

## EFFECT OF PIN GEOMETRY AND WELDING PARAMETERS ON PERFORMANCE OF FSW-JOINT HDPE

### UTICAJ GEOMETRIJE TRNA I PARAMETARA ZAVARIVANJA NA PERFORMANSE HDPE SPOJA ZAVAREN OG TRENJEM SA MEŠANJEM

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#### Keywords

- friction stir welding (FSW)
- pin geometry
- welding parameters
- ANOVA
- HDPE

#### Abstract

Recent advancements in polymer welding have spotlighted Friction Stir Welding (FSW) as a promising method for creating durable joints in high-density polyethylene (HDPE) without melting the material. This research delves into how three critical factors: tool pin shape, rotation speed, and travel speed affect the ultimate tensile strength (UTS) and ultimate elongation (UE) of the welded HDPE. Two distinct tool pin geometries, cylindrical and hexagonal, are employed to evaluate their effect on the quality of the welded HDPE. A full  $2^3$  factorial experimental design is used to study the effect of each parameter, while regression equations are employed to forecast the resulting mechanical properties. The study reveals that the tool pin geometry is the most influential parameter on both ultimate tensile strength and ultimate elongation, with the hexagonal pin yielding stronger welds due to improved stirring action. The welding gave generally good results concerning the UTS in the contrary of UE, where it gave unsatisfactory results. Statistical analyses, like ANOVA confirm the dominant influence of tool pin geometry and give a detailed information about the contribution of all parameters and their interaction on the final weld quality. These findings provide insights into optimizing FSW parameters for polymer welding applications.

#### INTRODUCTION

The Friction Stir Welding (FSW) is a solid-state joining process that has revolutionised the field of welding due to its energy efficiency, environmental friendliness, and ability to produce high-quality joints /1/. The majority of the friction stir welding studies are about aluminium and its alloys, but in recent years, the interest in FSW evolves to attain numerous other materials and their alloys, such as copper and its alloys /2/, magnesium alloy, steel, titanium, and composite materials /3/. FSW can also weld non-metallic materials such as polymers /4/. It is also used in the welding of dissimilar materials and is particularly effective in joining dissimilar materials like copper and aluminium, /5/. The

#### Ključne reči

- zavarivanje trenjem sa mešanjem (FSW)
- geometrija trna
- parametri zavarivanja
- ANOVA
- HDPE

#### Izvod

Nedavna dostignuća u zavarivanju polimera ističu zavarivanje trenjem sa mešanjem (FSW) kao obećavajuću metodu za stvaranje izdržljivih spojeva u polietilenu velike gustine (HDPE) bez topljenja materijala. Ovo istraživanje proučava kako tri kritična faktora, oblik klina alata, brzina rotacije i brzina kretanja utiču na zateznu čvrstoću (UTS) i krajnje izduženje (UE) zavarenog HDPE. Dve različite geometrije trna alata, cilindričan i heksagonalan, korišćeni su za procenu njihovog uticaja na kvalitet zavarenog HDPE. Korišćen je potpuni eksperimentalni dizajn sa  $2^3$  faktorijala za proučavanje uticaja svakog parametra, dok su regresijske jednačine korišćene za predviđanje rezultujućih mehaničkih svojstava. Studija otkriva da je geometrija trna alata najuticaj-niji parametar i zateznu čvrstoću i na krajnje izduženje, pri čemu heksagonalni trn daje jače zavarene spojeve zbog poboljšanog dejstva mešanja. Zavarivanjem se postižu generalno dobri rezultati u pogledu UTS za razliku od UE, gde su nezadovoljavajući rezultati. Statističke analize, poput ANOVA, potvrđuju dominantan uticaj geometrije trna alata i daju detaljne informacije o doprinosu svih parametara i njihovoj interakciji na konačan kvalitet šava. Ovi nalazi pružaju uvid u optimizaciju parametara FSW za primene kod zavarivanja polimera.

process involves a non-consumable rotating tool with a specially designed pin and shoulder. The tool is plunged into the joint line between two workpieces. The friction caused by the contact between the rotational shoulder and the workpieces engenders enough heat to soften the material without reaching its melting point. At the same time, the rotating pin stirs the softened area of the material. Then, the tool moves along the joint line, making the pin stir and join the softened material, inducing the welding of the workpieces /6/. Unlike traditional fusion welding methods, friction stir welding operates at a temperature lower than the melting point of the materials involved, which leads to joints with a more homogeneous grain structure and better mechanical

properties, such as tensile strength, hardness, and toughness, compared to fusion welding methods, /7/. This method is also more energy-efficient and environmentally friendly than fusion welding because it avoids melting the materials which significantly lowers energy consumption and emissions /8/. Additionally, FSW can weld some aluminium alloys that are known to be un-weldable /9/. Despite its advantages, FSW does have some drawbacks. One of them is the difficulty of welding thin sheets, especially sheets thinner than 2 mm, which results in welding distortion that leads to incomplete welds /10/. Another disadvantage of FSW is the initial investment for these systems, which is more expensive compared to some conventional methods. High-cost robotic systems are essential for joints with complex geometries. Additionally, since it's a solid-state welding process, abrasions can occur on the rotating tool and pin during the joining of materials, /11/. The gaps between the components to be welded need to be meticulously controlled since no filler metal is used in the process. Moreover, the need for clamping during the process, unlike other welding methods, makes it more challenging to ensure stability and alignment, /12/.

