Indian Journal of Engineering & Materials Sciences
Vol. 31, February 2024, pp. 58-66
DOI: 10.56042/ijems.v31i1.561

Optimization of friction stir welding process parameters for HDPE sheets using satisfaction function approach

Amit Muchhadiya[a], Kumar Abhishek[a*], Soni Kumari[b], Kuldeep Kumar Saxena[c], Din Bandhu[d], Jay Vora[e], Vadiyala Phaninder Reddy[f] & Navajyoth B[g]

[a]Department of Mechanical and Aero-Space Engineering, Institute of Infrastructure, Technology, Research and Management (IITRAM), Ahmedabad 380 026, India
[b]Department of Mechanical Engineering, GLA University, Mathura 281 406, India
[c]Division of Research and Development, Lovely Professional University, Phagwara 144 001, India
[d]Department of Mechanical and Industrial Engineering, Manipal Institute of Technology Bengaluru, Manipal Academy of Higher Education, Manipal 560 064, India
[e]Department of Mechanical Engineering, Pandit Deendayal Energy University, Gandhinagar 382 007, India
[f]Department of Aeronautical Engineering, Institute of Aeronautical Engineering, Hyderabad 500 043, India
[g]CSIR-National Institute of Science Communication and Policy Research (CSIR-NIScPR), Delhi 110 012, India

Received: 13 April 2023; Accepted: 27 December 2023

The weld strength of thermoplastics, such as high-density polyethylene and polypropylene sheets is influenced by friction stir welding (FSW) parameters. The determination of the welding parameters plays an important role in the weld strength. For the influential use of the thermoplastic joints, the weld should have adequate strength and elongation. The quality of the joint has been evaluated by examining the characteristics of the joint efficiency as a result of ultimate tensile strength and % elongation. In this study, the Taguchi approach of parameter design has been used as a statistical design of experiment technique to set the optimal welding parameters for HDPE sheets. The experiments have been planned according to Taguchi's L_{16} orthogonal array. The signal-to-noise ratio and the analysis of variance have been utilized to obtain the influence of the friction stir welding parameters on the weld strength and% elongation. The satisfaction function approach has been also used in order to optimize the multi-response attributes.

Keywords: Friction stir welding (FSW), Taguchi, High-density polyethylene (HDPE), Satisfaction function approach

1 Introduction

Polymers are taking the place of metals due to their lightweight and high tensile strength. Polymers are used in automobiles, aerospace, electronics, and other industrial applications due to their advanced properties[1]. For getting the final shape by joining different polymers without adhesive, the solid-state joining of polymeric materials has been used in recent years[2]. Fusion welding cannot be used because of its low melting point. One of the best methods to join the polymers is friction stir welding (FSW)[3]. Friction stir welding is a solid-state joining method. The four phases of friction stir welding are the plunging phase, dwelling phase, welding phase, and exit or retract phase. The rotating tool plunges into the material in the plunging phase. In the dwelling phase, the rotating tool dwells for a period of time and increases the temperature up to its hot working temperature. After the dwelling phase, the rotating tool traverses along the work material is called the welding phase. The tool extracted from the material at the end is called the exit or retract phase. The schematic diagram of friction stir welding is shown in Fig. 1[4,5].

Tool rotation speed, tool traverse speed, tool tilt angle, and plunge depth are the major processing parameter of friction stir welding. Wayne Thomas invented the Friction stir welding process at the welding institute in 1991[4]. Initially, friction stir welding of aluminium and its alloys was done due to their lower weight. Some researchers have found advantages of friction stir welding of polymers. Due to the varying welding behavior of polymers during FSW, obtaining effective polymer joints is a very challenging task. So, the process parameters and design of tools for friction stir welding of polymers are different from than welding of metals[6]. The main polymers like polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polycarbonate (PC),

---

*Corresponding author (E-mail: krabhishek1987@gmail.com)

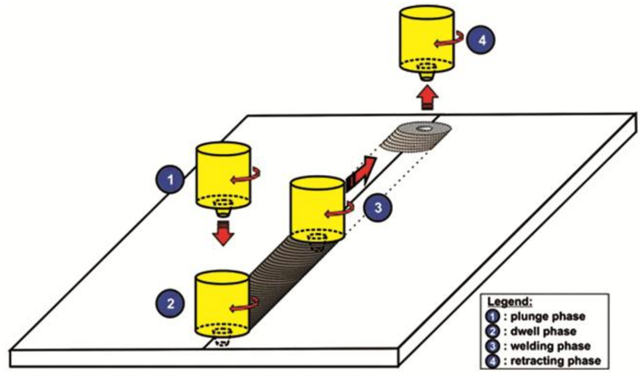

Fig. 1 — Correlation between compressive and split tensile strength.

