Kufa Journal of Engineering
Vol. 17, No. 2, April 2026, P.P. 275-291
Article history: Received 11 February 2025, last revised 5 May 2025, accepted 15 July 2025

EFFECT OF REINFORCEMENT MATERIALS AND PROCESS PARAMETERS ON THE WEAR RATE OF POLYETHYLENE SURFACE COMPOSITES MADE BY FRICTION STIR PROCESS

Abdulbasit Abdulqadir Hamza[1] and Shawnam Rashied Jalal[2]

[1] Department of Mechanical and Mechatronics Engineering, Engineering College, Salahaddin, University, Erbil, Iraq, Email: abdulbasit.hamza@su.edu.krd

[2] Department of Mechanical and Mechatronics Engineering, Engineering College, Salahaddin, University, Erbil, Iraq, Email: shawnam.jalal@su.edu.krd

https://doi.org/10.30572/2018/KJE/170216

ABSTRACT

This study employed the friction stir approach in conjunction with a stationary shoe tool system to fabricate high-density polyethylene matrix surface composite with adding various filler material particles, such as copper, graphene, silicon carbide, and silicon dioxide. Here, L9 Taguchi method was used to design of experiment and to show the effect of FSP parameters such as tool rotational speed, traverse speeds, and amount of particles on the wear rate behavior. According to the findings, fabricated HDPE composite's wear resistance have improved due to the presence of hard particles in the HDPE sheet. At the optimum set of parameters (rotational speed of 679 rpm, traverse speed of 22 mm/min, and volume fraction of 20%), the wear rate of the HDPE/SiC composite decreased by 84.81 % when compared with the base HDPE. But, the (SiO_2, Cu, and C) reinforced composites wear rate decreased with (76.94, 72.61, and 69.74) % respectively.

KEYWORDS

Polymer matrix composite; Surface Composites; Friction stir process; Wear rate; Reinforcement particle materials; High-density polyethylene.

1. INTRODUCTION

One of the most common polymeric materials in the world, is the high-density polyethylene (HDPE) which has a wide range of applications in the automotive industry, aerospace, electronic applications, construction, oil and gas industries, piping, and tank construction due to its good performance, high chemical resistance, excellent flexibility, easy processability as well as low cost and recyclability (Gao et al., 2018, Zinati and Razfar, 2015). However, some specific surface or joint properties such as strength, hardness, hydrophilicity, wear resistance, and lubricity are typically required for heavy-duty applications. Unfortunately, pure HDPE usually do not have the mentioned properties (Habeeb and Al-Roubaiy, 2018). As a result, there is increasing interest in applying engineering technologies to change the morphology and surface or joint composition of polymers to enhance their mechanical and wear-resistant properties without changing the bulk properties of the base material (Hamza and Jalal, 2022). It is possible to alter the surface or joint composition of materials by adding secondary materials such as metallic, ceramic, or polymeric particles (Rashid, 2024). This leads to the creation of polymer matrix composites (PMCs), which is a novel material that has multiple uses in various sectors. (Ramesh et al., 2017, Salih et al., 2018).

Nowadays, polymer composites are used in a variety of applications, particularly in the application of tribological stress conditions on machine parts (Iftikhar et al., 2021). Understanding the wearing mechanism under certain sliding situations is crucial for these machine parts. Consequently, due to their reliability and long-lasting, polymeric composite materials are increasingly being used in the production of machine parts (Chan et al., 2021). The type of filler material (Yan et al., 2023), particle size (Li et al., 2023), particle shape, amount of reinforcement material , degree of dispersion , and composite production method all have a significant impact on the mechanical and physical properties of the fabricated composites (Alyali et al., 2012, Yadav et al., 2023). Polymeric composites have been made using a variety of methods, including melt mixing (Madhu et al., 2014, Qiao et al., 2023) mechanical milling (Kamal et al., 2022) , vacuum arc deposition (Wu et al., 2023), and injection molding (Zhou and Hrymak, 2024). In these methods, melting temperature is typically used for mixing operation, and each of these manufacturing processes produces various product flaws. Due to the high temperature, these methods frequently result in voids, air bubbles, incomplete product formation, non-uniform distribution of the additional reinforcement materials, and insufficient conditions for bond formation at the interfaces between the reinforcement materials and matrix. To prevent these defects, additional processing techniques and advanced processing equipments are required. In the last few years, a novel surface modification approach named friction stir process (FSP) has been suggested as a substituted process for solving the outlined defects, because it is performed at temperatures below the melting point of the matrix. FSP is a solid -state material processing technique based on friction stir welding (FSW) (Abolarin et al., 2025). It is environmentally friendly green processes which is used to modify the structure of the surface of the material and it is a very attractive process to fabricate surface composites by introducing hard particulates of reinforcement material on the surface of matrix material (Alyali et al., 2012). The majority of the research papers on the fabrication of surface composites by using friction stir process, focused on the FSP of metals. Unfortunately, there are still few investigations on FSP of polymers.

Gao et al. (Gao et al., 2015) used FSW to join the HDPE and ABS (Acrylonitrile Butadiene Styrene) sheets with the addition of carbon nanotubes (CNTs) as the reinforcement material, then investigated the joint's efficiency and reported joint flaws at various volume fractions of the reinforcement, such as agglomeration and cracks. The composite's tensile strength was diminished by mentioned flaws. However, the joint strength increased by 63% with a middling volume (1.5%) of reinforcement. The friction stir technique was used by (Rostamiyan and Zaferani, 2019) to produce a polymer surface hybrid composite by reinforcing polyethylene matrix with nano-clay, MWCNTs, and their combinations. The study examined the effects of tool rotation speed, travel speed, and reinforcement type on mechanical properties of composite. Results showed that higher rotation speeds improved tensile and flexural strength due to better particle dispersion, while higher travel speeds reduced these strengths due to insufficient time for mixing. In addition, pure CNTs offered the highest tensile and flexural strength. HDPE composites via Friction Stir Processing using Fe-Fe_3O_4 powder was fabricated by Saeed Karimi (Karimi et al., 2021). The FSP parameters were fixed as rotational speed of 630 rpm, traverse speed of 12 mm/min, and tilt angle of 2°), they investigated the mechanical and tribological properties. Results showed that, the tensile strength increased by 60% and 13% for samples with and without fillers and reinforced samples showed 80% lower wear rate. Hamed Aghajani (Derazkola and Simchi, 2018). Studied the effect of the nano-particles amount of Alumina (Al_2O_3) on the mechanical properties and wear behavior of the (poly (methyl methacrylate) based composite fabricated by FSP. The findings showed that the tensile strength, flexural strength, impact energy, and hardness of PMMA-based nanocomposites grew steadily with increasing nanoparticle volume percentage. Simultaneously, the wear behavior reduced when the volume percentage of nanoparticles increased. However, different reinforcement materials on polyethylene matrix by FSP has not been reported so far. In this study, different material particles including (graphene (C), silicon carbide (SiC), silicon dioxide, and copper) were added as the reinforcement to the high-density polyethylene (HDPE) matrix by using the FSP technique to fabricate polymer matrix composite (PMC). This study is aimed to investigate:

