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Original Article

Assessing Mechanical Properties and Their Impact on Friction Stir Welding of Polypropylene with H13 Tool Steel: A Statistical Approach

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Abstract - *The present research is focused on the weldability and independent variables optimization of polypropylene friction stir fabricated joints. In this study, rotating spindle speed, transverse speed rate, and tool tilted angle are the independent variables at 3 levels that are chosen. Experiments are performed as per the L9 orthogonal array. The mechanical behavior, like hardness, elastic limit, UTS, and ductility of fabricated joints, are tested as per ASTM D638-10 TYPE IV standards. Statistical analysis using Minitab software has been done to analyze the interaction between independent variables, to know the more influential variable, to sequence the influencing variables, and to optimize the independent variables. It was observed that the polypropylene is successfully fabricated using friction stir welding. Interaction graph results reveal that all three variables are combined, influencing the quality of fabricated joints, not independently. It was observed that the tool-tilted angle is the most influential variable for UTS but the least influential variable for hardness. Also observed is that rotating spindle speed is the most influential variable for the hardness of a fabricated joint, and transverse speed rate is the least influential variable for the UTS of fabricated joints. 900 revolutions per minute. Rotating spindle speed, 40 mm per minute transverse speed rate, and 0.5° tool tilted angle are the optimized independent variables of fabricated joint hardness. 1100 revolutions per minute. Rotating spindle speed, 40 mm per minute transverse speed rate, and 0° tool tilted angle are the optimized independent variables of fabricated joints UTS.710 revolutions per minute rotating spindle speed, 40 mm per minute transverse speed rate, and 0° tool tilted angle are the optimized independent variables of fabricated joints percentage elongation.*

Keywords - *Friction stir welding, H13 tool steel, Main effect graphs, Interaction graphs, Mechanical properties, Tool rotating spindle speed, Transverse speed, and Tool tilted angle.*

1. Introduction

Friction stir welding is suitable for a variety of materials, like metals and polymers, due to its benefits over fusion welding processes because it is a solid-state welding process [1]. FSW technique is weld defect free like porosity, hot cracking and segregation since it is an emerging solid-state joining technique [2]. Thermoplastic polymer polypropylene (PP) has a high demand in automotive, aerospace, marine, textile, and rope industries due to its low cost, lightweight and fabricated from the monomer polypropylene. Because of these benefits, researchers focused on how independent variables such as transverse speed rate, tool pin profile, and rotating spindle speed affected friction stir fabricated joints [3]. In polypropylene (PP) friction, stir fabricated joints, the tool-tilted angle has a greater impact on Material flow, heat generation and UTS; 66 MPa UTS is obtained at an optimum tool-tilted angle of 1°. Higher tool tilted angle causes uneven material transfer and weld defects. The strength of the joint is affected by stir zone size and internal weld defects like shrinkage gaps, which cause cracks during testing. Fracture surface analysis revealed that the local stretching causes joint weakness [4]. 10 mm thick polypropylene plate friction stir fabricated joints produced defect-free welds with an offset left-hand threaded tool pin. Compared to the central tool position, due to storing more material in the butt line, the offset tool position raised material consolidation on the advancing side, which led to a higher UTS [5]. Friction stir spot welding independent variables are optimized for high-density polypropylene using the Taguchi design of experiments. Weld strength is 47.7% enhanced than base material compared to initial [6].

Polypropylene (PP) Friction Stir Welding (FSW) with fixed variables is examined to emphasize the tool shape to maximize joint UTS. The significance of the affected zone in fabricated joints is explained by fractures that happened there. The ideal tool pin profile is suggested to enhance weld strength and advance FSW procedures for polypropylene [7]. The temperature fluctuates during polypropylene Friction Stir Welding (FSW), and it is observed that the highest temperature is recorded at the stir zone on the advancing side; because of this reason, the face bending strength is affected. Highlighted how difficult it is to control temperature distribution in order to optimize welding variables and ensure joint strength and quality [8]. Polypropylene (PP) composite welds' tensile and impact strength are highly influenced by the type of fiber. Glass Fiber (GF) composites obtain the highest UTS at 2000 revolutions per minute rotating spindle speed, 8 mm per minute transverse speed, and a 6° tool tilted angle, Carbon Fiber (CF) composites obtained maximum UTS at 2500 revolutions per minute. Rotating spindle speed, 8 mm per minute transverse speed, and a 6° tool tilted angle. Explained the importance of the type of fiber rotating spindle speed, transverse speed, and tool tilted angle for better weld strength [9].

