SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V11I8P106

Volume 11 Issue 8, 50-57, August 2024

Original Article

Impact of Process Parameters on the Mechanical Properties of Friction Stir Welded Joints on Polypropylene Sheets

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Received: 08 June 2024 Revised: 17 July 2024 Accepted: 10 August 2024 Published: 31 August 2024

Abstract *- The FSW provides a number of benefits over standard welding processes, including better mechanical qualities, joint integrity, and environmental effects. This process is widely used in automobile and aircraft industries for various applications. Thorough investigation and evaluation regarding the welding process parameters, tool, and material pair are crucial in this process. The main objective of the current study is to check the weldability of polypropylene using friction stir welding tool material. In this study, H13 Tool steel with a cylindrical, tapered type of probe is used to examine the impact of process parameters on eight-mm-thick polypropylene sheets. Three levels of Rotational speed, Transverse Feed and Tilt angle are used as input process parameters and yield strength and hardness are used as response parameters. Experiments are conducted using L9 orthogonal array design of experiments at 710, 900, and 1100 rpm rotational speed, 40, 60, and 80 mm/min feed and 0, 0.5 and 1 degree tilt angle. In this work, an attempt is made to optimise these parameters. The optimal yield strength of 13.08 N/mm^2 was achieved at 1100 r.p.m., 60 mm/min feed rate, and 0° tilt angle. An optimum hardness of 50.6 SHORE D is achieved at 900 r.p.m., 40 mm/min feed rate, and a 0.5 degree tilt angle.*

Keywords *- Friction stir welding, Polypropylene, H13 tool steel, Tool rotational speed, Transverse feed, Tilt angle, Mechanical properties.*

1. Introduction

Friction Stir Welding (FSW) is a solid-state joining method that is mostly employed with thermoplastics. However, it may also be used for metals [1-5]. It was established in the early 1990s by the Welding Institute (TWI) in the United Kingdom [6-10]. Unlike conventional welding methods, which require melting of the materials to be joined, FSW uses the frictional heat generated by a revolving tool. Since the work parts are not melted during this process, problems like hot cracking and solidification defects that are often seen in fusion welding are eliminated [11-17].

The FSW tool comprises the shoulder and the probe, which is also referred to as a pin or probe. The shoulder exerts a downward force and assists in confining the material, while the probe generates frictional heat and stirs the material to produce a solid-state bond [18-24]. During Friction Stir Welding (FSW), the rotating tool is inserted into the joint line that connects the two workpieces. The material is softened by the frictional heat generated by the rotational movement without undergoing melting. While the tool moves along the joint, the rotating probe stirs the softened material, creating a strong connection by welding [25-29].

Compared to conventional welding techniques, FSW has the following benefits, particularly for thermoplastics: It creates joints with excellent mechanical qualities and great strength. Because it is a solid-state procedure, there is less chance of faults because melting is not required. It can be applied to combine materials of different thicknesses and characteristics. It produces very little residual stress and distortion in the workpieces [30-35].

It is used in the automobile sector to assemble thermoplastic components like fuel tanks and bumper beams. Although FSW offers many advantages, it also has certain limitations, such as the fact that a spinning tool may wear out over time and must be replaced or reconditioned. FSW may be difficult to implement in complicated geometries and works best on flat or gently curved surfaces, requiring careful control of parameters such as rotation speed, traverse speed, and axial force to obtain optimal welding conditions [36-38].

2. Methodology

2.1. Work Piece Material

The polypropylene sheets of 100 x 60 x 8 mm are used as workpiece material, as shown in Figure 1. The mechanical properties of polypropylene sheets are tabulated in Table 1.

Fig.1 Polypropylene sheet

Table 1. Mechanical properties of polypropylene sheet

S.No.	Property	Value
1	Ultimate Tensile Strength	32.37 N/mm^2
2	Yield Strength	30.05 N/mm^2
3	% Elongation	21.72
4	Modulus of Elasticity	895.38 N/mm^2
5	Hardness	71.6 SHORE D

2.2. Tool Material

H13 tool steel is used to fabricate the FSW tool. A cylindrical taper tool pin profile is selected to enhance good material flow by pushing material backwards. A cylindrical taper pin protects the workpiece materials from degradation due to high heat generation. The tool material has 45–50 HRC hardness. The tool is designed with a 20 mm shoulder diameter and 65 mm long. The Cylindrical tapered pin is designed. The length of the pin is 7 mm long and 7 mm and 3.5 mm maximum and minimum pin diameters, respectively, as shown in Figure 2.

