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Experimental Investigation on Friction Stir Welding of HDPE reinforced with SiC and Al and Taguchi Base Optimization

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Abstract
Light weight thermoplastics are the most prominent concerns of manufacturers due to their high performance characteristics in the current trend. Weld strength and weld quality are the performance measures of the thermoplastic materials, and determining the optimum weld parameters is the major research problem. This paper presents the optimization of weld parameters required for friction stir welding (FSW) of silicon carbide and aluminum reinforced in high density polyethylene. The improved mechanical properties of these composites are the resultant effects of the optimum process parameters like welding speed, rotational speed, tilt angle, and percentage of reinforcement; hence it is very essential to determine them and to study their influence on composites weld joint. The experimental analysis was carried out for three levels in each and different combinations of weld parameters in order to measure the tensile strength and hardness. The optimum set of nine experiments was designed based on L9 Taguchi's design. The elicited test results convey that rotation speed of the tool is the most influential weld parameter for tensile strength and weld speed is the most responsible for hardness response of FSW butt joint. The analysis reveals that the added silicon carbide and aluminium particles enhances the ductility and brittle characteristics to base HDPE sheet causing improved weld strength and in turn ensures the weld quality.

***Keywords*:** Friction Stir Welding; High Density Polyethylene sheet; Taguchi;

1. Introduction

The application of thermoplastics in many engineering field is increasing due to their enhancements in strength-to-weight ratios, toughness, and low costs especially in aerospace and automotive applications [1]. Polyethylene is the most significant and adaptable one of commercial thermoplastics. Moreover, polyethylene is utilized in an extensive usage in industrial applications because of its natural structure which can be easily transformed in many different forms. Polyethylene generally needs joining process for the larger and complex parts, though it offers a high intensity of design freedom and processing ability [2].

Welding is the most significant method to join the similar or dissimilar parts without losing the characteristics of the parent material. The welding of plastic materials can be separated into two basic types depends up on the heat generation mechanism [3]; first, heat generation due to mechanical movement (e.g., ultrasonic welding, friction welding, and vibration welding etc.), second, heat generation due to external arrangement (e.g. resistive, hot gas , hot plate and implant welding etc.) [4].The major steps involved in welding of thermoplastics are:

- Heating the weld surfaces to a molten state
- Bond formation by the application of pressure

• Holding the pressure until hardening.

All of these three steps provide a great advantage since they are performed at the same time as friction stir welding. Friction stir welding (FSW), is a solid-state welding method invented in 1991 (British TWI), which consists of a cylindrical shoulder and a pin on its crest serves the purpose of heat development and then joining is performed with the pressure exert by the shoulder [4-6]. In contrast with the traditional welding methods, FSW does not necessitate protective gas, additional wiring, and personal protective measures and it is an eco-friendly process too. Moreover friction stir welding can effectively overcome some drawbacks like porosity formation, gas cavities, and inclusions, etc. which are observed in normal the welding process. Friction stir welding based investigations have initiated on aluminum alloys [7–11], and later on magnesium alloys [12–14], but in recent years, plastic materials like low density polyethylene (LDPE) and high density polyethylene (HDPE), polypropylene (PP), nylon, polycarbonate, and acrylonitrile butadiene styrene (ABS) have been studied in the process of joining [1-4, 15–20]. Hence from the various investigations it is evidenced that friction stir welding can be used for welding of unfilled thermoplastic by modifying the process parameters such as rotational speed, welding speed, tilt angle, pin diameter or shape which will have significant effects on the performance of the welded joint. Ali et al. [26], indicates that friction stir welding is the suitable method for welding thermoplastic composites.

Mustafa et al. [20] used polypropylene (PP) sheet to investigate the effect of process parameters on the bond strength and identified the dwell time as the most dominant weld parameter than tool rotation speed and plunge depth. Zoltan et al. [27] investigation on polypropylene reveals that the tool geometry has stronger effect compared to rotational and linear speeds. Payeganeh et al. [24] showed that the pin geometry has significant effect on mechanical properties of polypropylene composite welds such as weld surface appearance and tensile strength.