Ultra-high Molecular Weight Polyethylene (UHMWPE) plates 8 mm thick are fabricated successfully using the friction stir welding technique with a threaded tool pin profile tool [10]. In polypropylene fabricated joints, enhancing rotating spindle speed significantly increases the tensile shear load capacity of the fabricated joint. 2253 N load capacity is recorded at 2350 revolutions per minute rotating spindle speed. It was observed that there is a direct correlation between the rotating spindle speed and the strength of the joint. It was also observed that the geometry of the welding tool plays an important role in the weld quality. Suggested that the pin tool with a 5° shoulder angle, which increases nugget area to increase load capacity. Finally, it was suggested that the 15° pin tool angle combined with the 5° shoulder angle [11]. In comparison to single-sided welding, double-sided welding produces defect-free welds and produces less torque and force on the tool. It was also observed that the double-sided welds produce joints with higher UTS compared to single-sided fabricated joints [12]. Friction stir fabricated joints of 6 mm thick polypropylene plates obtained a maximum UTS of 22.41 MPa, which is less than the base material UTS of 33 MPa. It indicates that further improvement is needed in joint strength [13].

2. Materials and Methods

2.1. Materials

Experimental investigation on polypropylene sheets with dimensions of 100 x 60 x 8 mm size was used as base materials illustrated in Figure 1. The workpiece materials were cleaned properly with acetone to avoid dust and foreign particles [14]-[15]. The mechanical properties of PP sheets are summarized in Table 1.

Fig. 1 Polypropylene sheet

Table 1. Mechanical properties of Polypropylene sheet

Property	**UTS (N/mm^2)**	**Elastic limit (N/mm^2)**	**% Elongation**	**Modulus of Elasticity (N/mm^2)**	**Hardness (shored)**
Value	32.37	30.05	21.72	895.38	71.6

2.2. Methodology

A vertical milling machine (HMT FM-2V type) with a 10 HP capacity was used to conduct Friction Stir Welding (FSW) experiments on polypropylene using an H13 tool steel. The machine specifications are as follows: a speed range of 35 revolutions per minute to 1800 revolutions per minute., a bed size of 800 mm in the 'X' direction, 400 mm in the 'Y' direction, and 400 mm in the 'Z' direction, and a transverse speed capacity ranging from 16 mm per minute to 800 mm per minute. The prepared and cleaned workpiece specimens were securely fixed on the machine's bed chart, as shown in Figure 2(b).

The FSW tool was designed with a cylindrical, tapered pin profile to enhance material flow by pushing the material backwards, thereby protecting the workpiece from degradation due to excessive heat. The tool features a 20 mm shoulder diameter and a total length of 65 mm, with the cylindrical, tapered pin measuring 7 mm in length and having maximum and minimum pin diameters of 7 mm and 3.5 mm, respectively, as illustrated in Figure 2(a). It was observed that the H13 tool steel is effective for welding polypropylene across all tested independent variables, underscoring the need to optimize these variables for enhanced results. The experiments were conducted using various independent variables set according to an orthogonal array design. The combinations of independent variables included tool rotating spindle speeds of 710, 900, and 1100 revolutions per minute. Tool travel speeds of 40, 60, and 80 mm per minute; and tool tilted angles of 0, 0.5, and 1°, as detailed in Table 2. In the FSW process, the rotating tool is inserted at the joint line and plunged into the material until the shoulder contacts the work surface, generating heat through friction. The tool is then advanced along the joint line of the workpiece. The friction produced by the tool's rotation and traverse movement softens the material, which is subsequently mixed and stirred as the tool moves along the joint, creating a solid bond, as shown in Figure 2(c).

Table 2. Independent variables used in the experimentation

S.No.	Independent variables	Level 1	Level 2	Level 3
1	Tool rotating spindle speed (Revolutions per minute.)	710	900	1100
2	Tool Traversing speed(mm per minute)	40	60	80
3	Tool tilted angle(^{0})	0	0.5	1

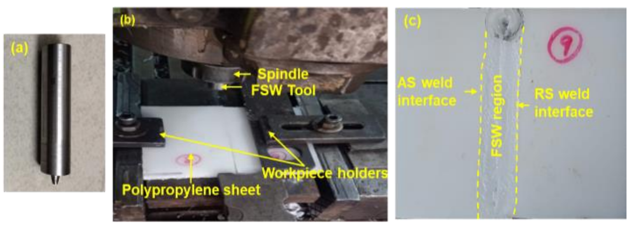

Fig. 2 (a) H13 FSW Tool, (b) Experimental setup, (c) Friction Stir fabricated specimen.