acrylonitrile butadiene styrene plastic (ABS), polytetrafluoroethylene (PTFE), polyamide (Nylon, PA), polymethyl-methacrylate (PMMA), polyethylene terephthalate (PET) and polymer composites, etc. have been used for friction stir welding process[7,8]. Friction stir welding of different polymers is still in development for fulfilling the need for joining the polymers and using them in industrial applications[9]. Two types of friction stir welding polymers are joining similar material and dissimilar material. So as per the requirement, similar and dissimilar polymeric materials are welded by the FSW technique. In this context, Kulkarni *et al.*[10] explored the FSW and joined two dissimilar materials namely AZ31 Mg alloy and DP590 steel. Phenomenological crystal plasticity formulation was used on the mesoscale for modeling the weld joints. The study examines the consequence of grain size, interface fracture toughness along with strength on the mechanical performance of the weldments. The study reveals that the overall joint performance was negligibly affected by the grain size of the work materials, whereas the mechanical attributes were extremely affected by the strength and fracture toughness. Furthermore, Kulkarni *et al.*[11] developed a cohe-sive-zone model (CZM) for estimating the structural performance of a dissimilar joint. The study involved experimental work and also proposed a finite element model for evaluating cohesive law parameters. These parameters were further utilized for the mechanical characterization of the weld interface attained in friction stir weldments. Similarly, a study done by Kayode and Akinlabi[12] spread some light on the welding of magnesium and aluminium alloys together using the FSW process. The article provides some important insights on suitable variables selection during the welding of aluminium and magnesium alloys using the FSW process.

From the existing literature, it is evident that the tensile strength, flexural strength, hardness, and microstructure analysis of polymers are key points for joining polymers. Tensile strength is used to measure the joint efficiency of polymers. Different tools and their geometries are developed for joining similar and dissimilar polymeric materials to obtain quality welds. For obtaining maximum joint efficiency and quality welding of polymers, optimization of FSW parameters must be necessary[13]. The purpose of this study is to assess the joining techniques for HDPE sheets via FSW. The HDPE sheets have a wide range of applications in the aerospace and automobile sectors. Adhesive bonding and mechanical fastening have been employed for several years to join thermoplastic materials. However, these processes have major drawbacks. The final structure (joint) resulting from the adhesive bonding cannot be put to any qualitative test. Thus, it is impossible to predict joint failure. Due to this, adhesive joining which is a temporary joint cannot be considered. Hence, an attempt has been to in this study where optimization of friction stir welding of high-density polythene sheets has been accomplished to achieve optimum parameters for maximum tensile strength and elongation (%). For achieving maximum tensile strength and percentage of elongation, optimization of different parameters like tool rotation speed, tool traverse speed, and tool tilt angle are carried out during the experimental investigation of FSW of high-density polythene sheets[14,15]. Taguchi technique is the most widely used method in the field of optimization of process parameters[16,17]. To reduce time consumption and the number of experiments, Taguchi's L_{16} method is used for the optimization of parameters during the FSW of the HDPE sheet[18,19].

2 Materials and Methods

2.1 Experimentation

In this experiment, a commercially available High-density polythene sheet is used which has dimensions of 100 mm × 50 mm × 6 mm. The measured tensile strength of the base material is 30.176 MPa. HDPE sheets are fixed in the fixture. Table 1 shows the physical properties of high-density polyethylene polymer.

The material of the FSW tool is H-13 tool steel (Fig. 2); which is the most widely used tool material.

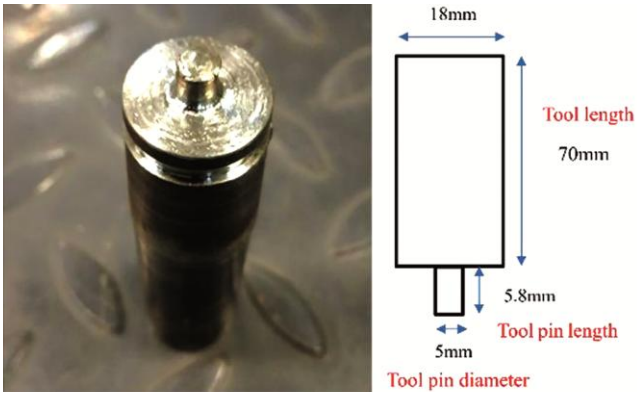

Fig. 2 — Tool used in FSW.

Table 1 — The physical properties of HDPE polymer

Property of the material	Value
Density (kg/m^3)	940
Ultimate tensile strength (MPa)	30.17
Melting temperature (˚C)	130
Thermal conductivity (W/mk)	0.42

The cylindrical FSW tool has a shoulder diameter of 18mm. The shape of the tool pin is plain cylindrical. The tool pin length is 5.8mm which is less than the thickness of the HDPE sheet. The tool pin diameter is 5mm. The FSW tool.