Fig. 2 H13 FSW tool

2.3. Process Parameters

The process parameters and their levels are chosen to carry out the experiments, as shown in Table 2.

Table 2. Process parameters and its levels

S. No.	Process Parameters	Level 1	Level 2	Level 3
1	Rotational speed(RPM)	710	900	1100
2	Traverse speed (mm/min)	40	60	80
3	Tool Tilt angle (deg)	0	0.5	1

2.4. Experimental Design

In this research, an L9 orthogonal array is selected, which is suggested by Taguchi for 3 process parameters and 3 levels. Rotational speed, feed and Tilt angle are input process parameters, and its 3 levels are tabulated in Table 3. Nine experiments are performed as per Table 3.

Table 3. Design of experiments as per L9 orthogonal array

Exp. No	Speed (R.P.M)	Feed (mm/min)	Tilt angle (Degrees)
1	710	40	0
2	710	60	0.5
3	710	80	1
4	900	40	0.5
5	900	60	1
6	900	80	0
7	1100	40	1
8	1100	60	0
9	1100	80	0.5

2.5. Experimental Setup

In this research, an HMT FM-2V type Vertical milling machine of 10 HP capacities are used as a friction stir welding machine as shown in Figure 3. The specifications of the machine are as follows. The speed range is 35 rpm to 1800 rpm. The bed size is 800 mm in the "X" direction, 400 mm in the "Y" direction, and 400 mm in the "Z" direction, and the feed capacity range is from 16 mm/min to 800 mm/min.

2.6. Experimental Procedure

The prepared and cleaned workpiece specimens are fixed on the bed table of the vertical milling machine, as shown in Figure 4. The designed FSW tool is fixed in the fixture of the machine. The process parameters are fixed as per the orthogonal array designed. The process involves, as shown in Figure 5, a rotating tool inserted at the joint line and plunged into the joint until the shoulder contacts the work surface, where it generates heat through friction. The tool then advanced along the workpiece joint line. Due to the rotation and traverse movement of the tool, friction is generated, and the material becomes softened. The softened plastic is then mixed and stirred as the tool moves along the joint line, creating a solid bond, as shown in Figure 6.

Fig. 3 Vertical milling machine

Fig. 4 Workpiece arrangemnet on milling machine

Fig. 5 The FSW process on the milling machine

Fig. 6 Friction stir welded specimen

3. Mechanical Characterization

The mechanical properties like yield strength, ultimate tensile strength, hardness and percentage of elongation are tested on friction stir welded joints. To test yield strength, ultimate tensile strength and percentage of elongation, test specimens are prepared as per ASTM D638-10-TYPE IV standards, as shown in Figure 7. Prepared tensile strength test specimens are shown in Figure 8.

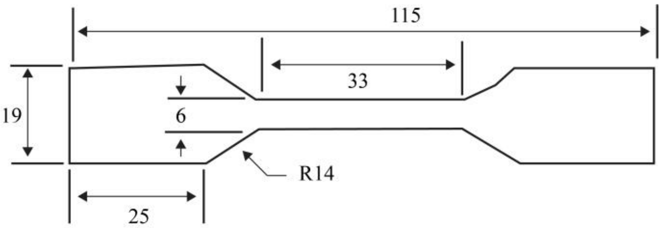

Fig. 7 Tensile specimen ASTM D638 standards

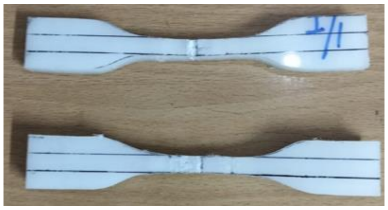

Fig. 8 Tensile strength of test specimens

Yield strength, Ultimate tensile strength and percentage of elongation are measured on the universal testing machine, as shown in Figure 9. The tested specimens are shown in Figure 10.

