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Estimating the wear behavior of hdpe composites reinforced with nano alumina fillers using taguchi method

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HIGHLIGHTS

- Test specimens consisting of HDPE + nano Alumina were prepared
- Experiments for wear behavior were designed using the Taguchi method
- Optimum conditions were 3% wt nano alumina, 20 N load, and 10 min sliding time
- SEM analysis showed that nano alumina improves wear resistance and hardness and prevents material loosening

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ABSTRACT

High-density polyethylene (HDPE), like other polymers is important in many applications due to its unique properties like low cost, weight, and availability. Recently, HDPE reinforced with ceramic fillers was considered in biomedical applications, especially in fabricating joint/bone replacements. Therefore, these applications required high wear resistance materials to serve under specific conditions. In this work, an optimization with Taguchi method was considered to associate the influence of nano alumina fillers, normal applied load, and sliding time on the wear rate values for hip joint replacement applications. In the first step, a TEM test was conducted on the prepared composites to ensure that the nanofillers were distributed within the matrix phase without agglomeration. The results indicated that the optimum wear resistance was seen in a composite made of HD PE +3% wt nano alumina fillers with a specific wear rate equal to 2.6652×10^{-6} in mm^3/N.m, as well as the most effective parameters on wear rate are arranged as nano content, applied load, and the sliding time. In contrast, SEM observation was considered to understand the wear mechanism. The addition of nano Alumina fillers prevented the test specimen surface from lessening by creating a transfer film separating the contact zone results from the self-lubricant behavior generated in prepared composites. In contrast, deep grooves, adhesive marks, and debris particles were generated in pure HDPE specimens, resulting in low hardness and weak wear resistance.

1. Introduction

In recent decades, polymers and their composites have invaded the industrial fields due to the high variation in their mechanical and physical properties, making the polymer composites required in many applications such as sports equipment, biomedical, ships, and aerospace [1-3]. High-density polyethylene (HDPE) is classified as one of the most popular thermoplastic polymers; the primary benefit is that it is cheap, flexible, easily workable, and has acceptable mechanical properties. Moreover, it is non-toxic and has good wear resistance. Due to its remarkable properties, HDPE is commonly reinforced with ceramic fillers, which are suggested for fabricating joint/bone replacements with high wear resistance [4-7]. Several studies investigated the influence of ceramic fillers on the wear resistance of HDPE composites such as, Srivastava [8] investigated the abrasive wear behavior of HDPE reinforced with nano alumina particles with weight fractions up to 5%, the results showed an improvement in wear resistance equals to 75% in comparative to unfilled HDPE, as well as, an overall enhancement in mechanical and thermal properties for the prepared HDPE composites. Mohammed [9] studied the influence of coating stainless steel by Polyethylene including nano alumina particles with different loading percentages on wear behavior; the results appeared that the combination of polyethylene with 3% nano alumina have the highest wear resistance in comparative to other loading percentages. Nabhan et al. [10] investigated the roll of nano Al_2O_3 particles with different weight fractions varies between 0.1and 0.5 on the tribological properties of HDPE composites, a noticeable improvement in hardness, coefficient of friction, and wear resistance accompanied the increasing in nano Al_2O_3 content. Shaji et al. [11] evaluated the effect of adding titanium dioxide on the mechanical and tribological properties of HDPE composites, they indicated that the increasing the titanium weight fraction improved the mechanical properties as well as the wear resistance in comparative to

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pure HDPE. Mahboba and Al-Shammari [12] indicated a clear improvement in wear resistance due to the addition of hybrid nanofillers consisting of Alumina and Zirconia p articles to HDPE composites, which is suggested to design a hip joint replacement with more than 15 years of estimation life. Pelto et al. [13] observed that the using of nano silica and nano titanium nitride fillers up to 2% wt increased the wear resistance of HDPE and enhanced the microstructure of the prepared composites by improving all the mechanical properties and reduced the friction coefficient. Yeshvantha et al. [14] observed the wear behavior according to the surface morphology of polyethylene/Al_2O_3 composites with (2, 6 and 10 wt%) filler content.