For the design of the experiment and selection process parameters, trial experiments were carried out. With the help of a trial experiment; the range of tool rotation speed (545 rpm-1500 rpm), tool traverse speed (20 mm/min -78 mm/min), and tool tilt angle (0˚- 3˚) has been found as shown in Table 2. Taguchi's L_{16} orthogonal array with 3 factors and 4 levels was applied for the optimization of friction stir welding of HDPE sheets. The rotating tool is plunged into the joining line of two HDPE sheets and heat is generated to soften the material then the rotating tool is passed along the line of HDPE sheets and the joining of two HDPE sheets is carried out. Friction stirs welded 16 samples of HDPE sheets are shown in Fig. 3.The L_{16} orthogonal array of sixteen rows and four columns for three process parameters is shown in Table 3.

The tensile strength was measured by a universal tensile test machine. The ASTM D638 standard is used for tensile test sample preparation. The universal tensile test machine and dog bone tensile test specimens are shown in Fig. 4 and Fig. 5 respectively.

Fig. 3 — Friction stirs welded HDPE sheets.

Table 2 — FSW process parameters and levels

Symbol	Process Parameters	Level-1	Level-2	Level-3	Level-4
A	Tool rotation speed (rpm)	545	765	1070	1500
B	Tool traverse speed (mm/min)	20	31.5	50	78
C	Tool tilt angle (˚)	0	1	2	3

Table 3 — L_{16} orthogonal array experiment

Experiment No.	Tool rotation speed (rpm)	Tool traverse speed (mm/min)	Tool tilt angle (˚)
1	545	20	0
2	545	31.5	1
3	545	50	2
4	545	78	3
5	765	20	1
6	765	31.5	0
7	765	50	3
8	765	78	2
9	1070	20	2
10	1070	31.5	3
11	1070	50	0
12	1070	78	1
13	1500	20	3
14	1500	31.5	2
15	1500	50	1
16	1500	78	0

2.2 Satisfaction function approach

Taguchi method is used for optimization in the field of different mechanical applications and is mostly used for improving quality and maximizing output performance. Several methods are used for optimizing quality response but they ignore the satisfaction of engineers regarding processing factors. Single response quality is obtained by the Taguchi technique but nowadays, for optimization of multiple response characteristics, Taguchi's satisfaction function model is used for selecting the proper goal by decision maker[20]. It is also known as a goal programming model for decision-makers [21]. The diagram for the satisfaction function model is shown in Fig. 6 [22].

Deviations $x$are shown in X-axis while the value of satisfaction function $f(x)$is represented by the Y-axis. Indifference threshold (x_{id}), nil satisfaction threshold (x_o), and veto threshold (x_v). The total satisfaction lies in the interval of [0,x_{id}]. During this interval, the decision maker's satisfaction value reaches the maximum value of 1. Satisfaction is suddenly going down during the interval (x_{id}, x_o]. The nil satisfaction threshold or dissatisfaction is indicated in the interval of (x_o, x_v]. The decision maker does not satisfy with the nil satisfaction function but it doesn't reject the solutions in this interval. Any value after the veto threshold is rejected[23]. The value of satisfaction interval [x_{id}, x_v] has lied between intervals[0,1]. The satisfaction function is successfully applied in the field of optimization of process parameters of welding [21]. In this research, the satisfaction function is applied to the process parameters viz, tool rotation speed, tool traverse speed, and tool tilt angle and converted to satisfaction values 0 to 1. The satisfaction function is linear. Specific values are obtained from the satisfaction function for friction stir welding variables. From these values, a distance function has been found that is similar to the Euclidean norm equation as shown in Eq.(1). It has been noticed that the most appropriate parametric setting is the smallest distance S_t from the top point. The best satisfaction values are obtained for the friction stir welding variables.

Fig. 4 — Tensile test of HDPE sheets.

$$S_t = [\sum_{i=1}^{n}(1-F_s)^2]^{\frac{1}{2}} \quad \ldots (1)$$

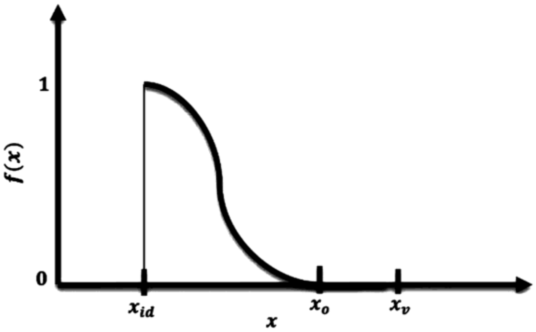

Fig. 6 — Diagram of satisfaction function model.