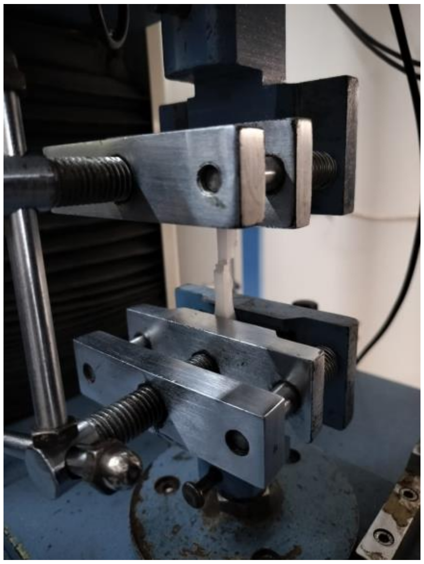

Fig. 9 Tensile strength test setup

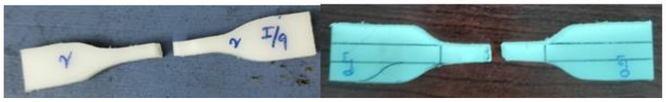

Fig. 10 Tested tensile strength specimens

The hardness of welded joints is measured as shown in Figure 11, using shore D Durometer hardness tester capacity of 0-100 HD and accuracy is 0.5 HD.

4. Results and Discussions

The test results and input values for the chosen parameters are shown in Table 4.

Table 4. L9 orthogonal array after assigning input values along with test results

Expt	Speed (R.P.M)	Feed (mm/min)	Tilt Angle (Deg)	Shore D Hardness value	% Elongation	Yield Strength (N/mm^2)	Ultimate Tensile Strength (N/mm^2)
1	710	40	0	42.2	3.66	11.16	12.05
2	710	60	0.5	39.25	2.91	8.09	8.09
3	710	80	1	37.2	1.65	6.67	6.67
4	900	40	0.5	50.6	2.38	9.95	9.95
5	900	60	1	48.2	1.59	4.19	4.19
6	900	80	0	48.8	2.05	9.76	9.76
7	1100	40	1	46	2.24	10.67	10.67
8	1100	60	0	40.2	3.24	13.08	13.12
9	1100	80	0.5	47.75	2.38	11.52	11.52

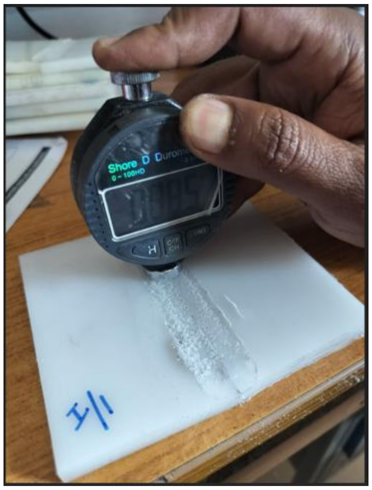

Fig. 11 Shore D hardness testing

Mechanical testing revealed yield strength of 13.08 MPa at 1100 RPM rotating speed, 60 mm/min transverse speed, and 0^0 tilt angles, as shown in Table 4. It was also found that maximum hardness, 50.6, is reached at 900 RPM rotating speed, 40 mm/min transverse speed, and 0.5^0 tilt angle, as shown in Table 4.

The highest percentage of elongation is achieved at a rotating speed of 710 RPM, a transverse speed of 40 mm/min, and a tilt angle of 0^0. For polypropylene materials, lower rotational speeds and lower transverse speeds and higher rotational speeds and moderate transverse speeds are suggestable to get the best results of yield strength, hardness and percentage of elongation. Moderate rotational speeds and moderate transverse speeds are not suggestable because the material becomes brittle.

5.1. Analysis Using the Column Effects Approach

Taguchi suggests a variety of approaches for analyzing findings, including the ranking method, column effect method, plotting method, ANOVA, and so on. The column effects approach is employed in this study to determine the interaction of the components.

The column effects approach involves studying the output values at different levels and determining the range. A greater range indicates a greater impact on the parameters.

The column effects technique determines the range by examining the output values at different levels. Out of all the characteristics, the tilt angle has the greatest influence on yield strength when compared to all other process factors, followed by rotation speed shown in Table 5.

Table 5. Analysis using the column effects approach

S.No	S1 (Sum of tensile strength for Speed)	S2 (Sum of tensile strength for Feed)	S3 (Sum of tensile strength for tilt angle)
1	25.92	31.78	34
2	23.9	25.36	29.56
3	35.27	27.95	21.53
Range	**11.37**	**6.42**	**12.47**

5.2. Effect of Process Parameters vs. Yield Strength

Figure 12 shows that many process parameters have a considerable impact on polypropylene yield strength during friction stir welding.