There are several types of friction stir welding. For example, Bobbin-tool FSW (BT-FSW), also known as self-reacting friction stir welding (SR-FSW), is an advanced variation of conventional friction stir welding that uses two opposite shoulders instead of one to eliminate the need for a backing plate and the defects on both sides at the same time. It is used especially for hard-to-weld materials and thick sections, /13/. Another type is stationary shoulder friction stir welding (SSFSW). Unlike traditional FSW, this type uses a stationary shoulder with a rotating pin. It helps maintain consistent pressure and heat distribution during the welding process. This design reduces the excessive heat generated at the surface between the shoulder and the workpieces, focusing the heat generation near the rotating pin. This welding method reduces the need for post-processing and provides a smoother surface with minimal flash /14/. Double-sided friction stir welding (DS-FSW) is another variation. In this kind of FSW, upper and lower tools operate on both sides of the workpieces simultaneously. This results in an even and symmetrical distribution of heat across the thickness, thus reducing residual stress and eliminating root defects observed in conventional friction stir welding. This form of FSW is most suited for welding thick sections and materials with low thermal conductivity, /15/.

In the FSW process, various parameters can affect the final result of the welding. Some tool variables include the shoulder diameter, probe shape, and various design elements, as they play an essential role in determining the quality of the weld, the heat generated, the flow of material, and the mechanical properties of the FSW joint. The diameter of the shoulder is particularly important, as it directly influences the amount of heat input and the overall strength of the weld /16/. The rotational speed, welding speed, and plunge depth are other essential parameters affecting the quality of the weld. Regulating the tool's rotational speed is essential for obtaining defect-free joints with superior mechanical properties in the FSW. The optimal speed provides enough heat for plastic deformation while maintaining the weld's

structural integrity /17/. Increasing the welding speed generally results in finer grain sizes and higher hardness in the SZ and HAZ. However, surpassing an optimal welding speed leads to the formation of defects and a reduction in mechanical properties /18/. When it comes to the effect of tool plunge depth, a higher depth enhances heat generation and material flow but may cause defects and surface flash, whereas reducing the plunge depth leads to incomplete mixing and internal defects, /19/.

High-density polyethylene (HDPE) is a synthetic thermoplastic. It is considered the third most used polymer in construction in the world /20/. HDPE is used in the food packaging and packaging industry, automotive parts, the textile sector, etc., due to its strength, lightness, and ease of processing /21/. It has good tensile strength between 20 and 40 MPa, a low density between 941-965 kg/m<sup>3</sup>, and a fairly low melting point of 120 °C /22/. The welding of HDPE is generally done by either electro-fusion or butt-welding /23/, but these methods are very costly in terms of time and money and are harmful to the environment. This is why researchers have moved towards the study of HDPE welding by FSW.

Ma'arif, M.S. et al. /24/ conducted a study to evaluate the impact of rotational speed on temperature, hardness, and tensile strength during friction stir welding (FSW). Their experimental results indicated that elevating the rotational speed significantly increases the peak welding temperature. Furthermore, they observed that the hardness within the weld nugget region is notably reduced compared to the base material, suggesting microstructural changes due to thermal cycling. Bilici, M.K. et al. /25/ focus on identifying common welding defects such as voids, material overflow, and cracks in FSW joints. Their analysis links these defects to two primary factors: improper heat generation (either insufficient or excessive) and suboptimal tool geometry, emphasising the critical role of balanced thermal management and tool design in defect mitigation. Mustapha et al. /26/ investigate the effects of two distinct shoulder geometries - concave and flat - on the tensile strength of HDPE welds, while also varying rotational and welding speeds. Their findings highlight the superior performance of concave shoulder tools, particularly at lower rotational speeds, where enhanced material flow and mixing results in fewer internal defects and stronger welds. Corroborating these results, Benyerou et al. /27/ independently confirm that concave shoulder designs consistently outperform flat shoulders in achieving higher weld integrity, likely due to improved heat distribution and material consolidation. Anaç /28/ explores the use of triangular and square pin profiles for HDPE welding. The study reports a marked reduction in hardness within both the heat-affected zone (HAZ) and the weld zone compared to the base material. Additionally, irregular weld morphology, including unwelded zones and discontinuous weld lines is observed, underscoring the challenges of achieving homogeneity with non-optimised pin geometries. Expanding on this, Khalaf et al. /29/ tested three pin profiles - frustum, triangular, and cubic - in their FSW experiments. Their comparative analysis reveals that the frustum-shaped pin produces uniform welds with minimal defects, attributing this outcome to its tapered geometry, which promotes smoother material flow and re-

duced stress concentrations during welding. To address limitations in conventional FSW, several researchers adopt unconventional approaches. Sheikh-Ahmad et al. /30/ experiment with preheating the lower HDPE plate prior to welding. Their work demonstrates that raising the material temperature above its melting point is essential for achieving proper fusion. Interestingly, they also note that optimal welding parameters paradoxically enlarge the flaw-free zone within the weld, which correlates with enhanced mechanical properties. Moreno-Moreno et al. /31/ introduce a non-rotational shoulder tool to isolate the effects of rotational and welding speeds on HDPE welds. Their conclusions emphasise that rotational speed exerts a far greater influence on material properties than welding speed, with higher speeds reducing crystallinity in the stir zone. Despite producing defect-free welds, the joints exhibit brittle fracture behaviour, indicating potential trade-offs between structural integrity and ductility. Mehdikhani et al. /32/ applies orbital friction stir welding (OFSW) to HDPE and analyses its impact on the material's crystalline structure. Their results show that the weld zone's crystallinity slightly increases relative to the base material, with no detectable chemical degradation, suggesting that OFSW preserves the polymer's molecular integrity. Nugroho et al. /33/ compare single- and double-side welding techniques for HDPE. Double-side welding not only improves flexural and tensile strength but also minimises angular distortion, whereas single-side welding consistently produces root defects due to incomplete material consolidation on the unprocessed side. Given the time-consuming and costly nature of FSW experimentation, researchers have increasingly turned to statistical methods for optimisation. Muchhadiya et al. /34, 35/ utilise the Taguchi method to design experiments, identifying rotational speed as the most influential parameter for maximising weld quality. Building on this, Muchhadiya et al. /34, 35/ develop a quadratic model incorporating feed speed, tool plunge depth, and their interactions. Through ANOVA, they validate the model's effectiveness in predicting and optimising FSW outcomes for HDPE. Similarly, Raouache et al. /36/ employ ANOVA to assess parameter significance, concluding that rotational speed has a statistically dominant effect on tensile strength, while welding speed shows negligible impact. This collective focus on statistical frameworks underscores their utility in reducing experimental iterations and costs.