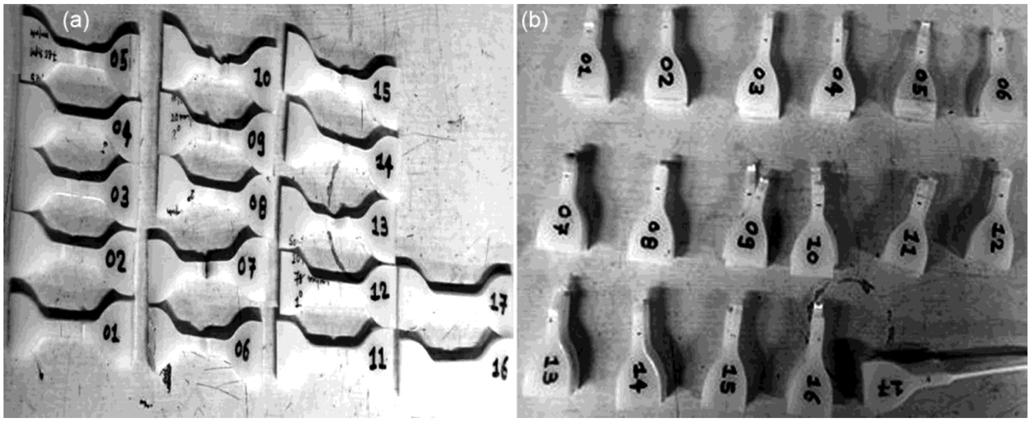

Fig. 5 — Tensile test samples (a) before the test, and (b) after the test.

If there is n number of performance characteristics, F_s is satisfaction value of i^{th} response.

The minimum value from the individual friction stir welding variables gives the best satisfaction value and maximum individual values give nil satisfaction or zero satisfaction. Optimum satisfaction for Lower-is-Better and Higher-is-Better is shown in Fig. 7.

Deviation

a = Deviation of Minimum Value of characteristic (Tensile strength and % Elongation)

x = Individual Characteristic

b = Deviation of Maximum Value of characteristic (Tensile strength and % Elongation)

Here,

The satisfaction function model for the parametric response process is shown in Fig. 8. First, the parameter and their domains are selected and experimental design is implemented using the Taguchi technique. After that experiment is conducted and output parameters (tensile strength and elongation (%)) are obtained. And finally, for parametric optimization, the satisfaction model is applied for multiple responses of welding variables. ANOVA and distance function is found out for optimization.

3 Results and Discussion

3.1 Experimental data, analysis of variance (ANOVA), and main effects plot

After the friction stir welding of HDPE sheets, tensile strength and elongation for samples are obtained by a universal tensile test machine as shown in Table 4. It has been noticed that parameters applied in experiment No.5 give the maximum tensile strength which is almost 60% of base material and parameters in experiment No.9 give the maximum percentage of elongation.

ANOVA (as shown in Fig. 9 and Fig. 10) is used for finding the influence or contribution (%) of the friction stir welding parameters on the output characteristics *viz.* tensile strength and elongation (%).

From the ANOVA (Fig. 9), it has been observed that the contribution of tool rotation speed is (45.79%)

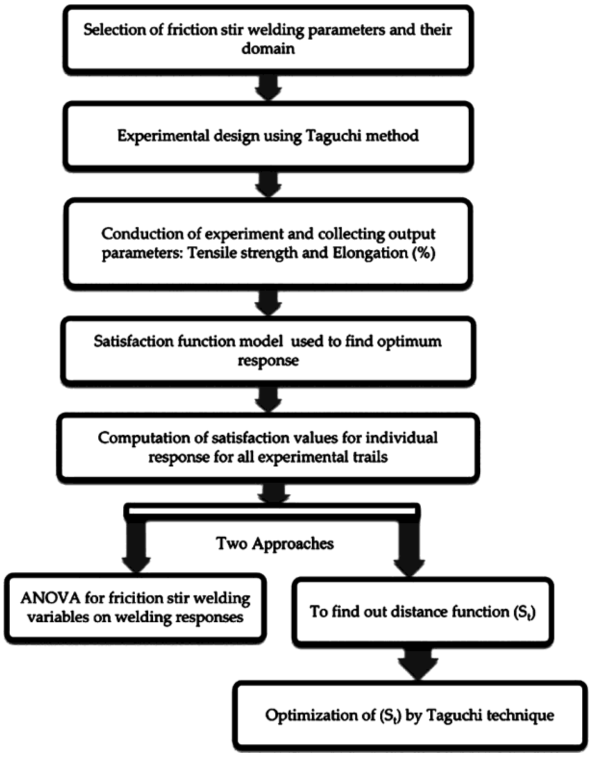

Fig. 8 — Flowchart of satisfaction function model for optimization.