- The influence of FSP parameters (tool rotational speed, tool linear speed, and amount of reinforcement particles) on the wear rate of the fabricated composites.
- The optimum set level of the selected parameters and determination of the percentage contribution of each parameter on the output performance.
- The effect of filler material and selecting the best filler in terms of wear resistance.

In addition to the aforementioned, the goal is to create a new class of polymer matrix composites by combining HDPE with various reinforcing elements. Additionally, a new type of polymer composite is anticipated to be introduced by this work, which may find use in a variety of sectors, including tribological ones.

2. MATERIALS AND METHODS

2.1. Materials

In this study, high-density polyethylene (HDPE) provided by the Turkish plastic company (TURKAY) was used as the polymer matrix. The supplied HDPE plates were sliced into sheets of (250, 80, and 10) mm, which were then used to make polymer surface composites. The powders that were used as reinforcement are shown in Fig. 1 and they include graphene (C), silicon carbide (SiC), silicon dioxide (SiO_2), and copper (Cu). Table 1 presents the information about the reinforcement powder used in this investigation

Fig. 1. Reinforcement powders materials

Table 1. Reinforcement powders specifications

Powder Name and Symbol	Average Particle Size (µm)	Purity (%)	Made in
Graphene (C)	10 - 45	over 99	India
Silicon carbide (SiC)		over 99	Japan
Silicon dioxide (SiO_2)		over 99	China
Copper (Cu)		over 99	Germany

Due to the absence of special machine for the FSP, an accessory as presented in Fig. 2 used to aid in securing the workpiece firmly and preventing it from sliding or moving as a result of the force produced during the FSP. It is composed of two special strips and a flat backing plate. The flat backing plate is fastened to the machine bed by four bolts and each strip firmly against the backing plate by three bolts.

Fig. 2. HDPE sheet clamping system

2.2. Experimental methods

The tool used in this work was constructed with two primary components: a stationary shoe and a cylindrical spinning tool. The tool shoulder is designed concavely to keep softened polymer material from escaping underneath it and to push it back into the treated area. Additionally, the conical pin shape with two grooves that improve friction at the tool-material interface and helps to decrease pileup and polymer sticking on the tool pin (Raza et al., 2018). Preventing the reinforcing particles from pushing out of the groove is the main purpose of the stationary shoe. The designed tool for FSP process is shown in Fig. 3. The mica is attached to the lower surface of the stationary shoe to avoid the possibility of a sticking occurrence between the polymer's surface and a stationary shoe. Based on the reinforcing material, Experimental work was divided into four groups.

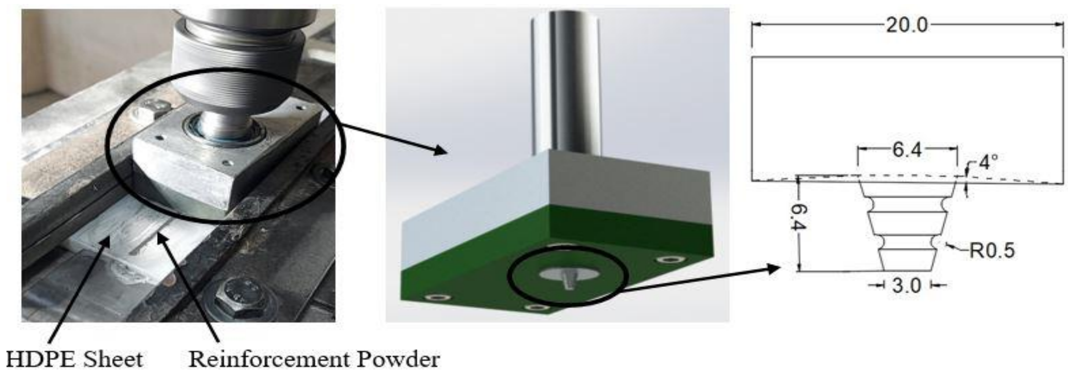

Fig. 3. Tool System with Geometry of Shoulder and Pin (Dimensions are in millimetres)

Considering the large number of FSP parameters, it was decided to use three factors with three levels as presented in Table 2. In order to reduce the number of experimental runs, the L9 orthogonal array from the Taguchi method was used to design the experimental work layout and the samples were prepared according to the design of experiment work layout.

Table 2. Processing parameters and their levels

Parameters	Symbol	Unit	Levels		
Rotational speed	Rs	rpm	478	679	925
Travers speed	Ts	mm/min	22	37	51
Volume fraction	Vf	%	10	15	20

To fabricate surface composites, the FSP procedures are schematically presented in Fig. 4. Initially, a channel was created in the center of the clamped HDPE plate along the processing direction with 2 mm in width and different depths which are (1.4, 2.1, and 2.8) mm Fig. 4a. Therefore, according to the following depths of the channel the volume fraction of the added particles were (10, 15, and 20) % which is calculated by using the volume fraction expression that is given below (Sharma and Tripathi, 2022). Then the reinforcement powders were placed and compressed into the created channels Fig. 4b.

