the tube and tube plate used in the present study are made of commercially

Fig. 1 FWTPET machine (developed in-house)

Fig. 2 Tube-to-tube plate welding tool

pure aluminum, and their chemical composition is shown in Table 1. The spindle used in the present study is made of waspaloy, and their chemical composition is shown in Table 2.

The experiment has been conducted using 6-mm rolled plates of commercially pure aluminum and cut into the required sizes (50× 70 mm) by means of a power hacksaw. Similarly, tubes of 16 mm external diameter have been cut into required size (35 mm height). This is followed by the drilling of 16-mm-diameter holes in the rolled plate. Then the tubes are fixed in their respective hole position. Tools made of tool steel are used to fabricate FWTPET joints in the present study. The assembly of the work piece is clamped on the machine table, and the tool has been fixed to the spindle of the machine. FWTPET weld joint before and after performing the friction welding process are shown in Figs. 6 and 7, respectively. 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. The fine scratches have been removed using emery sheet of different grades, and further polishing has been done using alumina and diamond paste using a disk polishing machine. This is followed by etching the macrostructures 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 1030 rpm, 1 mm, and 30 mm, respectively, are shown in Fig. 8a. The macrostructure observation reveals a better weld interface between the tube and the tube plate. The weld interface does not reveal defects such as crack, porosity, etc. because better bonding occurs at the interface between the tube and the tube plate. But in the case of other process parameters, macrostructure showed in Fig. 8b, c reveals small and large cracks, respectively, at the interface between the tube and the tube plate. The reason for large crack at the interface at 500 rpm is due to insufficient heat

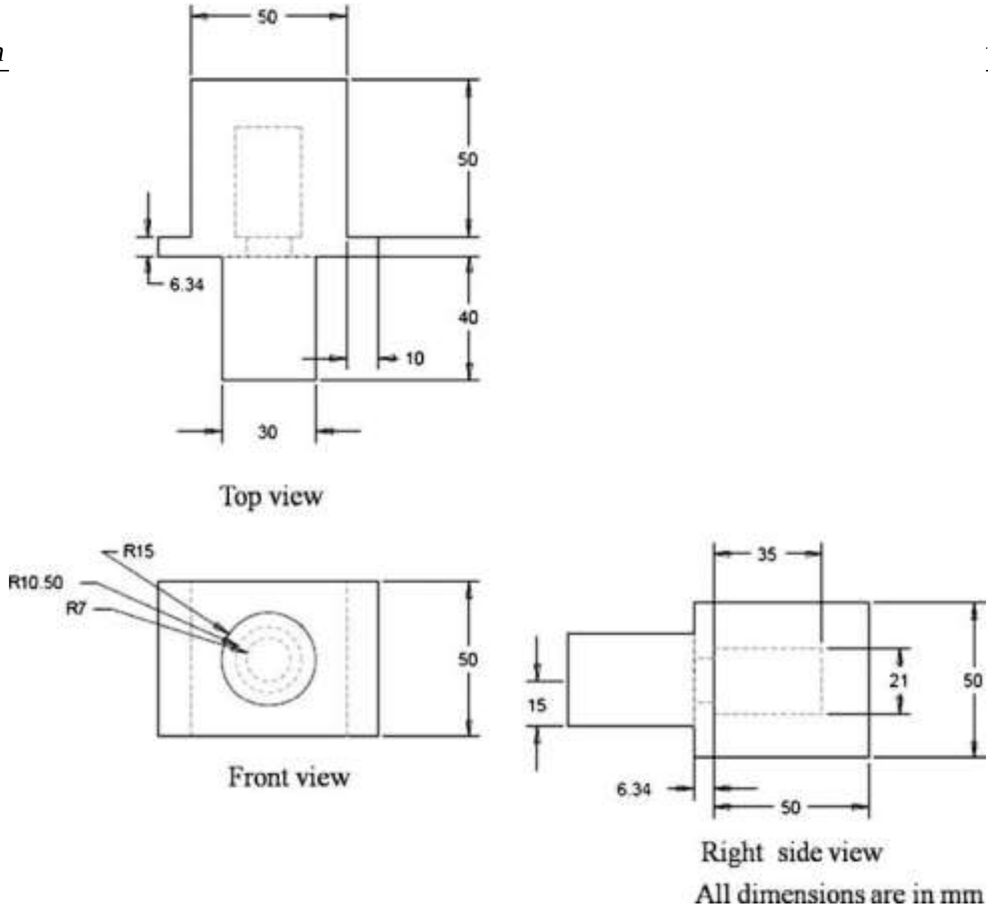


Fig. 3 2D views pertaining to workpiece and tool used in FWTPET process

generated at low speed between the tube and the tube plate. But in the case of joints produced at 1,500 rpm, excess heat is produced and excessive plastic deformation occurs at the interface which leads to poor metallurgical bond. The crack formation at the interface has been clearly observed with different magnification showed in Fig. 9.