3. Mechanical Characterization &Results and Discussions

The FSW joints were cut across the weld and polished properly to measure the hardness using a Shore D Durometer hardness tester capacity of 0-100 HD, having an accuracy of 0.5 HD, as indicated in Figure 3. UTS and elongation were also determined to assess the developed joint strength.

Fig. 3 Shore D hardness testing

3.1. Statistical Analysis of Polypropylene Friction Stir Fabricated Joints

The quality of friction stir fabricated joints is evaluated by statistically analyzing response factors such as UTS, hardness, and ductility. This analysis is used to optimize the independent variables that influence weld quality. Main effect graphs for means and SN ratios were examined to identify the most influential factor levels and to understand how these factors impact the response variables, thereby optimizing the friction stir welding process for polypropylene. The delta and rank values for means and SN ratios were interpreted to determine the factors with the most significant impact on the average response variable and the consistency or robustness of the response.

3.1.1. Interpretation of Main Effect Graph for Means and SN Ratio of Hardness

Hardness measurements across the weld revealed, through statistical analysis, that the average hardness is significantly higher at a rotating spindle speed of 900 revolutions per minute. Compared to 710 and 1100 revoluti ons per minute. Suggesting that moderate rotating spindle speed results in a harder joint, as indicated in Figure 4(a). Additionally, the average hardness is significantly greater at a transverse speed rate of 40 mm per minute compared to 60 and 80 mm per minute, indicating that a smaller transverse speed rate produces a harder joint. Furthermore, the average hardness is substantially higher at a tool-tilted angle of 0.5° compared to 0° and 1.0°, demonstrating that a moderate tool-tilted angle also contributes to raised joint hardness.

The mean of the Signal-to-Noise (SN) ratio graph is used to identify the factor levels that achieve the desired hardness while minimizing variability. The average SN ratio is significantly higher at a moderate rotating spindle speed, a lower transverse speed rate, and a moderate tool-tilted angle, indicating that these conditions improve the SN ratio in Figure 4(b). Optimizing the SN ratio involves identifying the specific levels of each factor that maximize the SN ratio using main effect graphs. From these main effect graphs, the optimized independent variables were determined to be a rotating spindle speed of 900 revolutions per minute. A transverse speed rate of 40 mm per minute and a tool-tilted angle of 0.5°. Under these optimized conditions, a harder and more effective joint is produced.

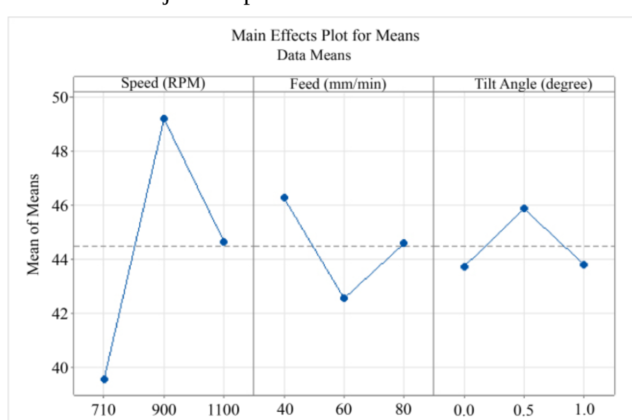

Fig. 4 (a) Main effect graph for means of hardness

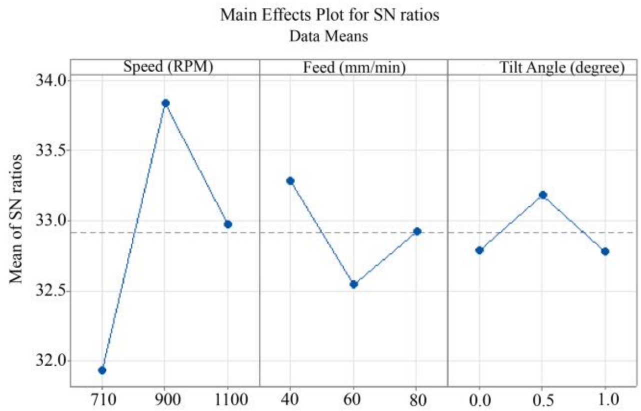

Fig. 4 (b) Main effect graph for SN ratio of hardness

3.1.2. Interpretation Response Chart for means of Hardness

The process variable with the biggest delta value for means indicates profound impacts on the average hardness. In this case, the rotating spindle speed has a larger delta than the transverse speed and tool tilted angle, which indicates that rotating spindle speed influences average hardness more than transverse speed and tool tilted angle; subsequently, transverse speed and tool tilted angle, respectively, in Table 3.