Volume fraction % (theoretical) = (groove area / projected tool pin area) *100 (1)

Groove area = width of groove * depth of groove (2)

The projected area of the tool pin is equal to 28.5 mm^2 which was determined by using the SketchUp program.

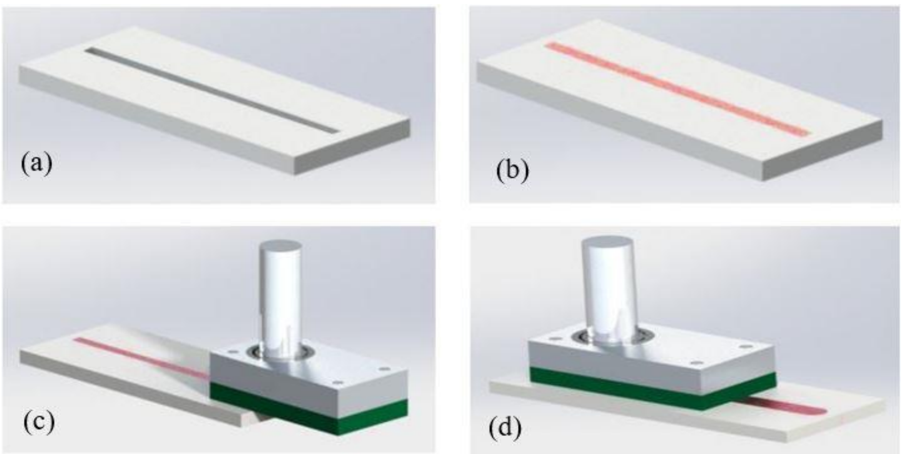

Fig.4. FSP steps for producing samples

At the last stage, the clockwise rotated tool probe was lowered gently until the tool probe completely entered the polymer matrix and the stationary shoe contacted with the matrix surface then the rotated tool stayed in its place for 30 seconds to soften the surface of the matrix Fig.4c and then the tool started to motion along the filled channel to produce a surface composite Fig.4d.

After finishing the FSP, the sheets were allowed to cool down to room temperature for almost 10 minutes and the produced sample as presented in Fig. 5 removed from the fixture.

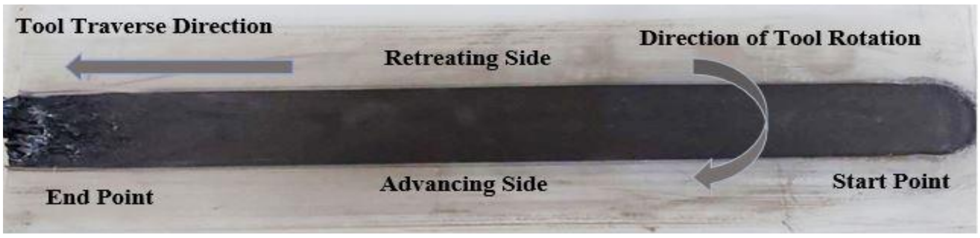

Fig. 5. Surface composite specimen fabricated by FSP.

2.3. Surface and cross-section appearance of fabricated Composites

Significant details regarding the material flow, reinforcing distribution, wear rate, and mechanical properties can be obtained from the surface and cross section of the resulting polymer composites. The quality of the fabricated surface composites depends on the generated heat. During the FSP process, heat is produced by friction between the tool and the matrix. Fig.6 displays Cu-reinforced samples surface and cross-sectional analysis which produced at different processing conditions. It is evident from Fig. 6(a) the reinforcing powders are not distributed equally over the FSP region for the composites that made with low rotating speed and high traverse speed. Moreover, causing the treated surface become shallow and scratched. On the other hand, the composite quality is not as good as intended because sufficient heat and time were not given for mixing the powders with the matrix. Fig 6(b) shows that by increasing the rotating speed and decreasing the traverse speed, excellent stirring action, particle distribution, and material flow were achieved. This result was attributed to the proper quantity of heat and enough time provided for the particles to mix with the matrix. Thus, the quality of the produced composites and their surface characteristics were improved. Furthermore, a uniform distribution of particles is observed from the cross section of the samples, excessive rotational speed weakens the fabricated composites due to burning the surface as seen in Fig.6(c), and it leads to decrease the quality of the composite.

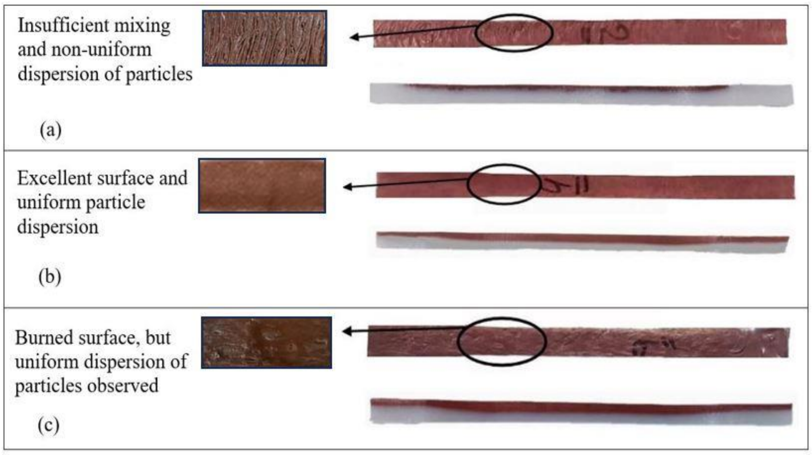

Fig. 6. Surface and cross section of composites at (a) low rotational speed (b) medium rotational speed (c) High rotational speed.

2.4. Performing Wear Test

The wear device (pin-on-disc) type (TQ-Model TE91) was used to perform the dry sliding wear tests under ambient temperature settings. The study adhered closely to ASTM G99-05 guidelines. The examined samples' beginning and final weights were measured using an electronic weight balance (Presica, Model XB 220A). The precision of the balance was up to four decimal places.