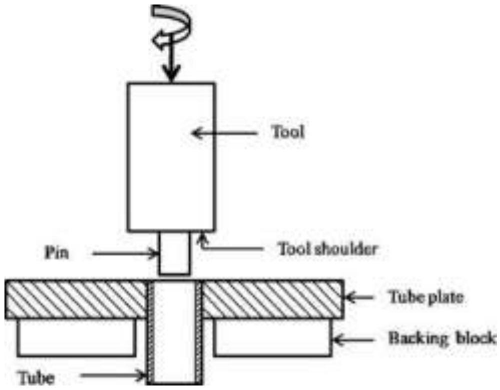


Fig. 4 FWTPET setupforce offered by the shoulder

2.1 Microstructure study

The microstructure aspects of the friction welded joints are studied through optical microscopy. The integrity of joints has been analyzed through the micrographs at the weld zone. The keller’s etchant has been used for microstructure studies

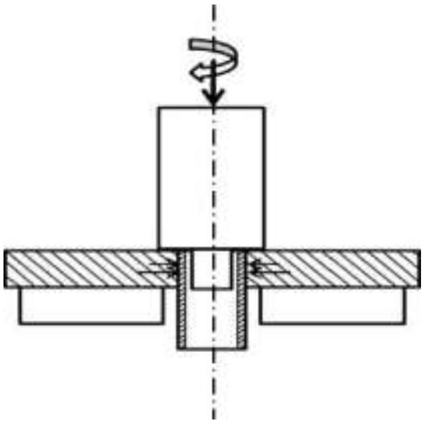


Fig. 5 Plasticized metal flows toward the tube axis due to downward

Table 1 Chemical composition of parent metal (weight percent)

Element	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

(composition: 2 ml HF, 3 ml HCl, 5 ml HNO_3, 190 ml distilled water). Typical micrographs of different zones in the welded joint have been presented in Fig. 10, and the cross section of the FWTPET joint with different magnification is shown in Fig. 11. The friction welded joints have been sectioned perpendicular to the bond line and observed using optical microscope. Typical micrographs showing different morphologies of microstructure at different zones of the friction welded joints have been presented and analyzed. Compared to base metal, the changes in microstructures are observed obviously at weld zone interface. The grains at base metal (plate and tube) are relatively coarser. Fine grain structure has been observed in the weld zone interface. In solid-state welding, especially in friction welding, due to severe deformation, the refined grain structure is observed at the weld zone which resulted in improved properties.

2.2 Tensile testing
Joints have been produced by FWTPET machine, and tensile test has been conducted using a tensometer. Tensile test specimen fixed in the tensometer is shown in Fig. 12. Three joints have been tested for each set of process parameters, and the mean value is obtained. The best input and output parameters obtained through Taguchi technique and genetic algorithm were used to process the friction joints experimentally.