Dashatan et al. [22] study on Polymethyl methacrylate and acrylonitrile butadiene styrene (ABS) sheets of friction stir spot welding (FSSW) shows that the most effective parameter was found to be tool plunge rate on the weld strength. The previous research studies show that when conventional friction stir welding is applied to polymers and composite materials, it is very difficult to achieve high quality welds due to low melting temperatures and low thermal conductivities of these materials [21-25].

The hardness of welded polymers in the FSW reduces due to the partially completed orientation of its molecular chains which is the resultant effect by the stirring, fusion, and rapid cooling in very less span. Zohoor et al. [1] The hardness is proportional to the degree of crystalline (the ratio of amorphous to crystalline regions) of welded polymers, would be less within the welded zone compared to the adjacent base material. Raza et al. [25] attempted to improve the hardness of HDPE by the graphite, silica, SiC, and alumina reinforcements and observed that the hardness of alumina and SiC-reinforced weld joints improved due ductile behaviour of composites.

The literatures reveal that there are very few publications related to friction stir welding applications in polymers and no publication has found on high density polyethylene (HDPE) especially with non ferrous and ceramic composites at weld portion. Hence this study attempts to investigate the effect of weld parameters on mechanical properties of HDPE sheets by using friction stir welding process. Taguchi based design of experiments is the sophisticated optimization procedure to avoid large number of experiments, which were too complex, time consuming, energy consuming, and uneconomical [20]. Taguchi method uses orthogonal array sets to determine the minimum number of experiments to be performed based on the number of parameters and their levels [3, 30].

The following are the key objectives of the present study:

- To examine the weld joint characteristics by the reinforcement of SiC and Al nano particles in HDPE weld joint.
- To identify best combination of composites on HDPE at the weld portion.
- To determine the optimum set of welding parameters to improve the weld strength and hardness of the weld joint.

The remainder of this paper contains three sections to express the details of the research work in more simple and keen way. Section 2 explains the materials and methods followed in the present work to carry out the experimentation and analysis, results are presented in Section 3 with an intense analysis related to objectives, and the conclusions drawn out from the result analysis are stated under Section 4 with scope for future work at last.

2. Materials and methods

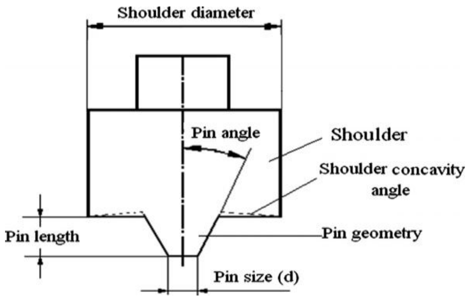
In this work the commercial HDPE sheets of 6mm thick are welded to form butt joint by using friction stir welding process, the schematic diagram of FSW process is shown in Fig. 2. The physical properties of selected HDPE sheets are given in Table1.

Table. 1. Physical properties of HDPE

Molecular weight (Grams)	Density (g/cc)	Young's Modulus (N/mm^2)	Melting Temperature (^oC)	Thermal Conductivity (W/m-K)	Softening Temperature (^oC)	Ultimate Tensile Strength (MPa)	Brinell Hardness (BHN)
28.0	0.930-0.965	1035	135	0.40-0.47	112-130	26-33	17.46

A Conical profile FSW tool is employed for the investigation has been machined from H13 tool steel having a shoulder diameter of 22mm, pin diameter 3 to 6mm and pin length 4.5mm is shown in Fig. 2 with its cross sectional view aside.

(a)



(b)

Fig. 1. (a) Conical pin tool used in friction stir welding and (b) Cross sectional view [31].

Fig. 2. Experimental setup for FSW.