The samples used for the wear test were taken out of the middle of the processed zone. The wear samples were 10 mm in length and 4 mm in diameter. The test was performed under the applied load, sliding time, and disc rotational speed of (10 N, 15 min, and 150 rpm) respectively. The measured wear rate for pure HDPE was $1.104*10^{-6}$ g/cm. For calculating the wear rate (g/cm) of the produced surface composites, the weight loss of each specimen was determined and the weight loss was converted into the wear rate (g/cm) by using the following formula (Hussian et al., 2016):

$$Wr = (\Delta W / SD) \quad (3)$$

Wr = Wear rate (g/cm)

ΔW= W1 – W2 = Weight difference of sample before and after test (g).

W1 = mass before test (g)

W2 = mass after test (g).

$$SD = V \times t \times 100 \quad (4)$$

SD = Sliding distance (cm)

V = Linear velocity (m/min)

t = Running time

$$V = 2\pi \times r \times n \quad (5)$$

r = The distance between the disc's and the pin's centers, (m).

n = Rotational speed of the dick (rpm).

3. RESULTS AND DISCUSSION

3.1. Analysis of Signal to Noise (SN) of Wear

The study objectives were to determine the optimum level of the FSP parameters and the link between the wear rate of the produced surface composites and the FSP parameters. The Taguchi approach, highly recommends analyzing data by using signal-to-noise (S/N) ratio. This ratio evaluates how well the output converges to the goal under various noise levels. There are three status of performance characteristics in the analysis of the S/N ratio: smaller is better, larger is better, and nominal is better. The experiment's objective is to lower the wear rate, hence S/N ratios were calculated based on the "smaller is better" hypothesis. Table 3 displays the design of experiment orthogonal array for FSP parameters and outcomes as the wear rate and related S/N ratio for each reinforcement and experimental runs. The S/N ratios for wear rates were calculated by using MINITAB program, following the "smaller is better" formula.

$$S/N = -10 \text{ Log} \frac{1}{n} \Sigma yi^2 \quad (6)$$

where (n) signifies the number of observations, while 'yi' denotes the data.

Table 3. An orthogonal array of process variables for produced surface composites.

Exp. No	ω (rpm)	f (mm/min)	v (%)	Graphene (C) Powder		Silicon Carbide (SiC) Powder		Silicon Dioxide (SiO_2) Powder		Copper (Cu) Powder	
				W. rate g/cm * 10^{-7}	S/N ratio	W. rate g/cm * 10^{-7}	S/N ratio	W. rate g/cm * 10^{-7}	S/N ratio	W. rate g/cm * 10^{-7}	S/N ratio
1	478	22	10	6.086	124.31	3.255	129.75	4.176	127.80	5.449	125.27
2	478	37	15	5.945	124.51	2.861	130.87	3.910	128.15	5.166	125.73
3	478	51	20	6.653	123.54	3.397	129.37	4.317	127.30	5.803	124.72
4	679	22	15	3.609	128.85	1.699	135.40	2.648	131.54	3.255	129.75
5	679	37	20	3.397	129.37	1.679	135.5	2.619	131.63	3.043	130.33
6	679	51	10	4.600	126.74	2.335	132.63	3.185	129.94	4.105	127.73
7	925	22	20	4.812	126.35	2.679	131.44	3.397	129.38	4.317	127.30
8	925	37	10	5.803	124.72	3.255	129.75	4.176	127.58	5.237	125.62
9	925	51	15	6.440	123.82	3.185	129.94	4.105	127.73	5.591	125.05

Calculated S/N ratios as shown in Table 4 for each level of the parameters, are statistically significant. The effect size, or delta, was determined by comparing the maximum and minimum average values. Rank 1 was assigned to the factor with the largest delta value, rank 2 to the factor with the second-largest delta, and so on. The experiment's most important variables influencing the wear phenomenon were the rotating speed, traverse speed, and volume fraction of the additional powders respectively.

Table 4. Represents the Mean Response Value of S/N Ratio (Smaller is better)

Reinforcing Powder	FSP Parameters	Signal to Noise Ratio (dB)			Delta (Max-Min)	Rank
		Level 1	Level 2	Level 3		
Graphene Powder	Rotational Speed (RPM)	124.1	128.3	125.0	4.2	1
	Traverse Speed (mm/min)	126.5	126.2	124.7	1.8	2
	Volume Fraction (%)	125.3	125.7	126.4	1.2	3
SiC Powder	Rotational Speed (RPM)	130.0	134.6	130.4	4.6	1
	Traverse Speed (mm/min)	132.2	132.1	130.7	1.5	2
	Volume Fraction (%)	130.7	132.1	132.2	1.5	3
SiO_2 Powder	Rotational Speed (RPM)	127.7	131.2	128.2	3.4	1
	Traverse Speed (mm/min)	129.7	129.1	128.3	1.4	2
	Volume Fraction (%)	128.4	129.3	129.4	1.0	3
Cu Powder	Rotational Speed (RPM)	125.2	129.3	126.0	4.0	1
	Traverse Speed (mm/min)	127.4	127.2	125.8	1.6	2
	Volume Fraction (%)	126.2	126.8	127.5	1.2	3

Furthermore, Fig. 7, 8 displays the main effect charts for the average wear rate and the associated S/N ratios with input factors. From the Fig. 7, the relation between rotational speed and wear rate revealed a high wear rate at low rotational speeds (478 rpm), which is related to the low heat input and inadequate mixing that results in producing a rough surface and it increases friction between the sample and rotating disc, that lower composites' wear resistance.