III. TAGUCHI METHOD

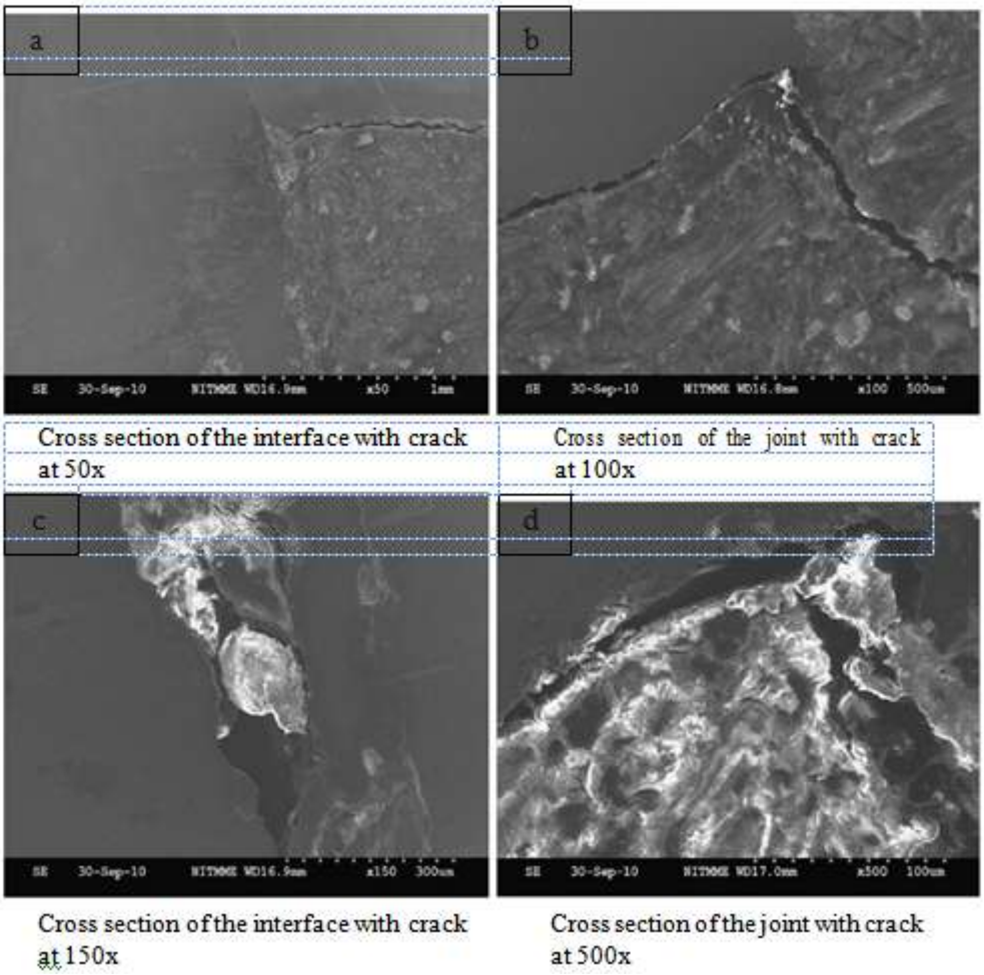
Taguchi's parameter design is a systematic approach for enabling the design optimization thereby ensuring both quality and performance [9]. The system performance could be optimized by means of systematic setting of design parameter and reducing the fluctuations [10]. Taguchi

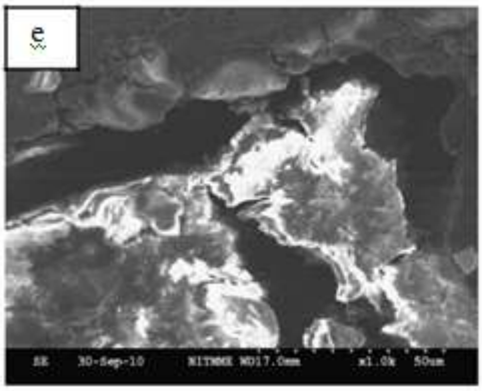
Element													
	Ni	C Co		Mn Ti		Si Al		Cr Mo			Bn Zr		Fe Co
wt.%	Bal	0.08	0.50	0.75	18	0.003	2	12	3.25	1.0	4	0.12	0.10

Table 2 Chemical composition of spindle materials (weight percent)

method employs the concept of orthogonal arrays to study entire process parameters space with small number of experiments [11]. 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_{27} 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_{27} orthogonal array is presented in Table 4. Taguchi recommends the use of the loss function to measure the deviation of the quality characteristics from the desired value. To consider several quality characteristics together in the selection of process parameters, Taguchi method needs to be modified to evaluate several loss functions corresponding to different quality characteristics. Taguchi's parameter design can optimize the performance through the setting of design parameters and reduce the fluctuation of system performance to sources of variation [12, 13]. In this study, weighting method is used to integrate the loss functions into the overall loss function. The value of the overall loss function is further transformed into a signal-to-noise (S/N) ratio. Usually, there are three categories of the quality characteristic in the analysis of the S/N ratio, i.e., the lower-the-better, the higher-the-better, and the nominal-the-better. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a large S/N ratio