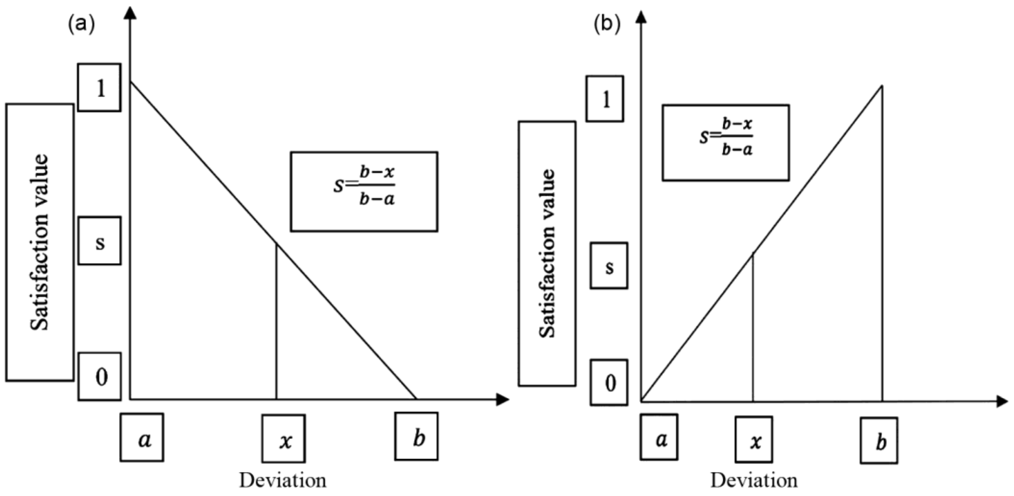

Fig. 7 — Optimum satisfaction for (a) lower-is-better and (b) larger-is-better.

Table 4 — Experimental data for tensile strength and elongation (%)

Sr. No	Tensile strength (MPa)	% of Elongation
1	11.047	6.8
2	10.907	6
3	10.083	7.32
4	8.778	4.4
5	17.828	6.24
6	15.126	6.54
7	15.632	8.24
8	13.384	5.92
9	14.06	**17.36**
10	10.454	8.16
11	8.714	5.76
12	13.199	11.84
13	7.615	4.72
14	11.143	8.56
15	16.147	7.6
16	13.659	9.21

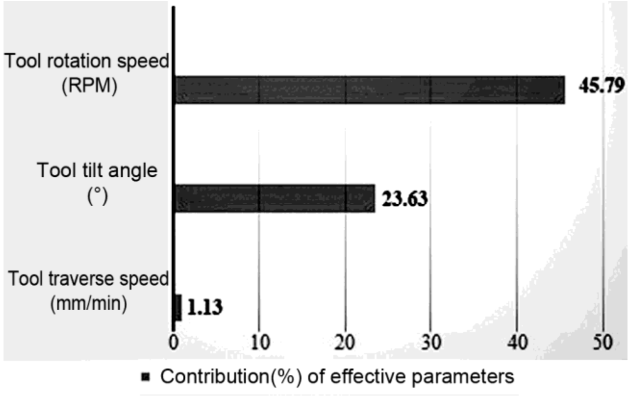

Fig. 9 — Analysis of variance for tensile strength.

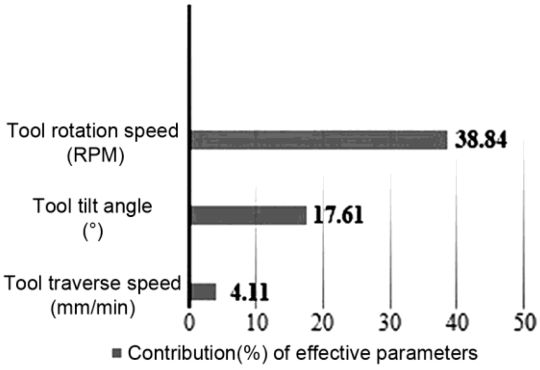

Fig. 10 — Analysis of variance for % elongation.

Table 5 — Response table for tensile strength (Larger is better)

Level	Tool rotation speed (rpm)	Tool traverse speed (mm/min)	Tool tilt angle (˚)
1	15.59	17.71	16.86
2	16.50	17.19	17.64
3	19.93	17.11	19.04
4	17.26	17.27	15.73

Table 6 — Response table for elongation (Larger is better)

Level	Tool rotation speed (rpm)	Tool traverse speed (mm/min)	Tool tilt angle (˚)
1	20.14	21.62	21.49
2	23.76	21.42	23.09
3	21.14	21.73	21.63
4	21.36	21.63	20.19

which is more than the contribution of tilt angle (23.63%) and tool traverse speed (1.13%) for tensile strength. Figure 10 is about the ANOVA of elongation (%). Tool rotation speed (38.84%) has more contribution than tool tilt angle (17.61%) and traverse speed (4.11%). Tool traverse speed has a lesser amount of contribution to tensile strength and elongation (%). Response tables for tensile strength and elongation are shown in Table 5 and Table 6 respectively.