Table 3. Response chart for means of hardness

Level	Speed (Revolutions per minute)	Transverse speed (mm per minute)	Tool tilted angle (°)
1	39.55	46.27	43.73
2	49.20	42.55	45.87
3	44.65	44.58	43.80
Delta	9.65	3.72	2.13
Rank	1	2	3

Table 4. Response chart for SN ratios of hardness

Level	Speed (Revolutions per minute)	Transverse speed (mm per minute)	Tool tilted angle (°)
1	31.93	33.28	32.79
2	33.84	32.54	33.18
3	32.97	32.92	32.78
Delta	1.91	0.74	0.40
Rank	1	2	3

3.1.3. Interpretation Response Chart for SN Ratios of Hardness

The most important influence on the consistency (robustness) of the hardness can be observed by the factor with the largest delta value for the SN ratio. In this case, rotating spindle speed has a larger delta for SN ratio than tool tilted angle and transverse speed; it indicates that rotating spindle speed has a greater impact on reducing variability in hardness to make the joint robust in Table 4.

3.1.4. Interpretation of Interaction Graph for Hardness Analysis

Interaction graphs demonstrate the relationship between the input independent variables. It explains whether the input independent variables are affecting the response variables independently or combinedly.

As per Figure 5, the rotating spindle speed and transverse speed both have an interaction with each other in affecting the hardness of the fabricated joint. It also represented that the rotating spindle speed and tool tilted angle also have an interaction with each other in affecting hardness. It demonstrates that the transverse speed and tool tilted angle also interact with each other to affect the hardness of the weld portion. Finally, it can be said that all three variables—spindle rotating speed, transverse speed, and tool tilted angle—have a relationship with each other in affecting the hardness; it implies that the three input independent variables collectively affect the hardness of the weld.

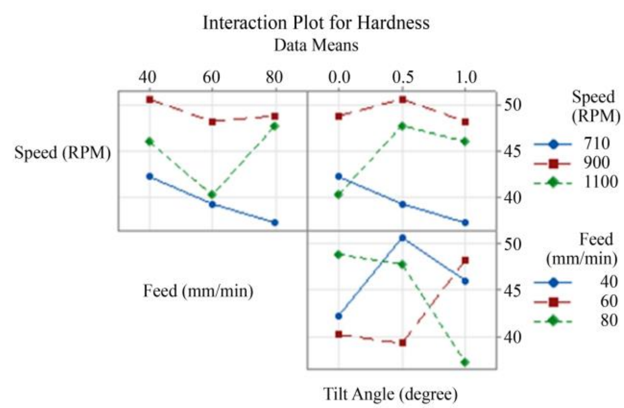

Fig. 5 Interaction graph for hardness

At lower and moderate rotating spindle speeds, the hardness of the weld joint is continuously decreased by enhancing the transverse speed rate from smaller to higher levels, but at higher speeds, the hardness of weld strength decreases from smaller level to moderate level transverse speed rates, while the hardness increases from moderate to higher level transverse speed rates. It was observed that in order to enhance the hardness of a weld joint, higher rotating spindle speeds and higher transverse speed rates are preferred.

The hardness of the weld joint continuously decreases at lower rotating spindle speeds by enhancing the tool's tilted angle from smaller to higher levels. At higher and moderate levels of rotating spindle speeds, the hardness of the weld joint increases by enhancing the tool-tilted angle from smaller to moderate levels, whereas the hardness of the weld joint decreases by enhancing the tool-tilted angle from moderate to higher levels. It was noted that in order to increase the hardness of a weld joint, moderate and higher rotating spindle speeds with moderate tool-tilted angles are preferred. The hardness of the weld joint is decreased continuously at higher transverse speed rates by decreasing the tool-tilted angle from smaller to higher levels. At moderate transverse speed rates, the hardness is decreased by enhancing the tool-tilted angle from smaller to moderate levels but increases from moderate to higher tool-tilted angles. The hardness of the weld joint is raised by enhancing the tool-tilted angle from smaller to moderate levels but decreases by enhancing from moderate to higher levels of tool-tilted angles. It was noted that in order to increase the hardness of a weld joint, moderate transverse speed rates with higher tool-tilted angles are preferred, as well as lower transverse speed rates with moderate tool-tilted angles, are preferred.

3.2. UTS Measurement

The mechanical properties, including elastic limit, ultimate UTS, hardness, and ductility, were determined for polypropylene friction stir fabricated joints to evaluate their performance. The test specimens were prepared as per ASTM D638-10 TYPE IV standards, as depicted in Figure 6(a). These standards ensure that the specimens meet the required dimensions and specifications for accurate and reliable testing. The prepared UTS test specimens, shown in Figure 6(b), were then subjected to rigorous testing procedures to determine the mechanical properties of the polypropylene FSW joints. The obtained properties are summarized in Table 5.