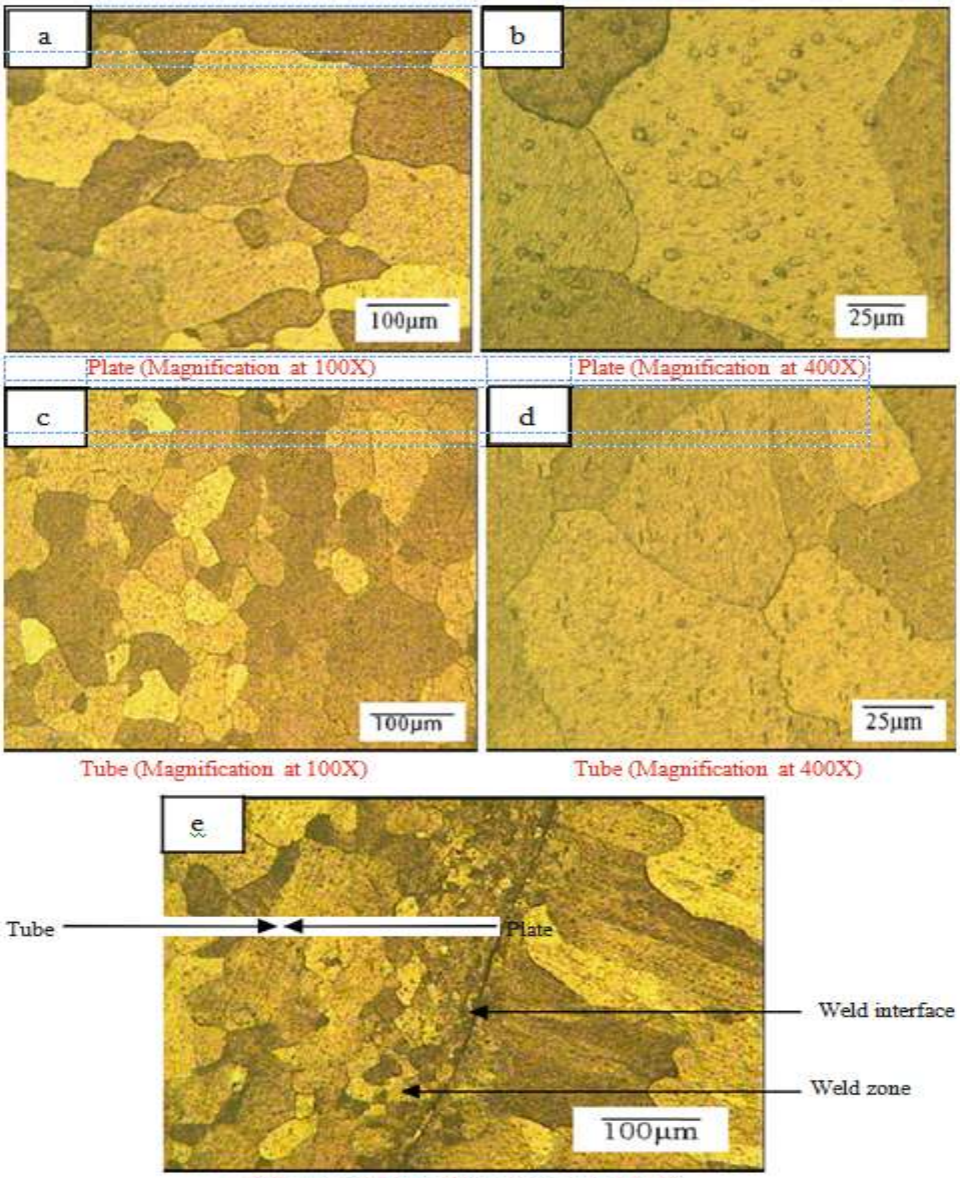
Fig. 6 Arrangement of tube-to-tube plate before FWTPET





Cross section of the joint with crack at 1000x

Fig. 7 Macrostructure of weld joint (with defects) obtained by FWTPET process showing in-terface with crack



Different weld zone (Magnification at 100X)

Fig. 8 Microstructure of dif-ferent zones obtained by FWTPET process

In this case, the objective is to minimize the mean squared error around a specific target value. Taguchi method has been conducted using MINITAB package in our study. 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, and the interaction value for S/N ratio is shown in Table 7. As inferred from Tables 6 and 7, speed has been prioritized as the first process parameter followed by shoulder diameter and pin clearance. The interaction plot between the process parameters generated by the conduct of Taguchi method is shown in Figs. 13 and 14, respectively [14]. The interaction plot reveals that high bond strength is assured