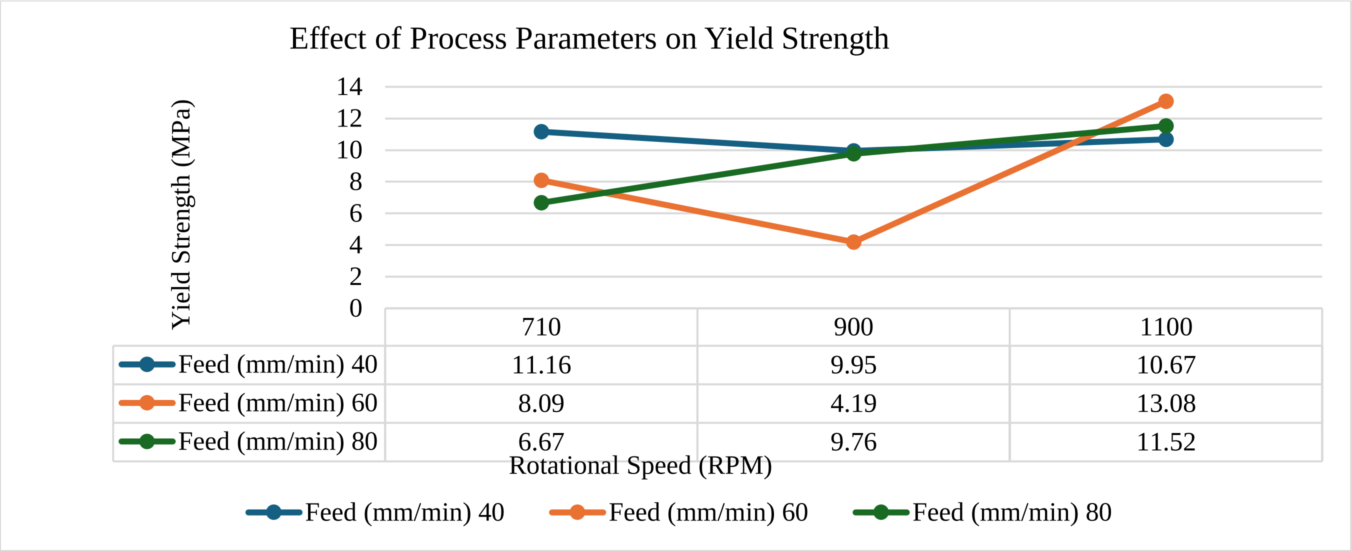

Fig. 12 Effect of process parameters on yield strength

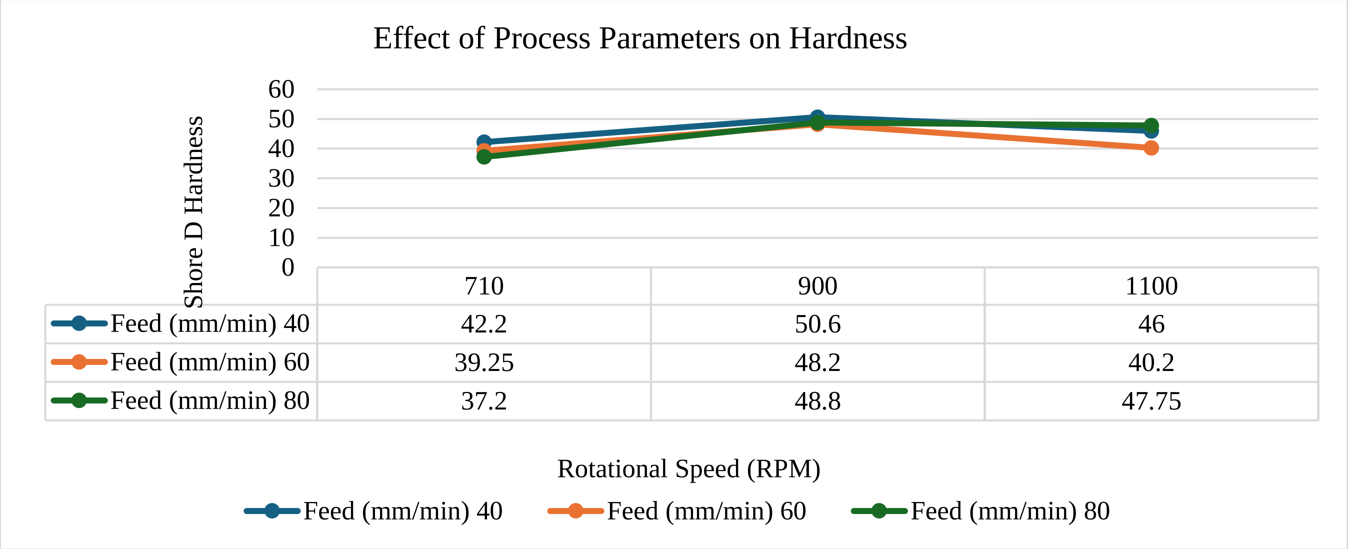

Fig. 13 Effect of process parameters on hardness

Figure 12 depicts that the third (high) level of rotational speed and the second (moderate) level of transverse speed are more impacted by the levels of process parameters. It is determined that high rotating speed, moderate transverse speed, and low tilt angle are the optimal parameters for welding polypropylene with H13 tool material to get the highest yield strength at the welded region. The maximum efficiency of yield strength at the welded portion is 43.52% of base material yield strength.

Polypropylene is a thermoplastic, and its properties can be significantly impacted by heat. During FSW, the heat generated can cause thermal degradation of the polymer chains, leading to a reduction in molecular weight and, consequently, the material's mechanical strength during FSW, leading to recrystallization. The process can disrupt the crystalline structure, reducing its strength. Residual stresses can be introduced into the welded joint, weakening the material. Improper welding parameters can cause voids and porosity, reducing the welded material's strength. Interfacial bonding is crucial, as it affects the weld zone's strength. Microstructural changes, such as phase separation or filler distribution, can also negatively impact the material's mechanical properties. Exposure to air and contaminants can lead to oxidation and contamination.

5.3. Effect of Process Parameters vs. Hardness

The column effects technique determines the range by examining the output values at different levels. A higher range indicates a greater effect from the parameters. Out of all the characteristics, rotational speed has the greatest impact, followed by feed, as shown in Table 6

Table 6. Effect of process parameters vs. Hardness

S.No	S1 (Sum of Hardness values for Speed)	S2 (Sum of Hardness values for for Feed)	S3 (Sum of Hardness values for Tilt angle)
1	118.6	138.8	131.2
2	147.6	127.65	137.6
3	133.95	133.75	131.4
Range	**29**	**11.15**	**6.2**