Mechanical testing revealed that the maximum UTS of 13.12 MPa was obtained at a rotating spindle speed of 1100 revolutions per minute., a transverse speed of 60 mm per minute, and a 0° tool tilted angle, as shown in Table 3. Additionally, the highest hardness value of 50.6 was obtained at a rotating spindle speed of 900 revolutions per minute. A transverse speed of 40 mm per minute and a 0.5° tool tilted angle are also indicated in Table 5. The maximum ductility was recorded at a rotating spindle speed of 710 revolutions per minute. A transverse speed of 40 mm per minute and a 0° tool tilted angle. For polypropylene materials, it is recommended to use lower rotational and transverse speeds or higher rotational and moderate transverse speeds to achieve optimal results in UTS, hardness, and ductility. However, moderate rotational and transverse speeds are not advisable as they tend to make the material more brittle.

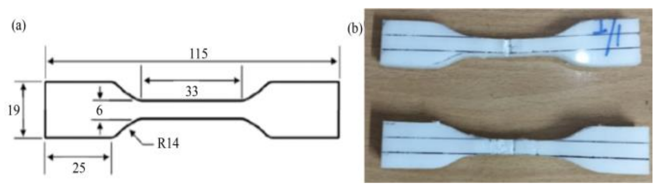

Fig. 6 Tensile Specimen ASTM D638 standards

Table 5. Mechanical Test Results of FSW Polypropylene with H13 tool

Expt	Speed (R.P.M)	Transverse speed (mm per minute)	Tool tilted angle (Deg.)	Shore D Hardness value	% Elongation	Elastic limit (N/mm^2)	UTS (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

3.2.1. Interpretation of Main effect Graph for means and SN Ratio of UTS

The average UTS is significantly higher at 1100 revolutions per minute. Compared to 710 and 900 revolutions per minute. This indicates that an increase in rotating spindle speed results in a stronger joint, as shown in Figure 7(a). When comparing transverse speed rates, the average UTS is notably greater at 40 mm per minute than at 60 mm per minute and 80 mm per minute, suggesting that a smaller transverse speed rate enhances joint strength. Additionally, the average UTS is substantially greater at a tool-tilted angle of 0° compared to 0.5° and 1.0°, indicating that a smaller tool-tilted angle contributes to a stronger joint.

The mean of the SN ratio graph was used to identify the optimal factor levels for achieving the desired UTS while minimizing variability, as shown in Figure 7 (b). The average SN ratio is significantly higher at a higher rotating spindle speed, a smaller transverse speed rate, and a smaller tool tilted angle, suggesting that these conditions improve the SN ratio. Optimizing the SN ratio involves determining the factor levels that maximize it using main effect graphs. From these graphs, the optimized independent variables were identified as 1100 revolutions per minute. A 40 mm per minute transverse speed rate and a 0° tool tilted angle. Under these optimized conditions, a strong and effective joint is produced.