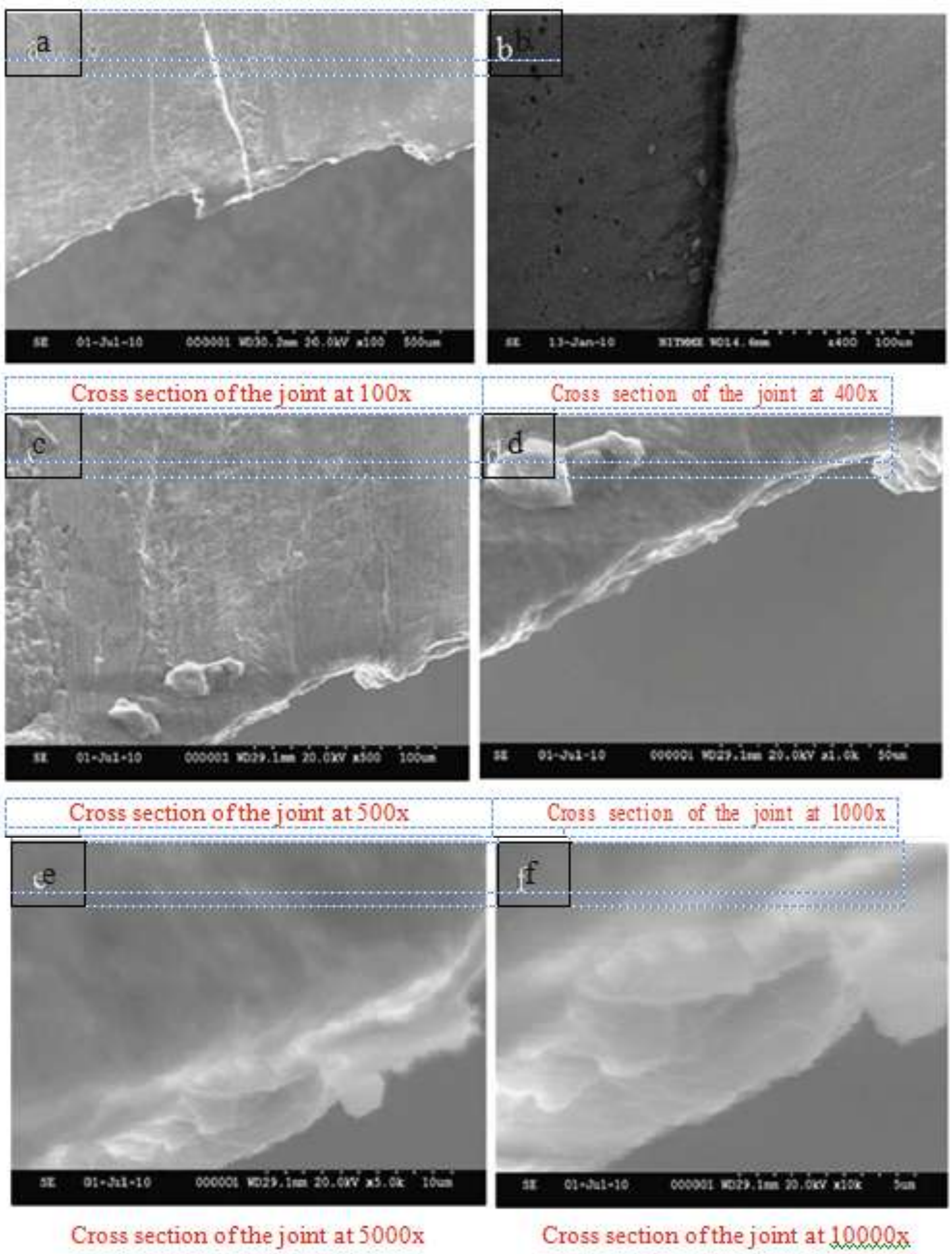


Fig. 9 Cross section of the joint obtained by FWTPET pro-cess

Table 3 Factors and levels

Factors	Levels		
	1	2	3
A (tool rotational speed, rpm)	500	1,030	1,500
B (pin clearance, mm)	1	2	3
C (shoulder diameter, mm)	20	25	30

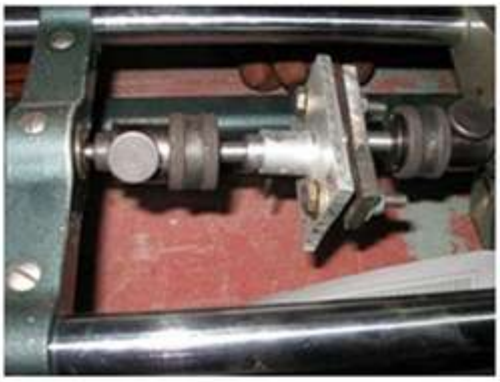


Fig. 10 Tensile test conducted using a tensometer

Table 4 Experiment layout using L_{27} orthogonal array

Experiment number		FWTPET parameters level		
		A (tool rotational speed, rpm)	B (pin clearance, mm)	C (shoulder diameter, mm)
A1	1	1	1	1
A2	2	1	1	2
A3	3	1	1	3
A4	4	1	2	1
A5	5	1	2	2
A6	6	1	2	3
A7	7	1	3	1
A8	8	1	3	2
A9	9	1	3	3
B1	10	2	1	1
B2	11	2	1	2
B3	12	2	1	3
B4	13	2	2	1
B5	14	2	2	2
B6	15	2	2	3
B7	16	2	3	1
B8	17	2	3	2
B9	18	2	3	3
C1	19	3	1	1
C2	20	3	1	2
C3	21	3	1	3
C4	22	3	2	1
C5	23	3	2	2
C6	24	3	2	3