The results showed that increased alumina filler improves the surface resistance to wear and minimizes debris initiation. Joseph and Panneerselvam [15] considered Taguchi method to select the optimum operating conditions of HDPE reinforced with tungsten particles under the influence of abrasive wear; the increase in tungsten percentage limited the effect applied load and sliding distance and caused a clear decrease in wear rate. Hence, the percent work aimed to use Taguchi method to optimize the best working conditions of HDPE reinforced with nano alumina particles under the influence of wear behavior used in hip joint replacements that are not covered by references [8-11] as well as a surface topography analysis will be considered to understand the mechanism of wear failure in HDPE and their composites.

2. Materials and methodology

2.1 Specimens preparation

Nano alumina (Al_2O_3) fillers with 10-15 nm diameters and 99.9% purity produced by XFNANO Company are used with weight fractions 1%, 2%, and 3% to reinforce HDPE powder with 75-100 µm diameters and density of 0.95 g/cm^3. After mixing and rotating HDPE with nano Al_2O_3 powders for 10 minutes in a rotating mixer to perform a uniform dispersion of nanofillers, the mixture was poured into a cylindrical copper mold with a 10 mm diameter and then heated by a furnace for approximately 45 minutes and then cooled in room temperature to complete the specimen preparation. TEM test was considered to evaluate the nano Al_2O_3 distribution as shown in Figure 1 (a, b and c), the diagnosis appeared that there is no clustering of nano alumina particles within the prepared HDPE composites. Finally, the prepared composites were cut with 20 mm length to produce the standard wear test specimens according to ASTM G99-05 [16] as shown in Figure 2. The mechanical properties of HDPE and their composites, obtained by tensile test, are reported in Table 1 [17].

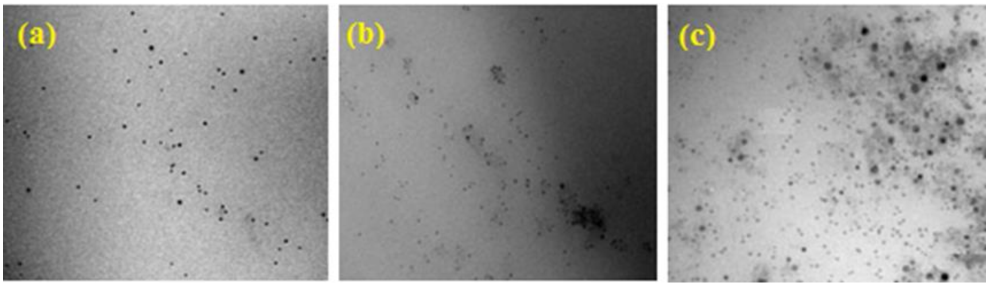


Figure 1: TEM images for (a) HDPE+1%Al_2O_3, (b) HDPE+2%Al_2O_3, and (c) HDPE+3%Al_2O_3

Figure 2: Standard and actual wear test specimens

Table 1: The basic mechanical properties of filled and unfilled HDPE

HDPE Composites	Yield Stress (MPa)	Ultimate Stress (MPa)	Young's Modulus (GPa)
Pure HDPE	24.37 ± 0.12	37.80 ± 0.22	0.85 ±0.02
HDPE +1%Al_2O_3	31.40 ± 0.17	42.63 ± 0.16	1.23 ± 0.05
HDPE +2%Al_2O_3	35.63 ± 0.09	48.34 ± 0.21	1.87 ± 0.03
HDPE +3%Al_2O_3	42.2 ± 0.15	56.33 ± 0.13	0.03