Figures 11 and 12 show the main effect plot for tensile strength and elongation (%) respectively. It has been noticed that tool rotation speed has more influence on output parameters viz. tensile strength and elongation (%).

3.2 Multi-response optimization using satisfaction function and distance-based approach

In the research work, the experiment is carried out by using the Taguchi method, and two outputs are obtained viz, tensile strength and elongation (%). For optimizing the friction stir welding parameter response variables like tensile strength and elongation (%), the satisfaction function approach is implemented using the Taguchi technique. The larger-is-better approach is applied for both output response variables. Individual values are converted into their equivalent satisfaction approach by using the satisfaction function. The normalized data for output response (Larg-er-is-Better) of tensile strength and elongation (%) are shown in Table 7. The satisfaction value lies between 0 to 1. For optimization, the satisfaction value for the whole response should be one.

Through trials of the experiment, the satisfaction value of each response has been estimated. From the highest satisfaction value, the distances of all parametric variables are calculated using the distance function. Optimization of these distance values is calculated as per the process shown in the flow chart (Fig. 8).

The satisfaction values of individual welding output responses (Tensile strength and Elongation)

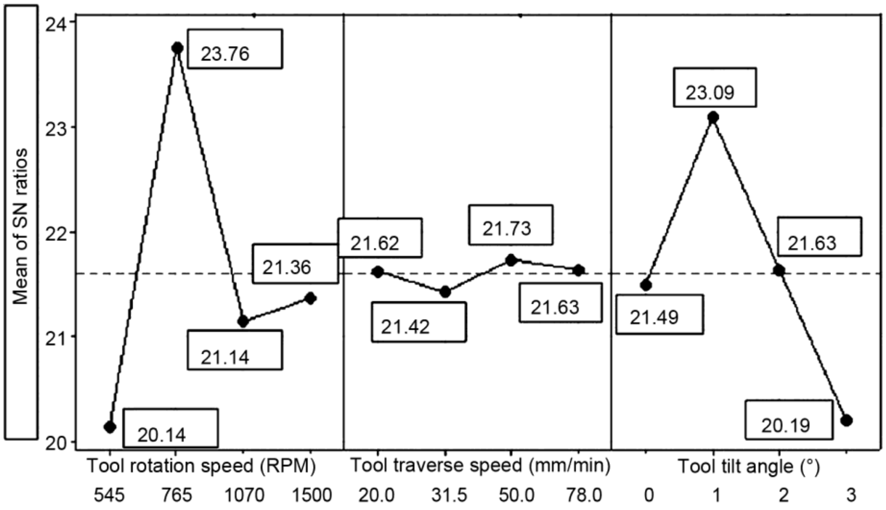

Fig. 11 — Main effect plot for tensile strength.

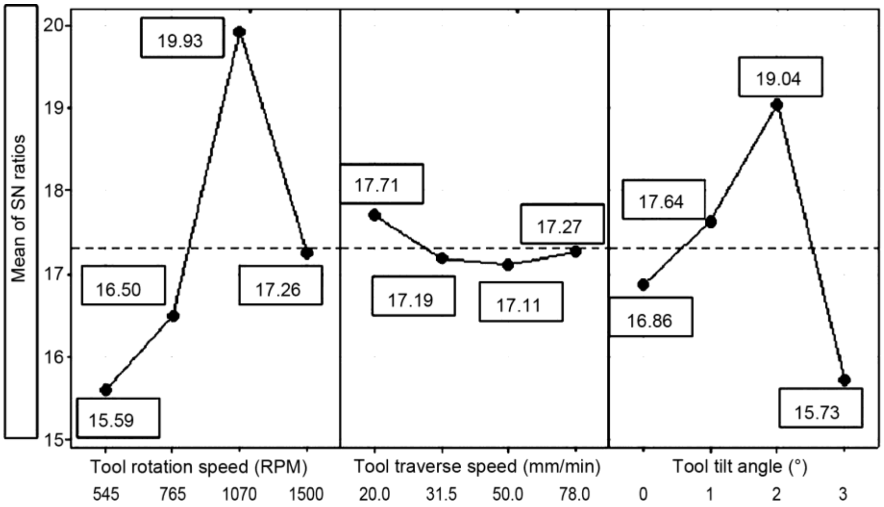

Fig. 12 — Main effect plot for elongation.