The majority of friction stir welding studies are addressed to metals especially for aluminium and its alloys, which led to insufficient works on other materials such as polymers. This work will try to explain the effect of friction stir welding on the tensile strength and elongation of high density polyethylene. We shall focus on the effect of pin form, rotational speed and welding speed along with an analysis of variance to see the contribution of each parameter on the final weld.

## MATERIALS AND METHODS

### Materials

High-density polyethylene (HDPE) is chosen as the base material due to its excellent weldability, chemical resist-

ance, and lightweight properties. It is widely used in various industries, including piping, automotive, and packaging applications. In this study, 100 mm (length)  $\times$  50 mm (width)  $\times$  6 mm (thickness) HDPE plates are welded using FSW. The plates are cut from a pipe manufactured by CHIALI Group, Sidi Bel-Abbes, in accordance with Algerian standards NA7700-2 /37/. Tensile tests are realised (Fig. 1), and the mechanical properties of the material are given in Table 1. This material was largely tested and studied in previous research /38-40/.

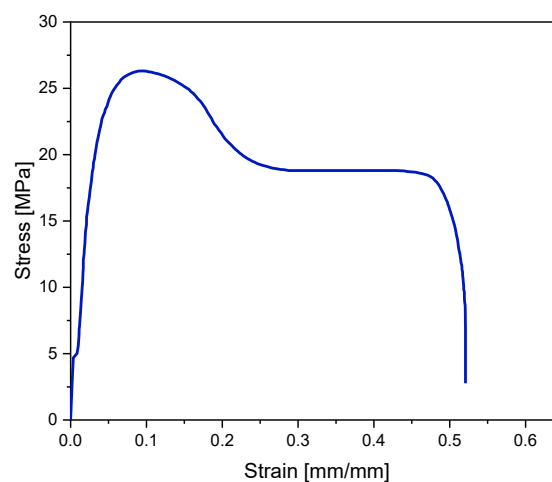


Figure 1. Stress-strain curve of a non-welded specimen.

Table 1. HDPE mechanical properties.

Material	Density [kg/m <sup>3</sup> ]	Yield strength [MPa]	Ultimate tensile strength [MPa]	Ultimate elongation [%]
HDPE	956-961	22.24	26.66	54.73

Two tools made from S235 structural steel are used to weld the plates. The tools have different pin profiles: one is cylindrical (Fig. 2a) and the other is hexagonal (Fig. 2b). All the dimensions of the tools can be found in Fig. 2.

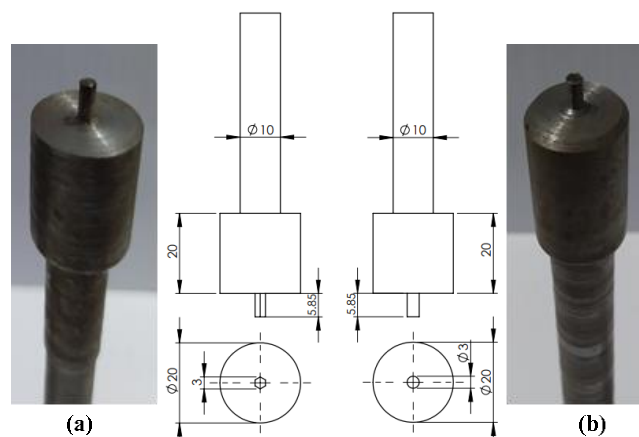


Figure 2. Welding tools: a) cylindrical pin; b) hexagonal pin.

### Design of experiments

The design of experiments is generally carried out during a complex and expensive experimental study, it allows us to minimise the number of tests while maintaining the effectiveness of the results, and these results are verified using a statistical method /41/. These methods will greatly reduce the work to be done because these chosen variables are modified

together instead of just one at a time and will allow us to understand the impact of the variables on each other, the DoE determines the relationship between factors affecting a process and the output of that process. It is widely used for optimising processes, identifying significant factors, and enhancing performance, /42/.

A general  $2^3$  factorial design is implemented for this study. The rotation speed (R), welding speed (W), and the geometry of the tool pin (G) are the variables introduced into the factorial plan, the ultimate tensile strength (UTS) and the ultimate elongation (UE) are the response we want our plan to predict. The parameter that represents the geometry of the tool pin (G) is defined as the number of faces on the pin profile, excluding the bottom face. This method offers a quantitative way to differentiate between various pin designs and assess their impact on weld quality, those for the cylindrical pin  $G = 1$  as it has a single continuous surface, and  $G = 6$  for the hexagonal prism pin profile corresponding to its 6 distinct flat faces, by defining G this way it will facilitate the establishment of correlations between pin design, process parameters, and weld performance. Two levels of rotational speeds (720, 1100 RPM) and two levels of welding speeds (20, 40 mm/min) are also chosen. The value of input process and their levels are represented in Table 2. The choice of welding parameters is guided by a previous numerical study aimed to determine optimal parameters in thermal point of view, /43/.

Table 2. Welding parameters and their levels.

The parameters	Symbol	Level	
		Low (-1)	High (1)
Rotation speed (RPM)	R	720	1100
Welding speed (mm/min)	W	20	40
Geometry	G	cylindrical (1)	hexagonal (6)

#### Experimental procedure

The friction stir welding (FSW) experiments on HDPE are conducted on a milling machine in a flat plate butt joint configuration, with proper clamping applied above the test plates to inhibit distortion and to maintain a consistent shoulder plunge depth, thus ensuring welding accuracy. The plunge depth is held constant at 0.1 mm for all experiments, and no tilt angle is given during welding (tilt angle =  $0^\circ$ ). Moreover, a dwell time of 8 s is provided in order for proper softening of the material before proceeding to welding. Rotating speed, welding speed, and tool geometry were the only parameters altered during the procedure, with all other parameters remaining constant. Figure 3 shows the experimental set-up prior to welding. After welding, specimens were maintained clamped for cooling for 15 minutes before removal to ensure uniform cooling and to minimise residual stresses. This procedure was repeated for all experimental conditions.