2.2 Wear test method

To perform a wear test, different methods were available to indicate the wear rate in materials; one of the most important techniques is the pin-on-disc method, which depends on calculating the reduction in test specimen mass that results from adhesion between the test specimen and the rotating disc under the influence of normal applied load, a multi-speed tribometer with 0.25 µm surface roughness of stainless steel disc initialized to evaluate the test specimens. The specific wear rate (S.W.R) can be obtained from Equation (1) in (mm^3/N.m) units, where the sliding distance (X) represents the result of multiplying the rotating disc diameter in m, rotating speed in rpm, and the sliding time in min by the constant ratio pi [18]. While (ρ) and W represents the density and normal applied load in g/cm^3 and N, respectively.

$$S.W.R = \frac{\Delta m \times 1000}{\rho \times W \times X} \quad (1)$$

2.3 Hardness test

To analyze the influence of nano alumina fillers on the cross-linkages of HDPE composites, a shore D hardness test was conducted according to ASTM D2240-15 [19]. The hardness number was measured for each test specimen by taking the average value of ten tests to minimize the error percentage.

2.4 Design of experiments

The experiment (DOE) design with Taguchi method was conducted with MINITAB 17 software. Is classified as an attractive method to optimize the operating parameters by obtaining much information with minimum time, cost, and effort by reducing the required number of tests possible [20,21]. Between different Orthogonal arrays available in the Taguchi method, (L9) orthogonal array was selected to optimize the wear behavior. Three parameters with three levels were used to simulate the working conditions selected based on several previous studies [8-15] conducted on HDPE composites, as illustrated in Table 2.

To analyze the wear behavior with Taguchi approach, all specific wear rate values transformed to signal-to-noise ratio (S/N) with Smaller is a better model to reduce the wear rate value obtained according to Equation (2) [22]. According to the above design of experiments, the methodology of this work is to create a new nanocomposite material suitable for hip joint replacement with a high wear resistance.

$$\frac{S}{N} = -\log\frac{1}{G}\left(\sum X^2\right) \quad (2)$$

Table 2: Selected working parameters

Design Parameters	Levels			Units
	I	II	III	
Nano percentage (a)	1	2	3	%
Applied load (b)	10	20	30	N
Sliding time (c)	10	20	30	min.

3. Results and discussion

3.1 Hardness test results

The influence of nano alumina particles on the hardness number for the prepared HDPE composites is illustrated in Figure 3. The addition of nano alumina fillers with 1%, 2%, and 3% wt leads to increasing the hardness value by 17.7%, 24.2%, and 32.25%, respectively, due to the brittleness and high hardness of nano alumina particles in comparison to pure HDPE. Moreover, this increasing hardness value improves the sustainability of HDPE composites against penetration from other materials. This can be attributed to the good interference between the nano alumina particles and the matrix material, which is made a defensive line to prevent the indenter from penetrating. This behavior is related to the overall improvement in mechanical properties due to the presence of nano-alumina particles. The increase in nano alumina content above 3% leads to drops in all mechanical properties due to the poor wettability and weak linkages between the nanofillers and the matrix material. These results agree with [9,10].

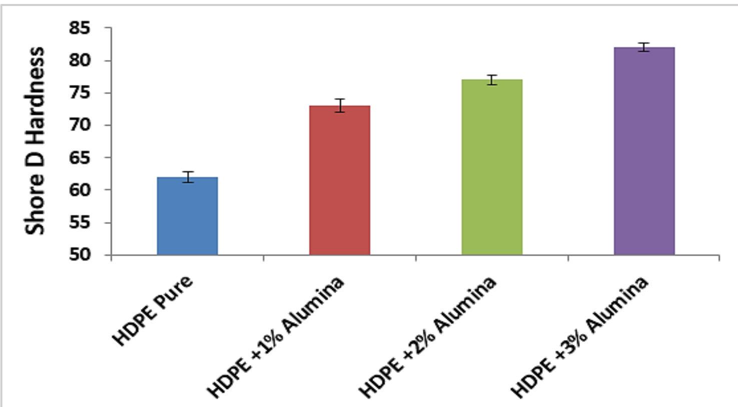


Figure 3: Effect of loading with different content of nano alumina on hardness

3.2 Wear test results

3.2.1 Optimization with taguchi method

Based on Taguchi method, nine experimental wear test conditions were suggested to evaluate the wear behavior, as shown in Table 3. Each test condition was carried out three times for more accuracy, and the average value was considered. The obtained specific wear rate values were inserted into MINITAB 17 software as a response to Taguchi modeling, transformed to (S/N) ratio form according to Equation (2), and then collected in Table 4.