Table 7 — Normalized data for both output response variables

Normalized data	
N-Tensile strength	N-Elongation
0.336042	0.18518519
0.322334	0.12345679
0.241653	0.22530864
0.113874	0
1	0.14197531
0.735435	0.16512346
0.78498	0.2962963
0.564868	0.11728395
0.631058	1
0.277979	0.29012346
0.107608	0.10493827
0.546754	0.57407407
0	0.02469136
0.345442	0.32098765
0.835406	0.24691358
0.591795	0.37114198

are calculated. The total distance value (St) is also calculated and tabulated (Table 8) with the help of satisfaction values of Tensile strength and Elongation (%). The S/N ratios of lower are better criteria with respect to overall distance value have been examined. The main effects plot of the Signal to noise ratios is shown in Fig. 13. The response table for overall satisfaction is shown in Table 9. It has been observed that an analyzed optimum friction stir welding parameters are 1070 rpm tool rotation speed with 20 mm/min tool traverse speed at a tool angle of 2˚. So, the prediction of the S/N ratio is calculated by Eq.(2) as shown below:

$$S/N_{predicted} = \underline{Y} + \left(TRS_{1070} - \underline{Y}\right) + \left(TS_{20} - \underline{Y}\right) + TA_2 - \underline{Y}) \quad \ldots (2)$$

where $\underline{Y}$ is the overall mean response of the S/N ratio; TRS_{1070} is the mean response of the S/N ratio at the

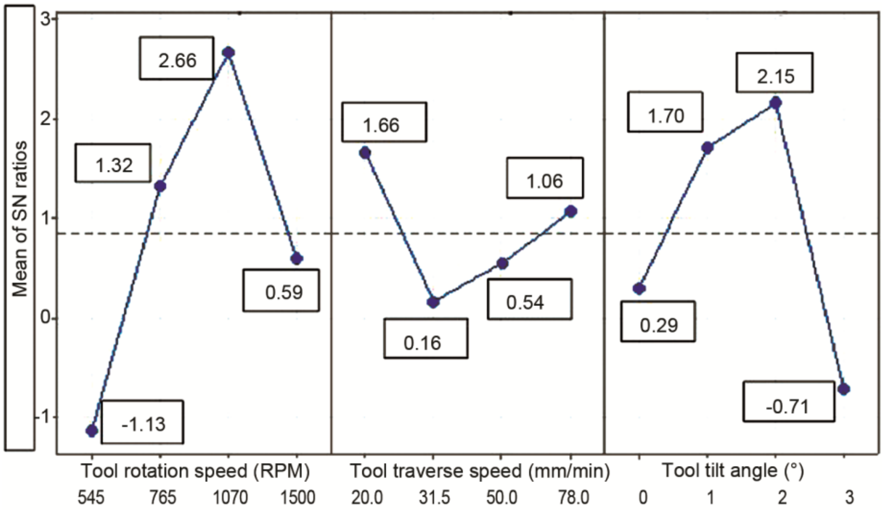

Fig. 13 — Main effect plot for overall satisfaction value.

Table 8 — Individual satisfaction value for tensile strength and elongation (%)

Satisfaction values	
S-Tensile strength	S-Elongation
0.44084	0.663923
0.459231	0.768328
0.57509	0.600147
0.785218	1
0	0.736206
0.069995	0.697019
0.046234	0.495199
0.18934	0.779188
0.136118	0
0.521314	0.503925
0.796364	0.801135
0.205432	0.181413
1	0.951227
0.428446	0.461058
0.027091	0.567139
0.166632	0.395462

Table 9 — Response table for SN ratio of overall satisfaction value

Level	Tool rotation speed (rpm)	Tool traverse speed (mm/min)	Tool tilt angle (˚)
1	-1.1353	1.6638	0.2967
2	1.3214	0.1655	1.7062
3	2.6607	0.5473	2.1517
4	0.5920	1.0621	-0.7159
Delta	3.7960	1.4983	2.8677
Rank	1	3	2

level of tool rotation speed (TRS = 1070 rpm); TS_{20} is the mean response of the S/N ratio at the level of tool traverse speed (TS = 20 mm/min); TA_2 is the mean response of the S/N ratio at the level of tool tilt angle (TA = 2˚).

Table 10 — Overall satisfaction values for output responses

Tool rotation speed (rpm)	Tool traverse speed (mm/min)	Tool tilt angle (˚)	Overall satisfaction	SNRA 1	PSNRA 1	PMEAN 1
545	20	0	1.0511	-0.4327	4.75688	0.68552
545	31.5	1	1.1080	-0.8904		
545	50	2	1.0841	-0.7013		
545	78	3	1.3361	-2.5169		
765	20	1	0.8580	1.3300		
765	31.5	0	0.8758	1.1520		
765	50	3	0.7358	2.6646		
765	78	2	0.9841	0.1389		
1070	20	2	0.3689	8.6608		
1070	31.5	3	1.0125	-0.1083		
1070	50	0	1.2639	-2.0344		
1070	78	1	0.6220	4.1246		
1500	20	3	1.3969	-2.9031		
1500	31.5	2	0.9431	0.5085		
1500	50	1	0.7709	2.2605		
1500	78	0	0.7497	2.5019		