#### Tests carried out

After welding the plates, samples were extracted for tensile testing in accordance with ISO 527-1 (Fig. 4) /44/ to evaluate the mechanical properties of the welded joints. The tensile testing is carried out on a universal testing machine produced by Shimadzu, PWG-100 kN, so that the force application and displacement measurements can be very

accurate. Specimens are prepared to the standard dimensional requirements, and any surface irregularities are removed prior to testing to eliminate any tendency for initiation of a premature failure. The tests are performed at a crosshead speed of 5 mm/min to measure accurately the UTS and UE of the welded joints. The fracture location is also examined to judge the integrity of the welds for any suspected defect or weakness. The tensile test results are used to relate the effects of different rotational speeds, welding speeds, and tool geometries on the mechanical behaviour of the FSW HDPE joints.

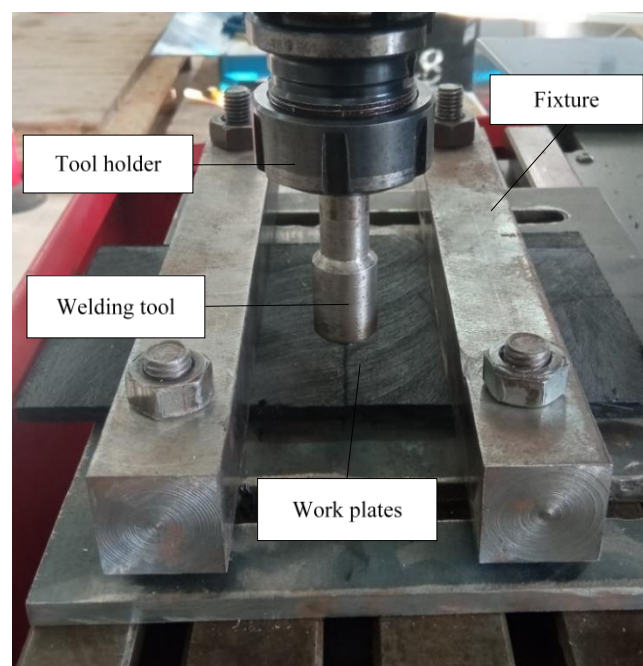


Figure 3. Experimental setup.

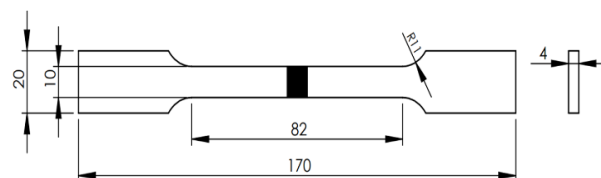


Figure 4. Standard tensile test specimen dimensions.

## RESULTS AND DISCUSSION

### Welding surface defects

Figure 5a shows a series of overlapping circular patterns (tool marks) and irregularities along the weld, this phenomenon is called weld crowns, weld crowns are generally not considered as welding defects unless if they are too excessive which is the case we have, the crowns are inconsistent and uneven, it is found that the weld crown is directly affected by the transversal speed, a high transversal speed will not provide sufficient heat to the welding joint /45/, in Fig. 5b the excess material of the softened HDPE forms what is known as flashes on the sides of the weld /46/. The main cause of flashes is high rotational speed. Increasing the rotational speed increases heat generation leading to an excessive softening of the material. Another cause of the apparition of flashes is an insufficient tilt angle as it is reported in previous works /47/. Figure 5c shows a continu-

ous cavity along the weld line. This defect is known as tunnel defect. Tunnel defects are directly affected by heat input. It is found that a too high transverse speed did not generate sufficient heat leading to less plasticised material. The same thing is observed for too high rotational speed /48/ in Fig. 5d. Looking at the material, it seems burned and has a texture more like a milled surface than a proper weld. This issue is mainly due to having both the rotational speed and welding (transversal) speed set too high. When these parameters are excessive, the heat generated through friction does not effectively soften and plasticise the HDPE as intended. Instead of melting or reaching a suitable plastic state, the surface of the HDPE undergoes thermal degradation while the layers beneath stay unaffected. As a result, the tool ends up mechanically scraping or cutting the material, creating rough, uneven surfaces with burn marks and a lack of proper material fusion. Figure 5e outlines the presence of voids in the weld line especially at the beginning of the weld. In a standard FSW tool, the outer regions of the welded material experience faster cooling rates than the inner sections. This temperature gradient can lead to uneven material properties, potentially causing residual stresses and defects such as voids, porosity, and incomplete fusion /8/. Unlike other figures, Fig. 5f represents what a good weld looks like, with minimal amount of defects and a good welded surface.

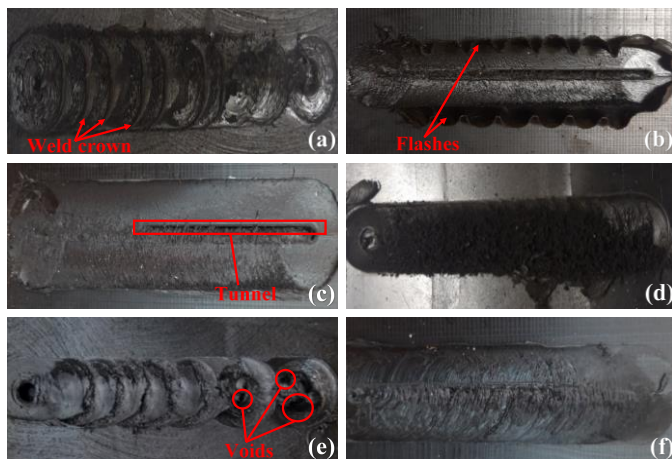


Figure 5. Welding surface defects.