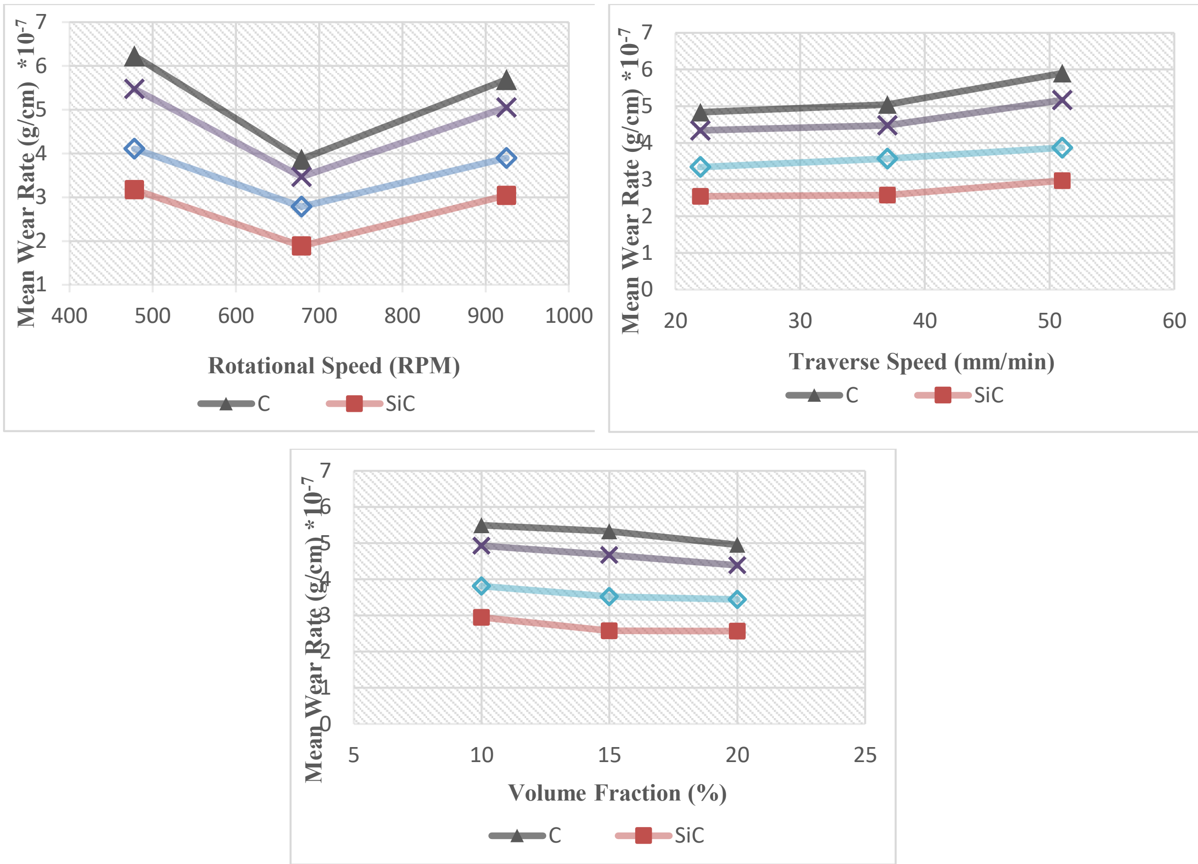

Fig.7. Main effects plot for wear rate of the fabricated composites (Data means)

However, as the heat is directly proportional to the friction between the FSP tool and the work sample, therefore increasing rotational speed up to (679 rpm) increases the amount of heat input. By doing this, the surface quality, particle mixing, and dispersion are all improved, resulting in composites with better wear resistance qualities as presented in the relation. Whereas, further increment in rotational speed (925 rpm), cause the stir zone to burn because more heat is generated and it is concentrated on the processed zone due to the polymers' limited heat conductivity. Additionally, the melted polymer being forced out of the stir zone by centrifugal force deteriorates the treated zone, produces surface flaws, and it causes to increase the wear rate.

From the relation between traverse speed and wear rate, it makes evident how wear rate increased when the traverse speed was increased up to 51 mm/min. This can be explained by the fact that, the low traverse speed provides more time for stirring action and particle dispersion in the matrix. What's more, low traversal speeds allow the polymer to consolidate and cause a low cooling rate and slower crystal development. Thus, this could enhance the spherulite structure of a polymeric composites and it leads to better mechanical and wear resistance qualities. Moreover, the relation between volume fraction and wear rate exhibits how wear rate decreased when the volume fraction was increased up to 20 %. This is explained by the fact that a dispersion of higher amount of hard particles over the same surface area and during the wear test these particles do not peel-off easily from the matrix and this means better wear resistance. As compared to the other reinforced composites, the HDPE/SiC composite exhibits superior wear resistance. Fig. 8 shows the relation between the S/N ratios with FSP factors. The Taguchi method states that the level that displays the highest signal-to-noise ratio is the ideal level for setting the FSP parameter and a similar result was reported by (Habeeb and Al-Roubaiy, 2018).