Table 3: Orthogonal (L9) array

Test No.	Alumina Percentage (%)	Applied Load (N)	Sliding Time (min.)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 4: Specific wear rate response

Test No.	Alumina Percentage % (a)	Applied Load N (b)	Sliding Time min. (c)	S.W.R $\times 10^{-6}$ $mm^3/N.m$	S/N ratio (dB)
1	1	10	10	5.6350	104.982
2	1	20	20	7.1140	102.963
3	1	30	30	8.4380	101.514
4	2	10	20	5.6760	105.036
5	2	20	30	4.5230	106.936
6	2	30	10	7.4420	102.615
7	3	10	30	3.1540	110.173
8	3	20	10	2.6652	111.701
9	3	30	20	3.4541	109.370

The highest (S/N) ratio for S.W.R is 111.701 dB. Moreover, the best working conditions with minimum wear rate for HDPE/ nano alumina composites provide the combination parameters a3, b2, and c1, which have the highest response values in response graphs, as shown in Figure 4. Between all the design parameters, the nano alumina filler has the highest influence on wear rate, followed by applied load and sliding time, as presented in Table 5. Moreover, nano alumina filler with 3% wt, 20 N applied load, and 10 min sliding time represents the optimum design conditions with 2.6652×10^{-6} $mm^3/N.m$. The good adhesion between the nano alumina fillers and HDPE base increases the prepared composites' load-carrying capacity, reducing the loosening material. This obtained wear resistance has great compatibility with the required wear resistance for a successful hip joint design that was seen by Fouly et al. [23] when associated with the roll of 2% nanographene particles as a reinforcement material to HDPE composite for hip joint replacements, based on stress analysis, for a successful hip joint design; the wear rate should be less than 2×10^{-5} $mm^3/N.m$ which represents one to a tenth of the obtained wear resistance by HDPE +3% nano alumina fillers. The interaction between the working parameters was analyzed using the ANOVA method, with no interaction between the design parameters when the graphic lines were parallel. In contrast, the interaction happens when the lines are crossed [24]. As shown in Figure 5, no interaction between the nano alumina content and the applied load was seen, while a limited interaction will happen between the nano alumina content and the sliding time. In contrast, a clear interaction between the applied load and the sliding time can be attributed to the high influence of both parameters in increasing the specific wear rate.

Table 5: Response of means

Level	Nano Filler	Applied Load	Sliding Time
1	0.000007	0.000005	0.000005
2	0.000006	0.000005	0.000005
3	0.000003	0.000006	0.000005
Delta	0.000004	0.000002	0.000001
Rank	1	2	3