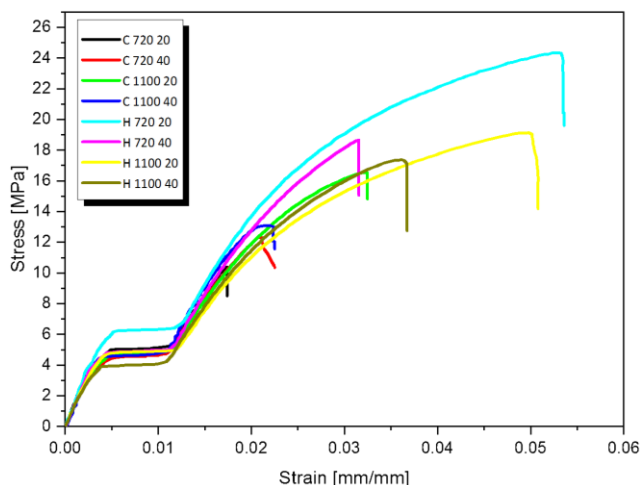


Figure 6. Stress-strain tensile test for welded samples.

Tensile test results

After conducting tensile tests on HDPE welds, a detailed table is created (Table 3) to show the key mechanical properties, such as UTS, the ratio of UTS to the base material (UTS/UTSb), UE, and the ratio of UE to the base material (UE/UEb). These measurements are taken for various rotational speeds (R), welding speeds (W), and tool geometries (G). Figure 6 is included to present the tensile test results of all welded specimens.

The analyses of the ultimate tensile strength show that there is a downturn in performance when compared to non-welded HDPE. This decrease in strength is primarily due to the welding process itself. In almost all tests, the HDPE specimens that were welded exhibited lower tensile strength, which can mainly be attributed to the formation of various defects, such as voids, lack of fusion, and residual stresses realised during welding. Moreover, the welding procedure changes the microstructure of the materials by taking into account the crystalline morphology and orientation of the polymer molecules and introducing other modifications that contribute to diminished mechanical properties. These microstructural changes reduce weld joint integrity and contribute to its weakness.

When it comes to the ultimate elongation, the best result we could get is 9 % of a non-welded specimen, the material is exhibiting brittle behaviour, with a minimal strain before fracture. This phenomenon can be observed in Fig. 7. The welded HDPE lost its high ductility which was one of its most important properties. This phenomenon is caused by different welding defects and mainly by the increasing the degree of crystallinity, resulting in hard, stiff and less ductile behaviour, /49/.

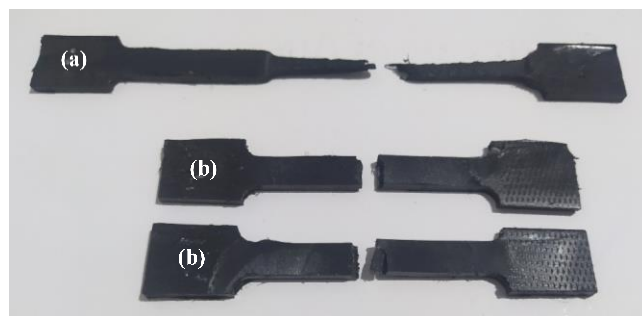


Figure 7. Tensile test specimens: a) non-welded specimen; b) welded specimens.

Table 3. Tensile test results.

Tests number	G [-]	R [RPM]	W [mm/min]	UTS [MPa]	UTS/UTSb [%]	UE [%]	UE/UEb [%]
1	1	720	20	9.00	34	1.75	3
2	1	720	40	11.40	43	2.03	4
3	1	1100	20	11.09	42	3.61	7
4	1	1100	40	12.55	47	3.04	6
5	6	720	20	23.07	87	5.06	9
6	6	720	40	18.68	70	3.04	6
7	6	1100	20	12.30	46	2.67	5
8	6	1100	40	16.28	61	3.49	6

Effect of welding parameters on UTS and UE

The graph in Fig. 8 shows the average UTS for the welded HDPE, it highlights noticeable patterns influenced by both

rotational speed (R) and the shape of the tool pin (G). At 720 RPM, the hexagonal pin shape achieves a higher UTS (around 21 MPa) compared to the cylindrical pin (about 10 MPa). This indicates that the enhanced stirring action and more effective material flow associated with the hexagonal shape improves joint strength. However, as the rotational speed increases to 1100 RPM, the UTS for the hexagonal pin falls significantly (approximately 14 MPa), whereas the cylindrical pin shows a slight rise (about 12 MPa). This drop in UTS for the hexagonal pin is likely due to excessive heat generation at higher rotational speed, which can cause the HDPE specimens to degrade, reduce molecular orientation, and potentially create defects as voids or incomplete fusion.

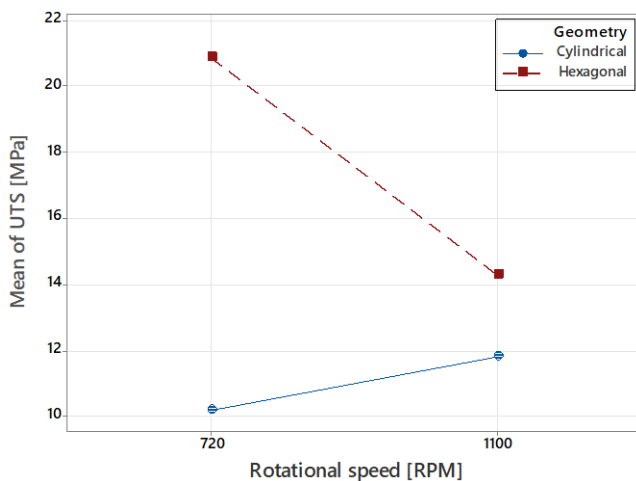


Figure 8. Effect of rotational speed on UTS.