The specified process parameters have a significant influence on the hardness of polypropylene during friction stir welding, as shown in Figure 13.

Figure 13 shows that the second (moderate) level of rotational speed and the first (low) level of transverse speed are more impacted by the levels of process parameters. It is determined that moderate rotating speed, low transverse speed, and moderate level tilt angle are the optimal parameters for welding polypropylene with H13 tool material to achieve maximum hardness at the welded section. The maximum efficiency of hardness at the welded portion is 70.67% of base material hardness.

The FSW process can increase the proportion of the amorphous phase in the polymer matrix. The amorphous regions have lower hardness and strength compared to the crystalline regions, leading to an overall decrease in hardness. The intense plastic deformation and heat input during FSW lead to recrystallization and changes in grain size in the welded region. The recrystallized grains are typically smaller and more equiaxed than those in the base material. While finer grains can sometimes increase hardness in metals, in polymers like PP, the welding process can disrupt the crystalline structure, leading to a less orderly and weaker structure.

6. Conclusion

- It has been observed that polypropylene is successfully welded using friction stir welding and H13 tool steel material.
- The tilt angle is the most significant parameter to affect the yield strength of FSW welded joints for polypropylene.
- The rotating speed is the most significant parameter to affect the hardness of FSW welded joints for polypropylene.
- The optimum process parameters to achieve optimum yield strength are 1100 rpm rotational speed, 60 mm/min transverse feed, and 0 degrees tilt angle. The optimum yield strength is 13.08 N/mm^2.
- The optimum process parameters to achieve optimum hardness are 900 rpm rotational speed, 40 mm/min transverse feed, and 0.5 degrees tilt angle. The optimum hardness is 50.6 SHORE D.
- Maximum yield strength efficiency is 43.52% of base material, and hardness is 70.67% of base material with H13 tool steel.

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