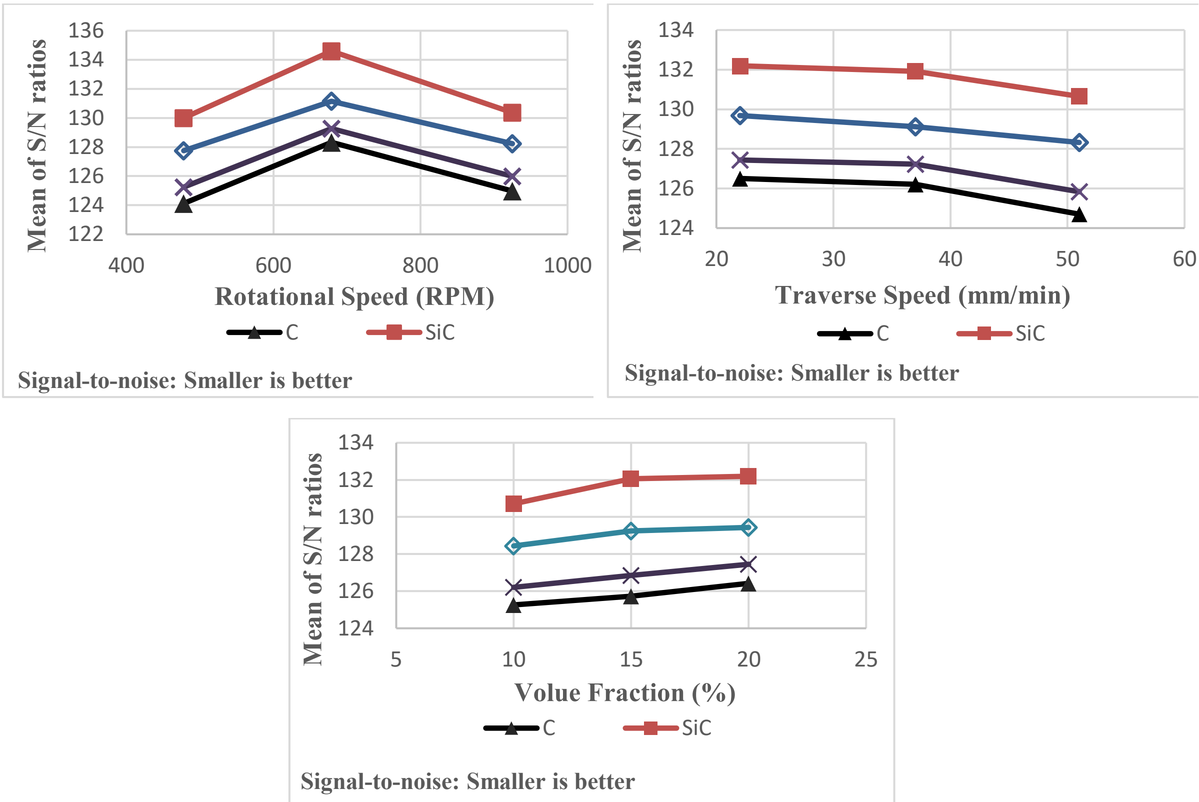

Fig. 8. Main effects plot for S/N rations at different FSP parameters (Data means)

Therefore, the rotational speed of (Rs_2 = 679 rpm), traverse speed of (Ts_1= 22 mm/min), and volume fraction of (Vf_3= 20 %) are the optimal set level of the FSP parameters in this study for all reinforcements, because the maximum S/N ratios were achieved at the mentioned levels.

Analysis of Variance (ANOVA) of Wear

One statistical method for assessing mean differences and estimating processes is ANOVA. The test's statistical significance is ascertained using it. The ANOVA is used to investigate the influence of FSP rotational speed, traverse speed, and volume fraction of the added particles on the wear resistance. By dividing the difference between specimen averages to the difference between specimens, the factor value (F-value) was determined. A higher F-value for a parameter indicates that it has a more significant impact on the quality of the product. Table 5 presents the F-value results for each type of powder.

Table 5. Presents ANOVA for S/N Ratios

Reinforcing Powder	Source	DF (Degree of Freedom)	Seq SS (Sequential Sums of Squares)	MS (Adjusted Mean Squares)	F (Factor value)	Contribution (%)
Graphene Powder	Rotational speed	2	29.6426	14.8213	647.83	79.37
	Traverse speed	2	5.6089	2.8045	122.58	15.02
	Volume fraction	2	2.0508	1.0254	44.82	5.49
	Error	2	0.0458	0.0229		
	Total	8	37.3480			
SiC Powder	Rotational speed	2	39.1403	19.5702	270.43	81.67
	Traverse speed	2	4.5778	2.2889	31.63	9.55
	Volume fraction	2	4.0616	2.0308	28.06	8.47
	Error	2	0.1447	0.0724		
	Total	8	47.9244			
SiO_2 Powder	Rotational speed	2	20.3155	10.1578	236.66	81.57
	Traverse speed	2	2.8069	1.4034	32.70	11.27
	Volume fraction	2	1.6950	0.8475	19.74	6.80
	Error	2	0.0858	0.0429		
	Total	8	24.9032			
Cu Powder	Rotational speed	2	27.5472	13.7736	317.01	79.83
	Traverse speed	2	4.5525	2.2763	52.39	13.19
	Volume fraction	2	2.3211	1.1606	26.71	6.72
	Error	2	0.0869	0.0434		
	Total	8	34.5078			

The contribution of each factors effect on the output performance of the products, was also determined. The confidence level within this study is 95%. According to the results presented in Table 4, The wear resistance of the fabricated samples was most significantly affected by the FSP tool's rotational speed, followed by traverse speed and volume fraction of the particles. The mentioned parameters are the crucial and controllable factors that must be consider during the FSP process.

4. CONFIRMATION TEST

A confirmation test is a follow-up experiment conducted after completing the main analysis or optimization process (such as a Taguchi method or ANOVA) to verify the accuracy and reliability of the predicted results. To perform the confirmation tests for wear resistance, FSP process parameters were adjusted to their ideal levels which are rotational speed 679 rpm, traverse speed 22 mm/min, and volume fraction 20% in order to produce the samples for conducting the confirmation tests. Three samples were created for each type of reinforcement powder, and the average result of the wear test were displayed in Table 6.

The Taguchi predicted optimum processing condition for wear rate gives an improvement in the performance characteristic results. From Table 5, it was observed that wear rate of predicted and optimal level of parameters is extremely close to one another. Error values are necessary for trustworthy statistical analyses and according to the references (Kıvak, 2014, Shahavi et al., 2016, Saurabh et al., 2022) must not exceed (10%). Therefore, the results obtained from the confirmation tests shows the successful optimization.

Table 6. Conformation test results for wear rate.

Fabricated Composites	Optimal process parameter		Error (%)
	Predicted	Experimental	
	Rs_2, Ts_1, Vf_3	Rs_2, Ts_1, Vf_3	
HDPE / Graphene composite Wear rate (g/cm) *10^{-7}	3.294	3.340	1.38
HDPE / SiC composite Wear rate (g/cm) *10^{-7}	1.654	1.676	1.31
HDPE / SiO_2 composite Wear rate (g/cm) *10^{-7}	2.502	2.545	1.69
HDPE / Cu composite Wear rate (g/cm) *10^{-7}	2.988	3.024	1.20

Fig.9 displays the SEM images at Taguchi-predicted ideal condition (679 rpm, 22 mm/min, 20%). Relative motion and shear stresses cause wear debris. The ideal state resulted in the least amount of wear, according to the analysis. It was also validated by the SEM picture. Fig. 9a shows the HDPE/C surface composite with the deepest and most severe wear scratches. In contrast, the HDPE/SiC surface in Fig. 9c displays smoother features and reduced wear. Moreover, it is evident that at the optimal FSP parameter settings, the added reinforcement particles were uniformly distributed along the fabricated surface composite.