In contrast, UE plot in Fig. 9 indicates an increasing trend in the cylindrical pin from 1.9 to 2.8 % with an increase in RPM, meaning improved ductility because of better material mixing, hence reduced residual stresses, at higher speeds. On the other hand, the hexagonal pin shows a reduction in UE from 4.1 to 3.1 %, which indicates that while initial welds at lower RPMs are favoured by enhanced flow and mixing, higher RPMs likely develop brittleness due to overheating and stress concentration around the pin edges.

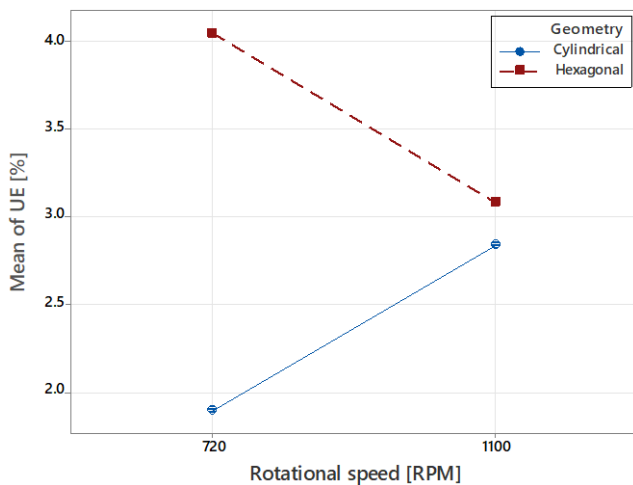


Figure 9. Effect of rotational speed on UE.

The impact of tool shape and welding speed on HDPE welding is depicted in Fig. 10. UTS values are consistently

higher for hexagonal pin geometry (approximately 17.6 MPa at 20 mm/min and 17.4 MPa at 40 mm/min) than for cylindrical pin geometry (approximately 10 MPa at 20 mm/min and 12 MPa at 40 mm/min). This implies that the hexagonal pin improves joint strength through more effective heat distribution and plastic deformation. The slight decrease in UTS of the hexagonal pin at higher welding speeds is attributed to less heat input and insufficient time for proper consolidation during which minor defects, such as voids and weak interfacial bonding, arise. However, the cylindrical pin shows a positive trend of UTS with increasing speed, which could, for one, be determined by thermal balance restoration and better material compaction occurring when welding speed is increased.

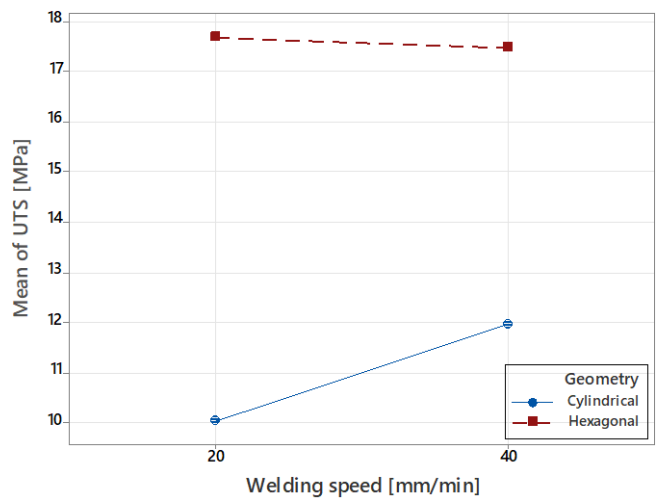


Figure 10. Effect of welding speed on UTS.

UE plots represented in Fig. 11 reveal that all pin geometries witness drop in ductility with increase in welding speed. The hexagonal pin drops from approximately 3.9 % to 3.3 %, while cylindrical pin diminishes from roughly 2.7 % to 2.1 %. This drop in UE could be related to the increasing rapidity of cooling rates and lower heat input at higher speeds, which could be attributed to increasing brittleness and residual stresses within the weld zone. The superior UE of the hexagonal pin, especially at lower speeds, points at improvement of mixing materials as well as more

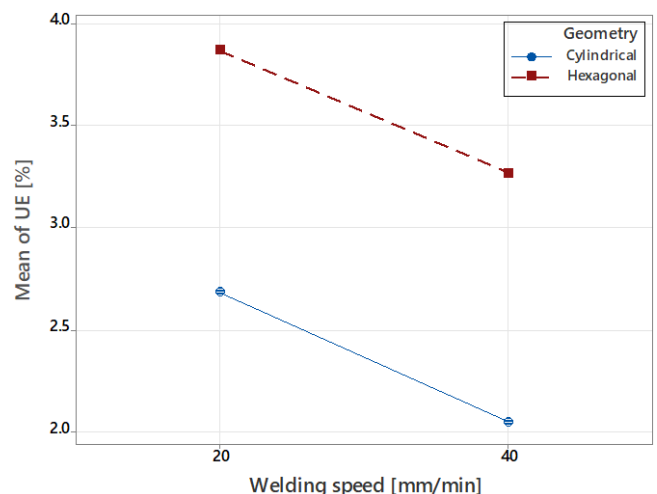


Figure 11. Effect of welding speed on UE.

uniform relative stress due to its geometric influence on the stirring process. Overall, the hexagonal pin geometry optimises strength and ductility at lower welding speeds, while the cylindrical pin benefits from moderate speed increases to achieve better mechanical performance. Balancing heat generation, material flow, and defect control is crucial for optimising FSW parameters in HDPE welding.