The HDPE sheet were butt welded using a HMT FN2 Vertical Milling Machine at first the samples were cut in a required shape by using cutting machine and they were fixed on the fixture maintaining zero gap. The bolts were tightened properly and the bed was fixed is shown in Fig. 3. Different combinations of Al and SiC powders are placed between the joining line (grooved portion) and pin face at the joint. The tool was traversed along that line of joining so as to reinforce the Al and SiC powders into HDPE sheets.

3. Experimental Method

The key input variables of the experimental procedure consist of three levels in each selected welding parameters such as Tool Rotational Speed (N), Welding Speed(S), Tool Tilt Angle (TA) and percentage of composition and were shown in Table 2.

Table 2. Levels in weld parameters.

Weld parameters	**Range**	**Level 1**	**Level 2**	**Level 3**
Tool rotational speed (N) in rpm	560-900	900	710	560
Welding speed (S) in mm/min	16-30	30	20	16
Tool Tilt Angle (TA) in degrees	$1^0 - 3^0$	1^0	2^0	3^0
Compositions in %	50-100	HDPE(Al)	HDPE(Al+SiC)	HDPE(SiC)

Taguchi L9 orthogonal array is selected to perform optimum set of experiments based on the process parameters [3, 15]. Design of the experimental sets according to L9 orthogonal array for the four welding input process parameters with Ultimate Tensile Strength results are shown in Table 3.

4. Results and Discussion

The conical pin employed for the present work has successfully welded the HDPE sheets and some of the experimental weld samples with a focus on weld joint are shown in Fig 3. The surface finish of samples observed at rotational speed 900 rpm, weld speed 30 mm/min, tilt angle 10 and HDPE with Al shows the fine finishing on advancing and retreating side of the joint. But the same combination with rotational speed 560 rpm, traverse speed 16 mm/min, and tilt angle 20 shows unequal propagation of Aluminum causes poor surface finish at the joint portion.

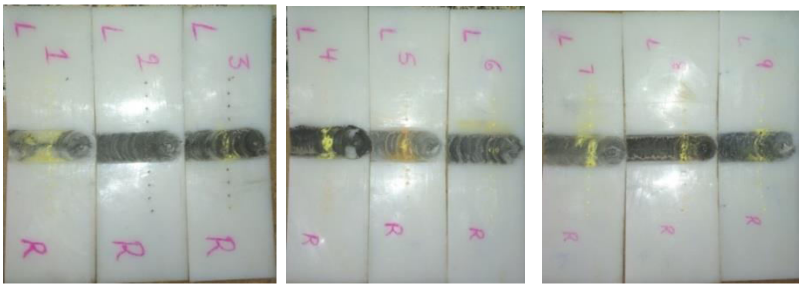
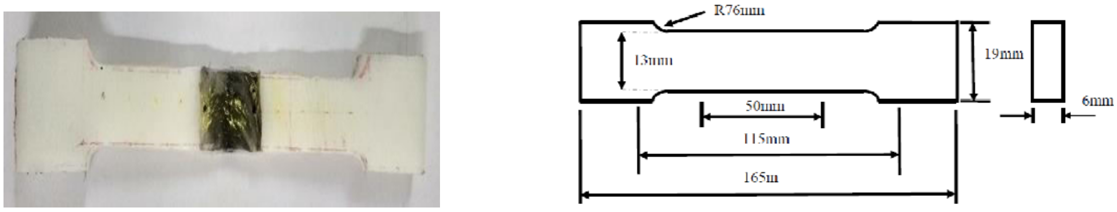


Fig. 3. Friction Stir Welded specimens of HDPE.

4.1. Tensile Test

The test results for finding the tensile strength of the weld samples are shown in the table 4, and it can be observed that a maximum tensile strength of 24.464 MPa was obtained at rotational speed 900 rpm, traverse speed 30 mm/min, tilt angle 10 and HDPE (with Al). The observed ultimate strength weld sample exhibits about 74.67 % of strength of base material. Similar observation was made by Sayeedi and Givi on welded polyethylene sheet and obtained joint 75% of base material [17]. Bagheri et al. [19] observed 88 % joint efficiency on welding of ABS sheet using a hot shoe. Specimen preparation for tensile test was shown in Fig 4.