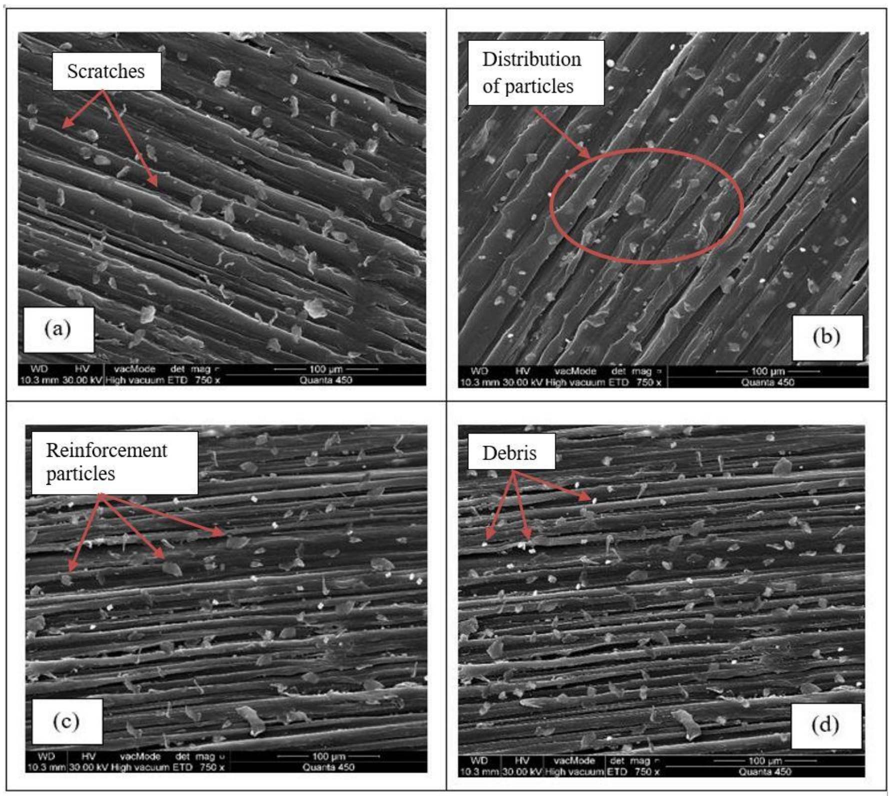

Fig. 9. Displays SEM pictures for various reinforcement particles: (a) HDPE/C composite, (b) HDPE/Cu composite, (c) HDPE/ SiO2 composite, and (d) HDPE/ SiC composite.

5. CONCLUSIONS

In this study, HDPE composites were successfully fabricated using the friction stir process by adding several reinforcing powder materials such as (Graphene, Silicon carbide, Silicon dioxide, and Copper) into the HDPE matrix. The effect of the FSP parameters such as tool rotational speed, tool traverse speed, and amount of the added reinforcing material on the wear resistance behavior were investigated. The Taguchi approach and ANOVA in MINITAB program were used to estimate the ideal level of FSP parameters and the percentage contribution of each process parameter on the output performance were also determined. The findings of this investigation can be summarized in the following points:

- Polymer surface composites were effectively fabricated by combining the friction stir process with a newly developed tool system that includes a stationary shoe-shaped shoulder and a tool with a concave shoulder and grooved conical pin geometry.
- The optimum set level of FSP parameters (rotational speed, traverse speed, and volume fraction) for minimizing the wear rate were 679 rpm, 22 mm/min, and 20%, respectively.
- Under all processing conditions and for all reinforced powders, the wear resistance of the produced composite samples rises (decreases the wear rate). This is attributed to the fact that these particles do not peel-off easily from the matrix during wear tests due to the good interfacial bonding between matrix and added particles.
- When it comes to wear resistance, silicon carbide reinforced composites outperform those made of silicon dioxide, copper, and graphene. The type of powder material, particle form, morphology, hardness, and other factors may be responsible for this. Additionally, the adhesion between the chemical groups in the matrix may have created an interfacial bonding as a result of a change in the nature of HDPE's bonding system.
- The most important factor for the creation of surface composites, according to the results of statistical analysis, was the rotational speed, which had a percentage contribution range of (79 to 82) % followed by traverse speed which had a contribution range of (9 to 15) %, and the volume fraction of the added powders which had a contribution range of 5 to 9 percent.
- According to the confirmation test results, the error between Taguchi predicted and the obtained value from the experiments of optimum set level of parameters was smaller than 10 % this indicating that the measured values were within the 95% confidence interval.

ACKNOWLEDGMENTS

The authors are grateful for the financial support towards the Mechanical and Mechatronics Engineering Department, College of Engineering. Salahaddin University, Iraq - Erbil. We wish to express our deepest thanks to the staff of the laboratories for their assistance.

6. REFERENCES

Abolarin, M. A. Ogunmola, B. Y. Alozie, N. S. Oluwo, A. Rajan, J. Jose, S. Oke, S. A. Agada, A. I. and Ibitoye, A. S. (2025) 'A CRITIC-BPNN APPROACH TO FRICTION STIR WELDING PARAMETRIC SELECTION AND PREDICTION USING AA6082-T6 MATERIAL', Kufa Journal of Engineering, 16(1),

Alyali, S. Mostafapour, A. and Azarsa, E. (2012) 'Fabrication of PP/Al2O3 surface nanocomposite via novel friction stir processing approach', International Journal of Advances in Engineering & Technology, 3(1), 598.

Chan, J. X. Wong, J. F. Petrů, M. Hassan, A. Nirmal, U. Othman, N. and Ilyas, R. A. (2021) 'Effect of nanofillers on tribological properties of polymer nanocomposites: A review on recent development', Polymers, 13(17), 2867.

Derazkola, H. A. and Simchi, A. (2018) 'Effects of alumina nanoparticles on the microstructure, strength and wear resistance of poly (methyl methacrylate)-based nanocomposites prepared by friction stir processing', Journal of the mechanical behavior of biomedical materials, 79(246-253.