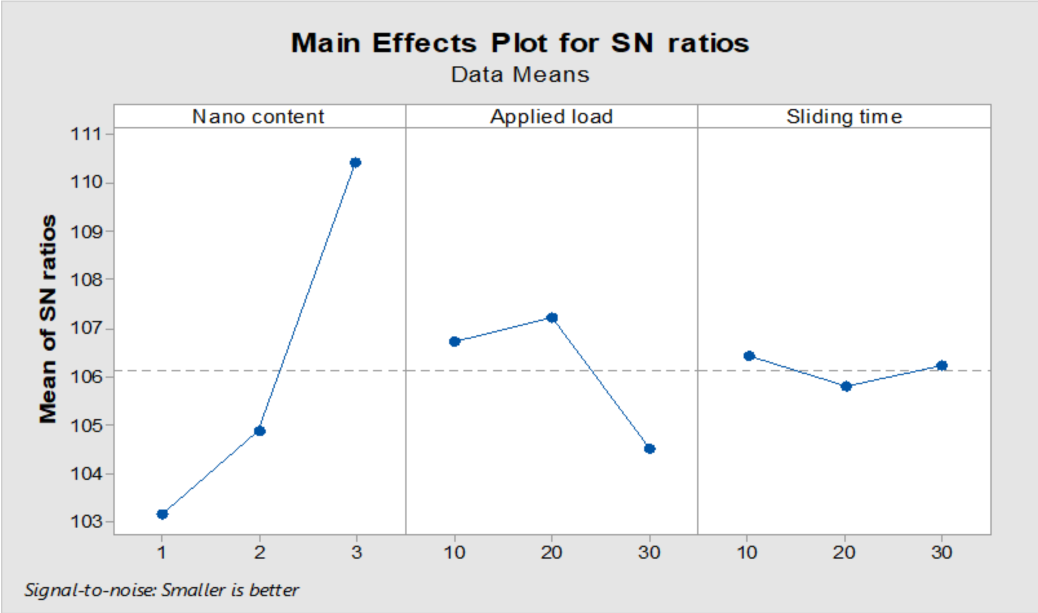


Figure 4: Specific wear rate response graph

Figure 5: The interaction between working parameters

3.2.2 Effects of design parameters

According to Taguchi optimization, the normal applied load is 20 N and 10 min. Sliding time is suggested as the optimum working parameter against wear. Therefore, a comparative test was made between the pure HDPE and HDPE +3% nano alumina particles to evaluate the influence of nano alumina fillers on wear resistance.

3.2.2.1 Effect of applied load

Figure 6 displayed the influence of applied load on specific wear rate for unfilled HDPE and HDPE +3% nano alumina particles that were optimized by the Taguchi method as the optimum reinforcement percentage to evaluate the effect of applied load; the sliding time was considered 10 min as suggested by Taguchi method as an optimum testing condition, it can be seen a proportional increasing in wear rate due to the increasing in applied load for all test specimens, as well as, a clear improvement in wear resistance results from the addition of 3% nano alumina particles with an enhancement in wear resistance by 154% in comparative to unfilled HDPE under 20 N applied load. The reason for this behavior results from the roll of nano alumina particles that sustain the applied load by taking a load-bearing element position lying between the contact surfaces. These results agree with Maro et al. [4] when evaluating the influence of nano alumina-toughened zirconia-reinforced HDPE on specific wear rates.