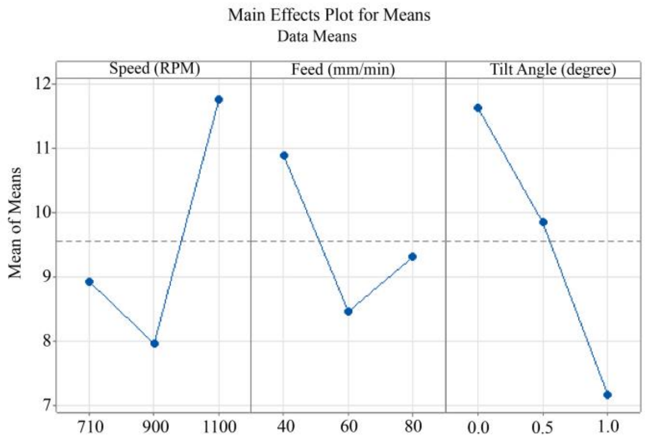

Fig. 7 (a) Main effect graph for means of UTS

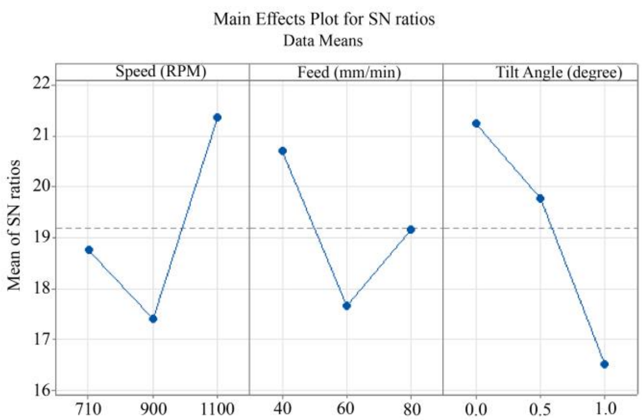

Fig. 7(b) Main effect graph for SN ratio of UTS

3.2.2. Interpretation Response chart for means of UTS

The process variable with the biggest delta value for means indicates the profound impacts of the average UTS. In this case, tool tilted angle has a larger delta than the rotating spindle speed and transverse speed, which indicates that tool tilted angle influences average UTS more than the rotating spindle speed and transverse speed, subsequently rotating spindle speed and transverse speed, respectively, in Table 6.

Table 6. Response chart for means of UTS

Level	Speed (Revolutions per minute)	Transverse speed (mm per minute)	Tool tilted angle (°)
1	8.937	10.890	11.643
2	7.967	8.467	9.853
3	11.770	9.317	7.177
Delta	3.803	2.423	4.467
Rank	2	3	1

3.2.3. Interpretation Response chart for SN ratios of UTS

The most important influence on the consistency (robustness) of the UTS can be observed by the factor with the largest delta value for the SN ratio in Table 7. In this case, the tool tilted angle has a larger delta for SN ratio than the rotating spindle speed and transverse speed; it indicates that the tool tilted angle has a greater impact on reducing variability in UTS to make the joint robust.

Table 7. Response chart for SN ratios of UTS

Level	Speed (Revolutions per minute)	Transverse speed (mm per minute)	Tool tilted angle (°)
1	18.75	20.71	21.26
2	17.40	17.65	19.78
3	21.38	19.17	16.50
Delta	3.99	3.06	4.76
Rank	2	3	1

3.2.4. Interpretation of Interaction Graph for UTS

As per image 8, the rotating spindle speed and transverse speed both interact with each other to affect the UTS of the fabricated joint. It also represented that the rotating spindle speed and tool tilted angle also have an interaction between each other in affecting UTS. It demonstrates that the transverse speed and tool tilted angle also have an interaction with each other in affecting the UTS of the weld portion. Finally, it can be stated that all three variables, rotating spindle speed, transverse speed, and tool tilted angle, have a relationship with each other in affecting the UTS; it implies that the three input independent variables are combined, affecting the UTS of the weld strength.

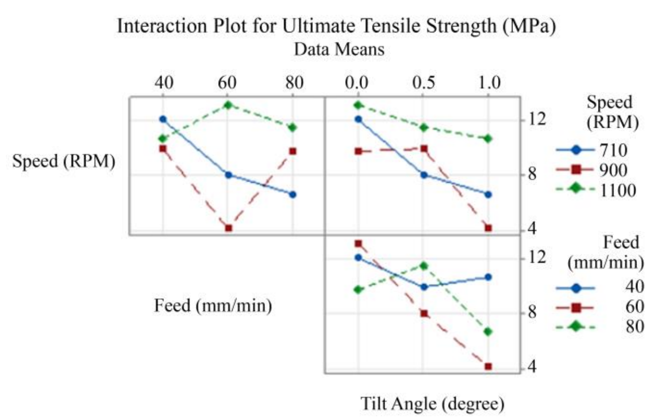

Fig. 8 Interaction Graph for UTS

The UTS of a fabricated joint is decreased continuously by decreasing transverse speed rates from smaller to higher levels at smaller rotating spindle speeds. At moderate rotating spindle speeds, the UTS of the weld joint decreases from smaller to moderate levels of transverse speed rates and increases from moderate to higher levels of transverse speed rates. UTS of weld joint is raised from smaller to moderate levels of transverse speed rates but decreases from moderate to higher levels of transverse speed rates at higher rotating spindle speeds. It was observed that in order to enhance the UTS of a weld joint, higher rotating spindle speeds and moderate transverse speed rates are preferred. At smaller and higher rotating spindle speeds, the UTS of the weld joint is continuously decreased by enhancing the tool tilted angle from smaller to higher levels. The UTS of a weld joint is raised by enhancing the tool-tilted angle from smaller to moderate levels, whereas the UTS of a weld joint is decreased by enhancing the tool-tilted angle from moderate to higher levels. It was noted that in order to enhance the UTS of a weld joint, moderate rotating spindle speeds and moderate tool tilted angles are preferred. The UTS of the weld joint is decreased continuously at moderate transverse speed rates by decreasing the tool tilted angle from smaller to higher levels. At higher transverse speed rates, the UTS increases by enhancing the tool tilted angle from a smaller to a moderate level but decreases from a moderate level to a higher-level tool tilted angle. The UTS of a weld joint decreases by enhancing the tool-tilted angle from smaller to moderate levels, but increases by enhancing the tool tilted angle from moderate to higher levels. It was noted that in order to increase the UTS of a weld joint, higher transverse speed rates and moderate tool tilted angles are preferred.