C7	25	3	3	1
C8	26	3	3	2
C9	27	3	3	3

Table 5 Input parameters of orthogonal array and the output characteristics

Experiment run		Input parameters			Output characteristics
		Speed (rpm)	Pin clearance (mm)	Shoulder diameter (mm)	Tensile strength (MPa)
A1	1	500	1	20	31.22
A2	2	500	1	25	35.39
A3	3	500	1	30	46.83
A4	4	500	2	20	30.81
A5	5	500	2	25	34.35
A6	6	500	2	30	43.71
A7	7	500	3	20	28.10
A8	8	500	3	25	32.27
A9	9	500	3	30	40.59
B1	10	1,030	1	20	47.46
B2	11	1,030	1	25	58.29
B3	12	1,030	1	30	64.53
B4	13	1,030	2	20	45.79
B5	14	1,030	2	25	49.96
B6	15	1,030	2	30	61.41
B7	16	1,030	3	20	44.96
B8	17	1,030	3	25	48.92
B9	18	1,030	3	30	59.95
C1	19	1,500	1	20	38.30
C2	20	1,500	1	25	43.72
C3	21	1,500	1	30	52.04
C4	22	1,500	2	20	36.64
C5	23	1,500	2	25	40.59
C6	24	1,500	2	30	47.88
C7	25	1,500	3	20	35.39
C8	26	1,500	3	25	39.55
C9	27	1,500	3	30	46.63

IV. OPTIMIZATION BY GENETIC ALGORITHM

GA is a nontraditional optimization algorithm based on the principle “Fit parents would yield fit offspring.” GA has wide variety of applications in engineering problems because of simplicity and ease of operation [15]. GA is a computerized search and optimization algorithm based on the mechanics of natural genetics and natural selection. According to Darwin’s natural selection theory, strong individuals of a population survive, while weak individ-uals do not. The surviving individuals mate to produce the next generation of individuals. It is clear that individuals in the next generation will be better than the individuals of the previous generations; individuals continue to get fitter as evolution continues. Thus, individuals ultimately become perfect [16]. GA is an evolutionary optimization method that uses a group of initial solutions. These solutions are represented by the design variables. GA improves these solutions by using certain genetic rules. The initial population is randomly determined. The generation of solutions is taken to be the first generation of the design, and each individual is considered to be a solution within a given generation. The solutions for each generation are coded using binary numbers in order that genetic operators can be readily applied. After determin- ing the initial population, the genetic evolution begins. At first, the fitness of each individual is determined according to their closeness to the optimum solution, and individuals are categorized according to their fitness. After that, the reproduction, crossover, and mutation operators are ap-plied to each generation to evolve a new generation. This evolution continues until the majority of the solutions are identical [17–19], i.e., the convergence has occurred. The minimum or maximum of a function is determined based on the variation of X_1, X_2, X_3 …… X_n beginning with one

Table 6 Ranking of most influence parameters by Taguchi's method

Level	Speed (rpm)	Pin clearance (mm)	Shoulder diameter (mm)
1	35.92	46.42	37.63
2	53.47	43.46	42.56
3	42.30	41.82	51.51
Delta	17.56	4.60	13.88
Rank	1	3	2

Table 7 The interaction value for S/N ratio generated by Taguchi's method

Level	Speed (rpm)	Pin clearance (mm)	Shoulder diameter (mm)
1	30.9888	33.1239	31.3729
2	34.4876	32.5897	32.4301
3	32.4610	32.2238	34.1344
Delta	3.4988	0.9000	2.7615
Rank	1	3	2

or more starting points. GA generally evaluates a set of points, and the basic elements of GA consist of a chromosome and fitness value. The fitness value describes how well an individual can adapt to survival and mating [20–22]. In the present study, the basic element of GA consists of values 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. 15 [23, 24]. The objective function is given by tensile strength [f (S, PC, SD)]. The parameters used in GA and their values are shown in Table 8.