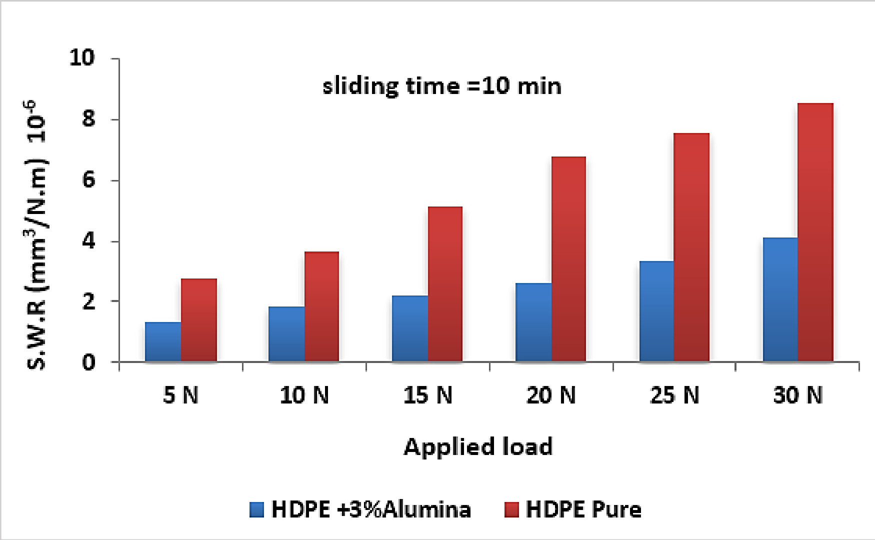


Figure 6: Effect of different applied loads on wear behavior for HDPE composites

3.2.2.2 Effect of sliding time

The effect of sliding time of neat and reinforced HDPE with 3% nano alumina was illustrated in Figure 7 conducted under a normal applied load equal to 20 N as suggested by Taguchi method. It can be seen that the increase in sliding time increased the specific wear rate, especially in neat HDPE, and the addition of nano alumina enhanced the wear resistance by 193% in comparison to pure HDPE under the optimum operating conditions. This enhancement in wear resistance results from the effects of nano alumina particles, which increase the bonding strength between the matrix and reinforced phases, thus increasing the composite durability and making it slide for longer without failure. This result agrees with Rao et al.[5] when evaluating the effect of carbon nanotubes on HDPE's wear behavior.

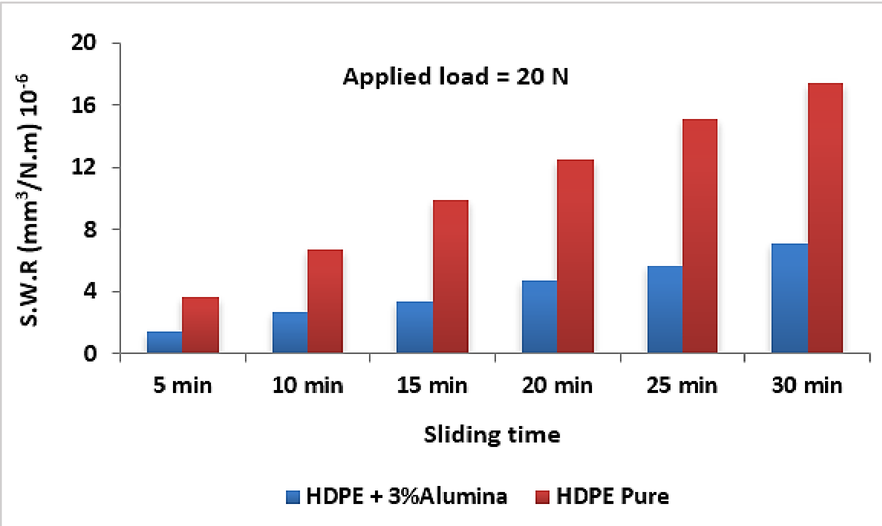
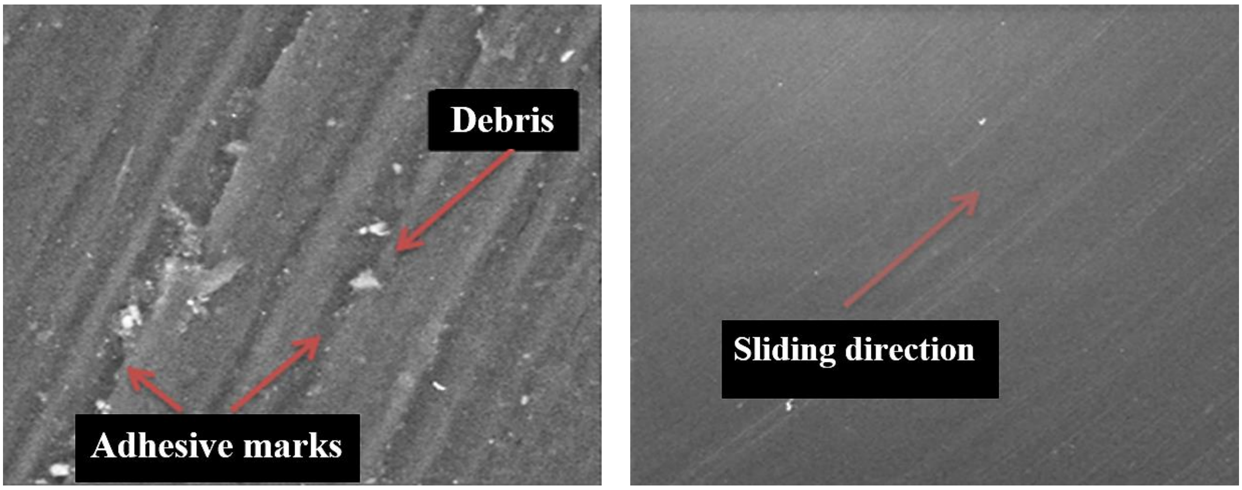