Regression equation

Following the completion of the weld joining process, regression analysis is carried out to evaluate the relationship between the process parameters (G, R,W) and the resulting mechanical properties (UTS, UE). This analysis is based on experimental data collected from the tensile tests and elongation measurements. The Minitab 20.1 software is used to conduct the calculation for the equations. Two equations are generated, Eq.(1) for predicting UTS and Eq.(2) for UE.  $UTS = -11.74 + 12.58G + 0.0197R + 0.454W - 0.01167G \cdot R - 0.2444G \cdot W - .00037R \cdot W + 0.000245G \cdot R \cdot W$ , (1)  $UE = -10 + 4.495G + 0.01438R + 0.2983W - 0.004688G \cdot R - 0.1113G \cdot W - 0.000363R \cdot W + 0.000123G \cdot R \cdot W$ . (2)

To validate the regression equations, two other experimental tests are carried out under new process conditions that are not accounted for in the original dataset. The validation is achieved by comparing the results of validation tests to the predicted values derived from regression models. Table 4 summarises the experimental and predicted results.

The findings indicate that both regression equations demonstrate excellent predictive performance, particularly in estimating the UE. Predicted UE values closely match the experimental data, highlighting the model’s strong capability in capturing the relationship between process parameters and elongation behaviour. Overall, Eq.(1) often yields UTS values that were lower than expected. This discrepancy might be due to the model’s inadequate response to some key factors or the presence of nonlinear effects that were not fully accounted for in the regression analysis. In contrast, Eq.(2) generally produces slightly higher-than-expected UE results. Although the overestimation was minor, it indicates that the model could be overfitting certain data points or emphasising particular process parameters, resulting in overly optimistic predictions in some tests.

Table 4. Comparison of experimental and regression equation predicted results.

Tests	UTS (exp.)	UTS (pred.)	Acc.	UE (exp.)	UE (pred.)	Acc.
C 1100 RPM 30 mm/min	13.51	11.82	88%	15.76	14.29	91%
H 1100 RPM 30 mm/min	2.59	2.8375	91%	2.98	3.082	97%

Analysse of variance

Statistical analysis provided in the Pareto Chart (Fig. 12) and ANOVA table (Table 5) describes an assessment of the effects of tool pin geometry (G), rotational speed (R), and welding speed (W) on the UTS of friction stir welded HDPE. The Pareto chart of standardised effects shows that factor G (tool pin geometry) has the highest impact on UTS, followed by interaction effects associated with G and R. All effects on UTS with values above the red threshold line (2.306) are considered statistically significant at  $\alpha = 0.05$ .

The ANOVA has validated the result that the overall model is significant ( $p < 0.05$ ) with a very high coefficient of determination ( $R^2 = 94.74\%$ , adjusted  $R^2 = 90.13\%$ ) showing that the chosen factors manage to explain well the variation in UTS.

Table 5. ANOVA of ultimate tensile strength (UTS).

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contrib.	Remarks
Model	7	307.929	43.99	20.58	0	95%	Signif.
Linear	3	200.504	66.835	31.26	0	62%	Signif.
G	1	172.845	172.845	80.84	0	53%	Signif.
R	1	24.698	24.698	11.55	0.009	8%	Signif.
W	1	2.962	2.962	1.39	0.273	1%	Insignif.
2-Way Inter.	3	85.738	28.579	13.37	0.002	26%	Signif.
G*R	1	67.427	67.427	31.54	0.001	21%	Signif.
G*W	1	4.544	4.544	2.13	0.183	1%	Insignif.
R*W	1	13.767	13.767	6.44	0.035	4%	Signif.
3-Way Inter.	1	21.688	21.688	10.14	0.013	7%	Signif.
G*R*W	1	21.688	21.688	10.14	0.013	7%	Signif.
Error	8	17.104	2.138			5%	\
Total	15	325.033				100%	\

S = 1.46219 ; R-sq = 94.74% ; R-sq(adj) = 90.13% ; R-sq(pre) = 78.95%

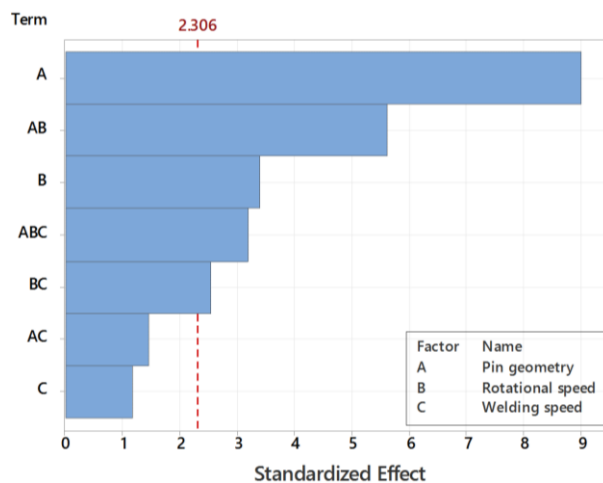


Figure 12. Pareto chart of standardised effects of UTS with  $\alpha = 0.05$ .

Among the different factors studied, it is found that tool pin geometry (G) contributes most to UTS (53 %) with very highly significant effects ( $p < 0.001$ ), endorsing its predominant role in tensile strength enhancement. This is followed by rotational speed (R) which is identified to be significant ( $p = 0.009$ ), contributing 8 % to the variability of UTS. On the other hand, the influence of welding speed (W) upon UTS is insignificant ( $p = 0.273$ ) and only contributes 1 % to the variability, meaning that within the range evaluated, changes in welding speed barely influence the tensile performance of the welded HDPE.

It is instructed here that GR (G-R interaction) has contributed more than any other two-way interaction (21 %,  $p = 0.001$ ) to UTS. The other statistically significant interaction, RW (R-W interaction), has made a comparatively minor contribution (4 %,  $p = 0.035$ ). The G-W interaction is not significantly different ( $p = 0.183$ , contribution of 1 %), meaning that no noticeable direct influence on UTS due to welding speed is induced, regardless of the pin geometry used. Finally, the three-way interaction (GRW) manifests a statistically significant effect on UTS ( $p = 0.013$ ) and contributes

some 7 %, indicating a rather complex relationship among all the three parameters where their combinations seem to affect UTS.