Gao, J. Li, C. and Shen, Y. (2018) 'Investigations into the mechanical, morphological and thermal analyses of friction stir processing of high-density polyethylene composites', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 232(7), 1193-1200.

Gao, J. Li, C. Shilpakar, U. and Shen, Y. (2015) 'Improvements of mechanical properties in dissimilar joints of HDPE and ABS via carbon nanotubes during friction stir welding process', Materials & Design, 86(289-296.

Habeeb, B. A. and Al-Roubaiy, A. O. (2018) 'Effect of adding boron carbide (B4C) to polymer for producing surface composite by friction stir processing', THE IRAQI JOURNAL FOR MECHANICAL AND MATERIALS ENGINEERING, 18(3), 436-445.

Hamza, A. A. and Jalal, S. R. (2022) 'A review on manufacturing the polymer composites by friction stir processing', European Polymer Journal, 178(111495.

Hussian, M. K. Salim, R. K. and Jameel, W. W. (2016) 'Effect of graphite particles addition and process parameters on the mechanical properties of polyethylene/graphite surface composite fabricated by friction STIR processing', Journal of Engineering and Sustainable Development, 20(3), 155-167.

Iftikhar, S. H. Mourad, A.-H. I. Sheikh-Ahmad, J. Almaskari, F. and Vincent, S. (2021) 'A comprehensive review on optimal welding conditions for friction stir welding of thermoplastic polymers and their composites', Polymers, 13(8), 1208.

Kamal, A. Ashmawy, M. S, S. Algazzar, A. M. and Elsheikh, A. H. (2022) 'Fabrication techniques of polymeric nanocomposites: A comprehensive review', Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 236(9), 4843-4861.

Karimi, S. Arab, S. M. Hosseini Zeidabadi, S. R. and Javadpour, S. (2021) 'Tribological behavior and mechanical properties of friction stir processed HDPE/Fe-Fe3O4 composites', Synthesis and Sintering, 1(3), 176-182.

Kıvak, T. (2014) 'Optimization of surface roughness and flank wear using the Taguchi method in milling of Hadfield steel with PVD and CVD coated inserts', Measurement, 50(19-28.

Li, Z. Qi, X. Liu, C. Fan, B. and Yang, X. (2023) 'Particle size effect of PTFE on friction and wear properties of glass fiber reinforced epoxy resin composites', Wear, 532(205104.

Madhu, G. Bhunia, H. Bajpai, P. K. and Chaudhary, V. (2014) 'Mechanical and morphological properties of high density polyethylene and polylactide blends', Journal of Polymer Engineering, 34(9), 813-821.

Qiao, Y. Fring, L. D. Pallaka, M. R. and Simmons, K. L. (2023) 'A review of the fabrication methods and mechanical behavior of continuous thermoplastic polymer fiber–thermoplastic polymer matrix composites', Polymer Composites, 44(2), 694-733.

Ramesh, B. Elayaperumal, A. and Satishkumar, S. (2017) 'Drillability study of pultruded and sheet moulding compound thick polymeric composites', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 231(2), 268-285.

Rashid, W. T. (2024) 'OPTIMIZATION OF WEAR RESISTANCE OF ALUMINUM MATRIX COMPOSITE (AL-7050/10WT% EGGSHELL) BY STUDY OF EFFECT STIRRING SPEED AND STIRRING TIME', Kufa Journal of Engineering, 15(4), 83-97.

Raza, K. Shamir, M. Qureshi, M. K. A. Shaikh, A. S. and Zain-Ul-Abdein, M. (2018) 'On the friction stir welding, tool design optimization, and strain rate-dependent mechanical properties of HDPE–ceramic composite joints', Journal of Thermoplastic Composite Materials, 31(3), 291-310.

Rostamiyan, Y. and Zaferani, M. (2019) 'Fabrication of polyethylene-based surface composite reinforced by carbon nano-tube and nano-clay through friction stir processing', Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 233(4), 580-587.

Salih, S. I. Oleiwi, J. K. and Abd Alkhidhir, S. (2018) 'Comparative study of some mechanical properties of hybrid polymeric composites prepared by using friction stir processing', Journal of Advanced Research in Dynamic and Control Systems, 10(02), 1316-1326.

Saurabh, A. Joshi, K. Manoj, A. and Verma, P. C. (2022) 'Process optimization of automotive brake material in dry sliding using taguchi and ANOVA techniques for wear control', Lubricants, 10(7), 161.

Shahavi, M. H. Hosseini, M. Jahanshahi, M. Meyer, R. L. and Darzi, G. N. (2016) 'Clove oil nanoemulsion as an effective antibacterial agent: Taguchi optimization method', Desalination and Water Treatment, 57(39), 18379-18390.

Sharma, V. and Tripathi, P. K. (2022) 'Approaches to measure volume fraction of surface composites fabricated by friction stir processing: a review', Measurement, 193(110941.

Wu, C. Xu, F. Wang, H. Liu, H. Yan, F. and Ma, C. (2023) 'Manufacturing technologies of polymer composites—a review', Polymers, 15(3), 712.

Yadav, R. Singh, M. Shekhawat, D. Lee, S.-Y. and Park, S.-J. (2023) 'The role of fillers to enhance the mechanical, thermal, and wear characteristics of polymer composite materials: A review', Composites Part A: Applied Science and Manufacturing, 175(107775.

Yan, Y.-F. Kou, S.-Q. Yang, H.-Y. Shu, S.-L. Shi, F.-J. Qiu, F. and Jiang, Q.-C. (2023) 'Microstructure-based simulation on the mechanical behavior of particle reinforced metal matrix composites with varying particle characteristics', Journal of Materials Research and Technology, 26(3629-3645.

Zhou, S. and Hrymak, A. N. 2024. Injection Molding of Polymers and Polymer Composites. MDPI.

Zinati, R. F. and Razfar, M. R. (2015) 'Finite element simulation and experimental investigation of friction stir processing of Polyamide 6', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 229(12), 2205-2215.