3.3. Interpretation of Main Effect Graph for Means of Ductility

The average ductility is significantly higher at 710 revolutions per minute. Compared to 900 and 1100 revolutions per minute. Suggesting that a smaller rotating spindle speed results in a more ductile joint, as shown in Figure 9(a). When comparing transverse speed rates, the average ductility is notably greater at 40 mm per minute than at 60 and 80 mm per minute, indicating that a smaller transverse speed rate enhances ductility. Additionally, the average ductility is substantially greater at a tool tilted angle of 0° compared to 0.5° and 1.0°, suggesting that a smaller tool tilted angle increases the joint's ductility.

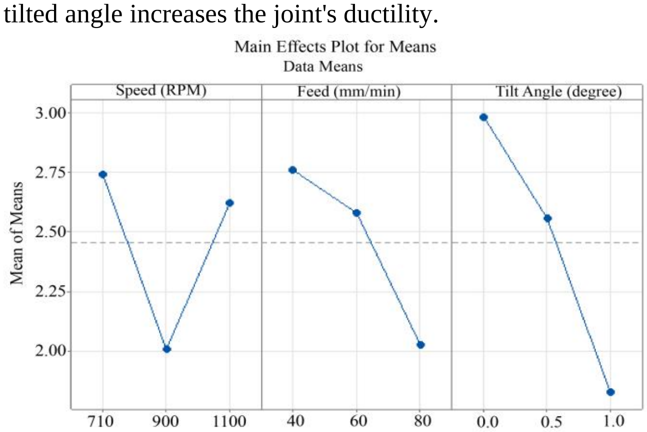

Fig. 9(a) Main effect graph for means of ductility

The mean of the SN ratio graph was used to identify the optimal factor levels for achieving the desired ductility while minimizing variability, as shown in Figure 9(b). The average SN ratio is significantly higher at a low rotating spindle speed, a low transverse speed rate, and a low tool tilted angle, indicating that these conditions improve the SN ratio. Optimizing the SN ratio involves determining the specific levels of each factor that maximize it using main effect graphs.

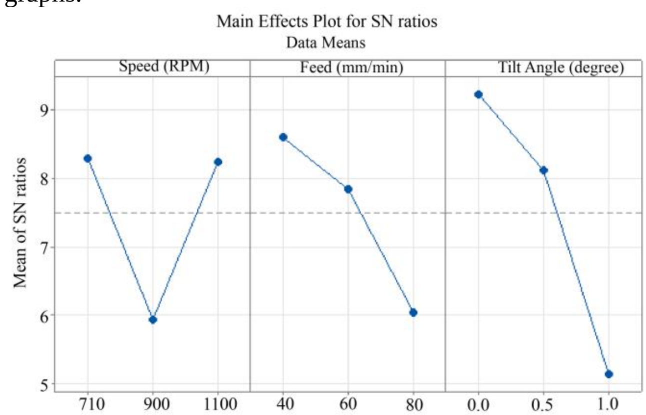

Fig. 9(b) Main effect graph for SN ratio of the ductility

From these graphs, the optimized independent variables were identified as 710 revolutions per minute. A 40 mm per minute transverse speed rate and a 0° tool tilted angle. Under these optimized conditions, a more ductile joint is produced.

3.3.1. Interpretation Response Chart for means of Ductility

The process variable exhibiting the greatest delta value for means significantly affects the average ductility. The variation in the tool tilted angle exceeds that of the rotating spindle speed and transverse speed, indicating that the tool tilted angle has a bigger impact on the average ductility than the rotating spindle speed and transverse speed, as shown in Table 8.

Table 8. Response chart for means of ductility

Level	Speed (Revolutions per minute)	Transverse speed (mm per minute)	Tool tilted angle (°)
1	2.740	2.760	2.983
2	2.007	2.580	2.557
3	2.620	2.027	1.827
Delta	0.733	0.733	1.157
Rank	2	3	1

3.3.2. Interpretation Response Chart for SN Ratios of Ductility

The factor that has the highest delta value for the SN ratio has the most significant impact on the elongation percentage's consistency (robustness). In this instance, the delta for the SN ratio is larger for the tool-tilted angle than for the rotating spindle speed and transverse speed. This suggests that tool tilted angle has a greater influence on the reduction of variability in the percentage elongation to ensure the joint is robust, as illustrated in Table 9.