(a) (b)

Fig. 4. (a) Sample specimen prepared for tensile test and (b) Dimensional view [15].

Table 3. Tensile test results and S/N ratio values.

Exp.No	Rotational speed (rpm)	Weld speed (mm/min)	Tilt angle (degrees)	Compositions (%)	Ultimate Tensile Strength (Mpa)	S/N Ratio
1	900	30	1	HDPE(AL)	24.464	27.7705
2	900	20	2	HDPE(AL+SiC)	17.732	24.9752
3	900	16	3	HDPE(SiC)	18.829	25.4965
4	710	30	2	HDPE(SiC)	17.490	24.8558
5	710	20	3	HDPE(AL)	18.003	25.1069
6	710	16	1	HDPE(AL+SiC)	18.829	25.4965
7	560	30	3	HDPE(AL+SiC)	11.985	21.5728
8	560	20	1	HDPE(SiC)	15.512	23.8134
9	560	16	2	HDPE(AL)	4.789	13.6049

The Taguchi S/N ratio analysis is present in the Table 4, considering the main effects of weld parameters on weld strength of the joint. The table shows the highest ranked tool rotational speed as the most effecting weld parameter on weld strength and tilt angle as next important parameter.

Table 4. S/N response table for weld strength.

S. No	Weld Parameter	Mean S/N ratio				
		Level-1	Level-2	Level- 3	Max –min	rank
1	Rotational speed	19.66	25.15	26.08	6.42	1
2	Weld speed	21.53	24.63	24.73	3.20	3
3	Tilt angle	25.69	21.15	24.06	4.55	2
4	Compositions	22.16	24.01	24.72	2.56	4

4.2. Effect of Parameters on Tensile Strength

Taguchi's S/N ratio analysis gives the main effects plots which are shown in Fig: 5 in addition to the contour plots, presenting the influence of weld parameters on joint strength. Plots shows that tool rotational speed and tool tilt angle are the most effecting weld parameters on weld strength. As the heat generation is majorly governed by the rotational speed, raise in the rotational speed from 560 rpm to 900 rpm causes to generate more heat for deformation of the thermoplastic material and to well mix with Al and SiC particles. High temperatures at weld zone are desirable for the increased rates of the material softening and liquidity, which will ensure the high weld strength at the joint portion. On the other hand at low tool rotational speed the amount of weld strength is less due to low melting and deformation of thermoplastic.

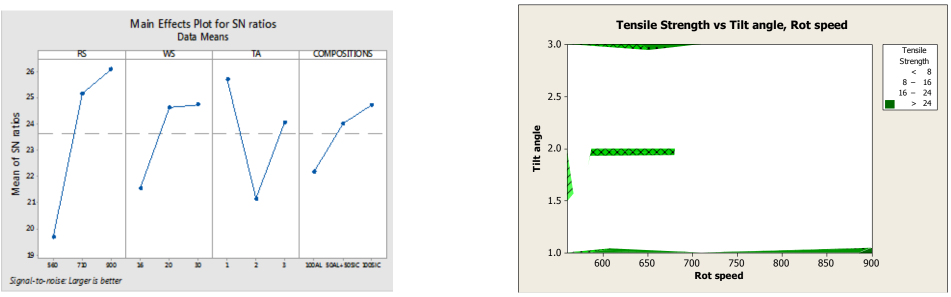


Fig. 5. Mean S/N ratio and contour plots for tensile strength.

4.3. Brinell Hardness Test (BHN)

Brinell hardness test was conducted along the joint portion with 60 kg-f applied load, 2.5 mm diameter of indenter and the results are presented in the table 5. It was observed that the maximum hardness of 41.90 BHN obtained at 710 rpm rotational speed, 30 mm/min weld speed, 20 tilt angle, and HDPE (with SiC), which is more than that of the un-welded base material (17.46 BHN).

Table. 5. Hardness test results and S/N ratio values.