Figure 7: Effect of different sliding time on wear behavior for HDPE composites

3.3 Worn surface topography

To understand the wear mechanism, the worn surfaces of pure HDPE and HDPE +3% nano Al_2O_3 specimens were associated with Scanning Electron Microscopy (SEM). Both specimens were tested under the optimum working conditions suggested by Taguchi method (20 N applied load and 10 min. sliding time). As illustrated in Figure 8(a), an adhesive mark was seen on the harmed surface of the HDPE specimen, resulting from the weak resistance against the normal applied load as well as a small debris detachment from the specimen surface, which works as a third body effect between contact surfaces leads to increase the specific wear rate. In contrast, a smooth surface with the free surface defect was seen in HDPE +3% nano Al_2O_3 test specimen shown in Figure 8(b). The high wear resistance can be attributed to the following reasons. The first one is that adding nanofillers improved the hardness value, making the prepared composite more resistant to mass loosening due to wear. Furthermore, the nano alumina particles work as a solid lubricant to prevent contact surfaces by creating a transfer film separating the contact zone, reducing the specific wear rate value. This finding has a great similarity with that seen by Dabees et al. [25] when associated with the specimen surface morphology of HDPE reinforced by carbon nanotubes under the influence of wear behavior, the CNT particles generate a lubricant shell covering the contact zone prevents the test specimen from material detachment as a small debris which results due to the continuous loading.



(a) **(b)**

Figure 8: SEM images for worn surfaces: (a) Pure HDPE, (b) HDPE+3%Al_2O_3

4. Conclusion

In this study, the influence of nano alumina particles on the wear behavior of HDPE was investigated. The results showed a clear increase in mechanical properties such as yield stress, ultimate stress, and modulus of elasticity due to the addition of nano alumina particles. The optimum mechanical properties were seen with HDPE +3% Al_2O_3 composite, and a considerable decrease in the specific wear rate value of HDPE resulted from the addition of nano Alumina fillers. Moreover, the hardness of the prepared composites is superior to neat HDPE. Thus, the hardness value increased by 17.7%, 24.2%, and 32.25% due to adding nano alumina fillers with 1%, 2%, and 3%, respectively. The optimization with Taguchi method suggested the best design working conditions (reinforcing with 3% wt nano Alumina particles, 20 N normal applied load, and 10 min. sliding time) with a specific wear rate equal to 2.6652×10^{-6} $mm^3/N.m$ and the sequence of design parameters that effected on particular wear rate is arranged as follows; the nanofiller content, applied load, and then the sliding time. Furthermore, adding 3% nano alumina particles improved the wear resistance of HDPE against the normal applied load and sliding time by 154% and 193% respectively under the optimum testing conditions suggested by Taguchi method. Finally, a scanning electron microscopy observation indicated that the addition of nano Alumina fillers prevented the test specimen's surface from lessening by creating a transfer film that separated the contact zone. In contrast, deep grooves, adhesive marks, and debris particles were generated in pure HDPE specimens, resulting from low hardness and weak wear resistance. Investigating and analyzing the created transfer film separating the contact zone can be a future work for the present study.

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Data availability statement

The data supporting this study's findings are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest.

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