4.1 Welding constraint

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

Parameter bounds:

Bounds on tool rotational speed (S)

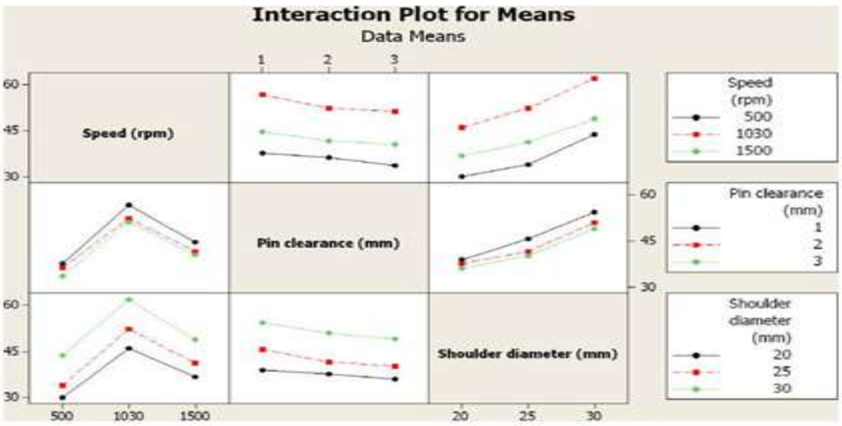


Fig. 11 Interaction plot for pro-cess parameters generated by the conduct of Taguchi's method

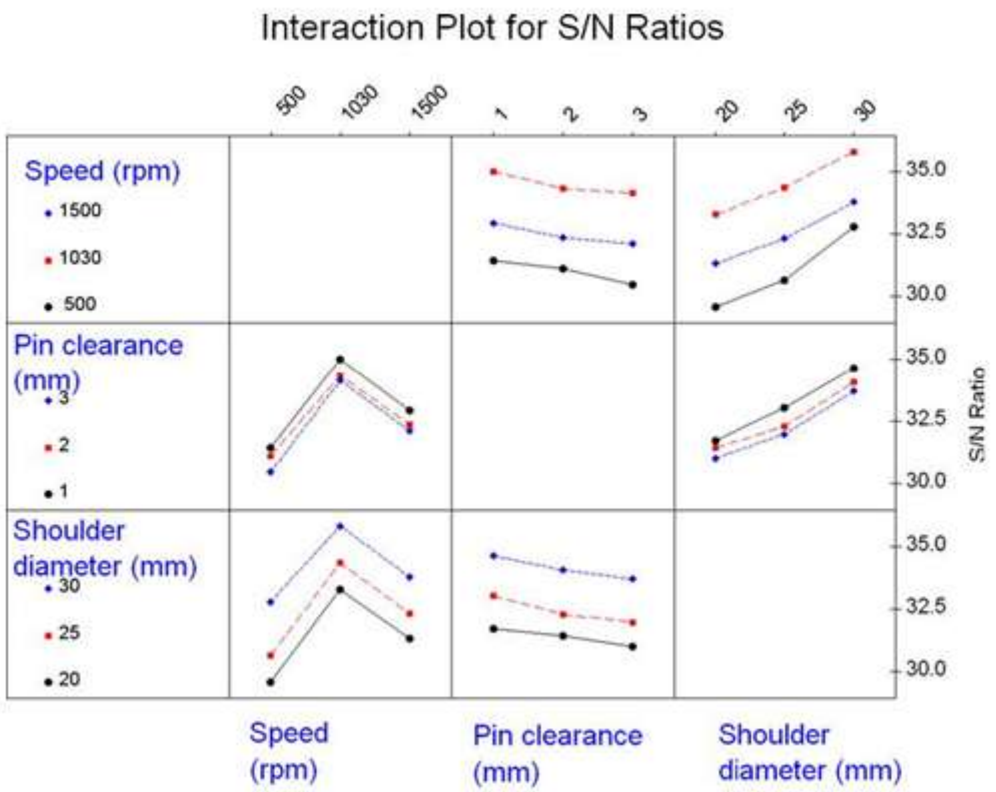


Fig. 12 Interaction plot for S/N ratios process parameters gener-ated by the conduct of Taguchi's method

Perform reproduction

Perform cross over

Perform mutation

No

Stopping

criterion

Yes

Best offspring

Generation of optimized result

The problem of GA has been solved using MATLAB.

Figure 16 depicts the convergence result obtained in GA.