The very low residual error (5 %) as regards the overall variability in this analysis affords another good argument for backing up the model. Additional to this, the findings are further supported by the low standard deviation ( $S = 1.46219$ ) and high predictive capability ( $R^2_{pred} = 78.95\%$ ). In summary and conclusion, the results suggest that the most important parameter influencing UTS is tool pin geometry; rotational speed is the next important one. The significant interaction observed between the two parameters G and R implies that it is important to optimise these two jointly for the attainment of higher tensile strengths in friction stir welded HDPE. That W is found to be insignificant indicates that its effect will be inconsequential for optimising the process, which should therefore focus primarily on tool geometry and rotational speed.

The Pareto chart for the UE response in Fig. 13 clearly indicates that the most significant factor-influence is tool pin geometry G, followed by the three-way interaction GRW and a two-way interaction GR. The reference red line at 2.306 marks the threshold for statistical significance at 0.05 level of alpha; any effect exceeding this value is considered significant. The chart indicates that G has the highest standardised effect, confirming its unique and potent influence on elongation. A significant three-way interaction G\*R\*W indicates that the parameters have a rather complex relationship, with their joint contribution being critical to UE.

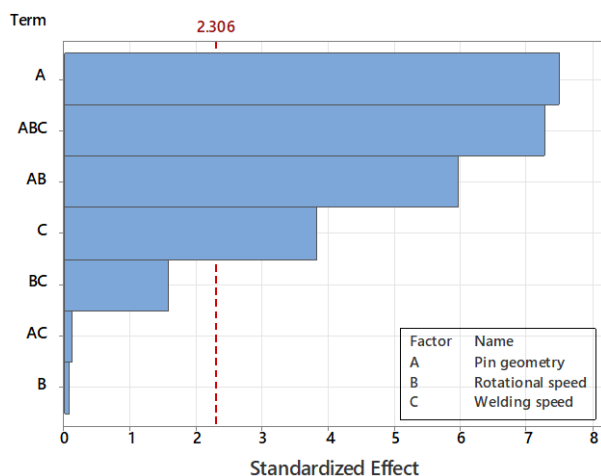


Figure 13. Pareto chart of standardized effects of UE with  $\alpha = 0.05$ .

In addition, the Pareto chart indicates that GR interaction is greater than the threshold and thus is supported by the ANOVA table (Table 6) for significance. The other factors such as R and their interactions, like GW and R\*W, are all low at their standardised effects without crossing significance threshold. This is further confirmed by the ANOVA results, which show them to be insignificant. The welding speed W, found significant in ANOVA, exceeds the reference line in the Pareto chart too, confirming its mean contribution to elongation behaviour.

The combined insights from Pareto and ANOVA show that the geometry has more effect on elongation, while the rotational speed alone is insignificant. Rotational speed, how-

ever, interacts with G significantly, meaning that optimising UE will need both adjustments because of their simultaneous interaction. In addition, significant three-way interactions highlight the fact that all three welding parameters must always be combined for maximum elongation in a case of friction-stir welded HDPE.

Table 6. ANOVA of ultimate elongation (UE).

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contrib.	Remarks
Model	7	16.6247	2.37496	23.16	0	95%	Signif.
Linear	3	7.2758	2.42526	23.65	0	42%	Signif.
G	1	5.7648	5.7648	56.22	0	33%	Signif.
R	1	0.0006	0.00055	0.01	0.943	0%	Insignif.
W	1	1.5104	1.51044	14.73	0.005	9%	Signif.
2-Way Inter.	3	3.913	1.30435	12.72	0.002	22%	Signif.
G*R	1	3.6557	3.65574	35.65	0	21%	Signif.
G*W	1	0.0013	0.00126	0.01	0.914	0%	Insignif.
R*W	1	0.256	0.25604	2.5	0.153	1%	Insignif.
3-Way Inter.	1	5.4359	5.43589	53.01	0	31%	Signif.
G*R*W	1	5.4359	5.43589	53.01	0	31%	Signif.
Error	8	0.8203	0.10254			5%	\
Total	15	17.445				100%	\

$S = 0.320218$ ;  $R-sq = 95.30\%$ ;  $R-sq(adj) = 91.18\%$ ;  $R-sq(pre) = 81.19\%$

CONCLUSIONS

In this research study, the influence of the FSW process parameters: tool pin geometry (G), rotational speed (R), and welding speed (W) on mechanical properties, such as UTS and UE is determined mainly for high-density polyethylene (HDPE) welds. The findings demonstrate the remarkable effect of these parameters on weld quality, defect formation, and mechanical performance.

Among all parameters considered in the study, tool pin geometry is the single-most factor affecting UTS and UE. The hexagonal pin always gave better flow of material and consequently better mechanical properties over the cylindrical pin, especially at lower rotational speed. However, excessive heat generated at higher speeds weakened most welds, leading to defects such as voids, flashes, and lowered mechanical strength. Rotational speed is therefore critical in the balancing of heat, where beyond some optimal speeds, the increase results in higher level of material plasticisation but too much degradation by heat and ultimately lower quality welds. Welding speed gave a lesser but still very important effect, such as development of defects where very high speeds reduce material fusion and thus elongation.

The results of the tensile test prove that configuration welded HDPE had lesser UTS and UE than the base material on which it was needed mainly to microstructural changes and flaw formation. The best mechanical properties of the hexagonal pin at moderate speeds of rotation and welding are optimised for material flow and heat distribution. regression modelling and ANOVA were some of the techniques for statistical analysis that were utilized in the study to validate relationships of process parameters with mechanical properties and high accuracy in the prediction of UTS and UE. The study also reveals very strong interaction effects especially between tool pin geometry and rotational speed and puts a high demand for the optimisation of parameters in FSW.

This is meant to provide great avenues for ideal understanding of the FSW of HDPE, showing it can be well optimised for polymer welding while also bringing up factors that can be optimised related to joint strength and ductility. Further studies should investigate other pin geometries, temperature monitoring methods, and complex modelling to bring more refinements in FSW process parameters to improve weld performance.

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