Table 9. Response chart for SN ratios of percentage of elongation

Level	Speed (Revolutions per minute)	Transverse speed (mm per minute)	Tool tilted angle (°)
1	8.299	8.602	9.239
2	5.932	7.839	8.114
3	8.249	6.039	5.128
Delta	2.368	2.563	4.111
Rank	3	2	1

3.3.3. Interpretation of Interaction Graph for Ductility

As per Figure 10, the rotating spindle speed and transverse speed both interact with each other in affecting the ductility of the fabricated joint. It also stated that the rotating spindle speed and tool tilted angle also have an interaction between each other in affecting the ductility. It demonstrates that the transverse speed and tool tilted angle also interact with each other to affect the ductility of the weld portion. Finally, it can be decided that all three variables, like rotating spindle speed, transverse speed, and tool tilted angle, have a relationship with each other in affecting the ductility; it is stated that the three input independent variables are collectively affecting the ductility of the fabricated portion.

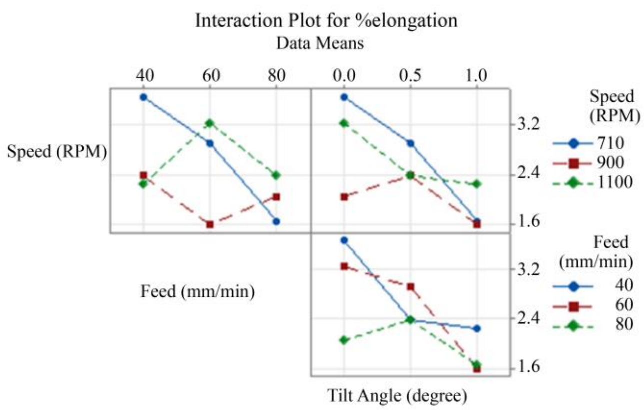

Fig. 10 Interaction graph for ductility

The ductility of the fabricated joint is decreased continuously by decreasing transverse speed rates from smaller to higher levels at smaller rotating spindle speeds. At moderate rotating spindle speeds, the ductility of the weld joint decreases from smaller to moderate levels of transverse speed rates and increases from moderate to higher levels of transverse speed rates. The ductility of the weld joint is raised from smaller to moderate levels of transverse speed rates but decreases from moderate to higher levels of transverse speed rates at higher rotating spindle speeds. It was observed that in order to maximize the ductility of a weld joint, smaller rotating spindle speeds and smaller transverse speed rates are suggested.

At smaller and higher rotating spindle speeds, the ductility of the weld joint is continuously decreased by enhancing the tool tilted angle from smaller to higher levels. The ductility of the weld joint increases by enhancing the tool tilted angle from smaller to moderate levels, whereas the ductility of the weld joint decreases by enhancing the tool tilted angle from moderate to higher levels. It was noted that in order to enhance the ductility of a weld joint, lower rotating spindle speeds and smaller tool tilted angles are preferred.

The ductility of the weld joint is decreased continuously at low and moderate transverse speed rates by decreasing the tool tilted angle from smaller to higher levels. At higher transverse speed rates, the ductility increases by enhancing the tool tilted angle from a smaller to a moderate level but decreases from a moderate level to a higher level tool tilted angle. It was suggested that in order to increase the ductility of a weld joint, lower transverse speed rates and smaller tool tilted angles are preferred.

4. Conclusion

The study focused on evaluating the quality of friction stir fabricated joints by analyzing UTS, hardness, and ductility using statistical methods. By examining main effect graphs for means and SN ratios, the most influential independent variables were identified, enabling the optimization of the welding process for polypropylene.

- The optimal conditions for achieving a harder and more consistent joint in friction stir welding are a rotating spindle speed of 900 revolutions per minute., a transverse speed rate of 40 mm per minute, and a tool tilted angle of 0.5°, as these variables significantly increase hardness and improve the signal-to-noise ratio.
- Maximum UTS, hardness, and elongation for polypropylene friction stir fabricated joints are obtained at specific rotational and transverse speeds, with smaller or higher rotating spindle speeds and moderate transverse speeds being recommended. The optimal UTS in friction stir fabricated joints is 1100 revolutions per minute., 40 mm per minute transverse speed rate, and 0^0 tool tilted angle. These circumstances optimize joint strength and signal-to-noise ratio.
- The optimal ductility in friction stir fabricated joints is obtained with a rotating spindle speed of 710 revolutions per minute., a transverse speed rate of 40 mm per minute, and a tool tilted angle of 0°, as these conditions significantly increase elongation.

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