Table 9 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

Table 8 Parameters and their values used in GA

Parameters	Values
population size	100
length of chromosome	20
selection operator	Stochastic uniform
crossover probability	0.8
mutation probability	0.2

fitness parameter Tensile strength

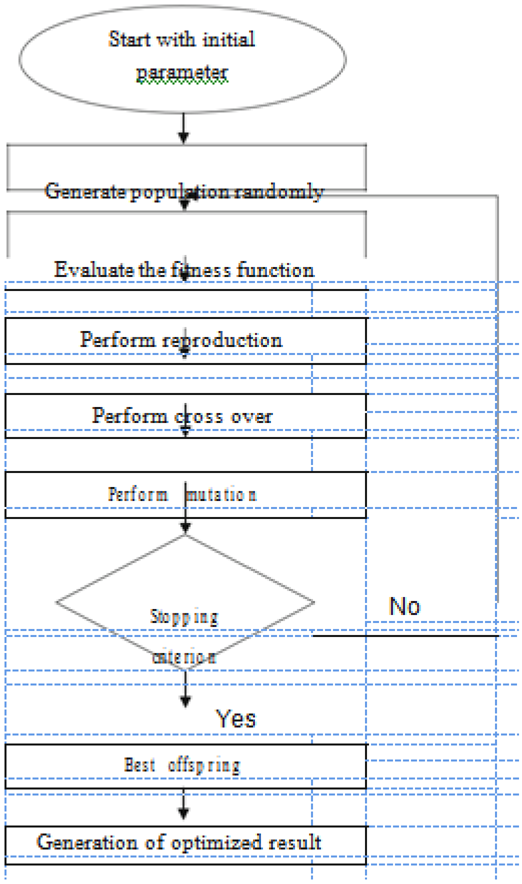


Fig. 13 General structure of genetic algorithm

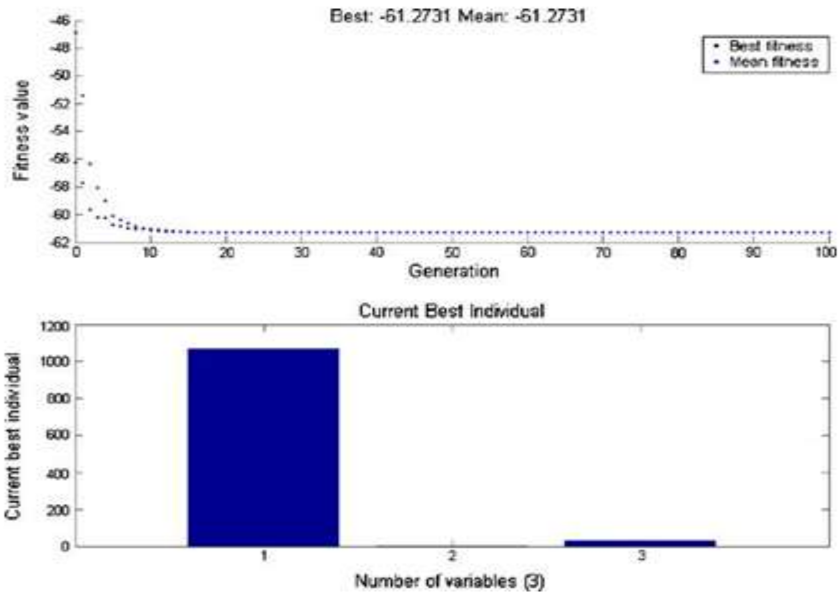


Fig. 14 Screenshot depicting the convergence result obtained using GA

Fig. 15 Tensile test sample

theoretically predicted and experimentally obtained values for tensile strength which confirm the practical applicability of GA to FWTPET process. The weld performed with optimized process parameters; fractured away from the joint is shown in Fig. 17. Hence, a maximum possible strength has been achieved by the optimization study.

V. CONCLUSIONS

In this study, FWTPET process has been used to join tube-to-tube plate which is a new and innovative process and has wider applications. This process is capable of producing high-quality and defect-free weld joints with enhanced mechanical and metallurgical properties with lesser energy consumption. Taguchi L_{27} orthogonal array has been used in this study. Ranking contributions of the parameters have been found, and the speed contributes to the maximum followed by the shoulder diameter and the pin clearance. The optimization of

Table 9 Optimized results

	Tool rotational speed (rpm)	Pin clearance (mm)	Shoulder diameter (mm)	Tensile strength (MPa)
GA	1,067	1.15	29.74	61.27
Experimental value	1,030	1	30	64.53

the process parameters has been carried out using GA. The optimized values of tool rotational speed, shoulder diameter, pin clearance, and ultimate tensile strength are 1,030 rpm, 1 mm, 30 mm, and 64.53 MPa, respectively. The synchro-nization between the theoretically optimized and the exper-imentally obtained values of the process parameters ensures the high potential of applying GA to the FWTPET process.

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