Exp. No	Rotational speed (rpm)	Weld speed (mm/min)	Tilt angle (degrees)	Compositions (%)	Hardness (BHN)	S/N Ratio
1	900	30	1	HDPE(AL)	30.56	29.7031
2	900	20	2	HDPE(AL+SiC)	30.56	29.7031
3	900	16	3	HDPE(SiC)	30.56	29.7031
4	710	30	2	HDPE(SiC)	41.90	32.4443
5	710	20	3	HDPE(AL)	30.56	29.7031
6	710	16	1	HDPE(AL+SiC)	35.63	31.0363
7	560	30	3	HDPE(AL+SiC)	41.90	32.4443
8	560	20	1	HDPE(SiC)	35.63	31.0363
9	560	16	2	HDPE(AL)	30.56	29.7031

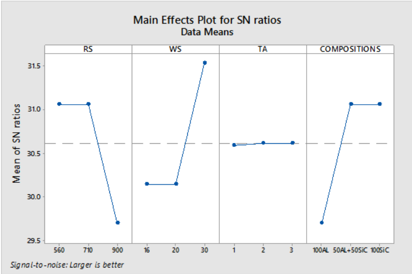
Table 6 shows the highest deviation of mean S/N ratio contributed by weld speed and ranked as the most effecting weld parameter on hardness and weld quality compared with remaining weld parameters.

Table 67. S/N response table for hardness.

S. No	Weld Parameter	Mean S/N ratio				
		Level-1	Level-2	Level- 3	Max –min	rank
1	Rotational speed	31.06	31.06	29.07	1.36	2.5
2	Weld speed	30.15	30.15	31.53	1.38	1
3	Tilt angle	30.59	30.62	30.62	0.02	4
4	Compositions	29.70	31.06	31.06	1.36	2.5

4.4. Effect of parameters on hardness

The main effects and contour plots of weld parameters on the hardness of the welded joint is shown in Fig. 6. From the plots it was observed that the weld speed is the major factor responsible for hardness of the weld joint. The maximum hardness of 41.90 BHN observed at weld speed 30 mm/min, rotational speed 710 rpm and tilt angle 20 for SiC+HDPE composite. The hardness across the SiC reinforced weld joints is increasing with the increase in weld speed, while that Al composite remains constant at minimum value for the variations of weld parameters. This observation is in accordance with reduction in ductile nature depicted by the SiC+HDPE weld joint and the moderate ductile behavior exhibit by the Al+HDPE weld joint.



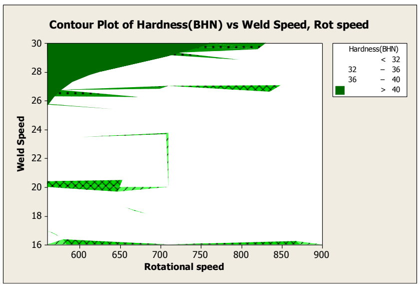


Fig. 6. Mean S/N ratio and contour plots for hardness.

5. Conclusions

Taguchi based analysis on the effects of SiC and Al particle reinforcement on HDPE in addition with other weld parameters for evaluating the weld strength and hardness weld joints was successfully carried out in the friction stir welding process. The following conclusions are drawn from the results and discussions.

- The rotational speed and weld speed are the main influencing factors on weld strength and hardness respectively, means the weld quality is proportional to speeds of the FSW tool at the weld zone.
- The optimum weld-parameters for retaining 74.66% base material weld strength are 900 rpm rotational speed, 30 mm/min traverse (weld) speed , 10 tilt angle and HDPE combined with Al particles. The maximum hardness of 41.90 BHN at welded portion, obtained at 710 rpm, 30 mm/min, 20 and HDPE combined with SiC parameters set.
- It may be noted that the weld quality of joint is also dependent of reinforced particles of SiC and Al. The effect of improved tensile strength is in accordance of better Al particle entrapment in base HDPE sheets during stirring process causes ductility, where as hardness is due to the SiC particles enhancing the contrast nature to base materials.

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