So, $S/N_{predicted}$ can be calculated as shown in Eq. (3):

$$S/N_{predicted} = 0.8596+(2.6607-0.8596)+(1.6638-0.8596)+(2.1517-0.8596) \quad \ldots (3)$$

$$S/N_{predicted} = 4.7568$$

A maximum value of the predicted S/N ratio is preferred; so, the calculated Signal to Noise ratio for each trial of the experiment is compared with the predicted S/N ratio. Each value of S/N ratio is shown in Table 10. It has been observed that optimum welding parameters are found in experiment No. 9. It has also noticed that the predicted Signal to Noise ratio (4.7568) value is lower than the corresponding experimental Signal to Noise ratio (8.6608). So, the derived optimum combination is acceptable.

4 Conclusion

Friction stir welding with different process parameters is used for the joining of HDPE sheets. Taguchi's satisfaction function model is used for the optimization of the output response variable of friction stir welding. The research covers the following findings:

1. In this research work, for multiple quality responses of output variables, the satisfaction function model is successfully applied to find out optimized parameters of friction stir welding of HDPE sheets.
2. This work is to determine the optimum welding parameters for thermoplastic welding using the Taguchi approach of parameter design. The maximum value of the predicted S/N ratio was sought to achieve the desired joint efficiency
3. The FSW welding parameters of experiment No 9 viz. tool rotation speed of 1070 rpm with a tool traverse speed of 20 mm/min at a tool tilt angle of 2° are the best optimum parameters for maximum output response. This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.
4. The Signal to Noise ratio was calculated for each trial, and the results were compared with the predicted S/N ratio. It was noticed that the predicted S/N ratio value was lower than the experimental S/N ratio value. However, since the derived optimum combination is within an acceptable range.

References

1 Bozkurt Y. *Mater Des*. 35 (2012) 440.
2 Nandan R, Debroy T & Bhadeshia H, *Prog Mater Sci*. 53 6 (2008) 980.
3 Sahu S K, Mishra D & Pal K, *ProcInst Mech Eng B J Eng Manuf*, 236(5) (2022) 522.
4 Godavarthi B, Nalajala P & Ganapuram V, *In IOP Conf Series: Mater Sci Eng*, 225(1) (2017) 012262.
5 Fraser K, Kiss L, St-Georges L & Drolet D, *Metals (Basel*), 8(2) (2018)101.
6 Ebrahimi M & Par MA, *J Alloys Compd, 781*(2019) 1074.
7 Gao J, Cui X, Liu C & Shen Y, *Mat Sc & Tech, 33* (10)(2017) 1145.
8 Lambiase F, Derazkola HA & Simchi A, *Materials,* 13 (10) (2020) 2291.
9 Ebrahimi M, Wang Q &Attarilar S, *Prog Mater Sci*, 131 (2023) 101016.
10 Vijayakumar Y, Nagaraju P, Yaragani V, Parne S R, Awwad N S & Reddy M R, *Physica B: Condensed Matter*, 581 (2020) 411976.
11 Budarapu P R, Yb S S, Javvaji B &Mahapatra D R, *Front StructCivEng*, 8 (2014) 151.
12 Kayode O & Akinlabi E T, *Mater Res Express*, 6(11) (2019) 112005.
13 Paoletti A, Lambiase F& Di Ilio A, *Procedia CIRP*, 33 (2015) 562.
14 Akbarpour MR, Ebrahimi M&Torknik FS,*Mater Res Express*, 6 5 (2019) 056537.
15 Paoletti A, Lambiase F & Di Ilio A, *Procedia CIRP*, 33 (2015) 562.
16 Gupta N, Gupta A, Saxena K K, Shukla A &Goyal S K, *Mat Today: Proc,* 44 (2021) 12.
17 Bandhu D, Abhishek K, *Mat & Manuf Proc, 36 12* (2021), 1384.
18 Kumari S, Sonia P, Singh B, Abhishek K & Saxena K K, M*ater Today Proc*, 26 (2020) 2458.
19 Murali Mohan M, Venugopal Goud E, Deva Kumar MLS, Kumar V, Kumar M & Dinbandhu, *Rec Ad in Smart Manuf & Mat*, (2021) 289.
20 Rahul, Abhishek K, Datta S, Biswal B B & Mahapatra SS, *J BraziSoc of Mech Sc & Eng, 39 9* (2017), 3499.
21 Kumari S, Bandhu D, Muchhadiya A & Abhishek K,*Ad in Mat & Proc Techn*, (2023) 1.
22 Martel JM &Aouni B, *J Operat Res Soc,* 41 (12) (1990)1121.
23 Rahul, Datta S, Biswal B B, Mahapatra S S, *Arab J SciEng*, 425 (2017) 1999.