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EXPERIMENTAL STUDY OF ALUMINUM-POLYTETRAFLOUROETHYLENE FUNCTIONALLY GRADED MATERIALS TRIBOLOGICAL PROPERTIES

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Abstract

The current work aims to experimentally investigate the sliding wear characteristics of three, four, and five-layer PTFE-Al functionally graded materials (FGMs). FGMs with different layers of (75-25, 50-50, 25-75, and 0-100) wt.% Aluminium and PTFE have been synthesized using the powder compaction technique. The tribological properties of such materials are investigated using a Pin-on-disc wear test machine with three process parameters: applied loads (1, 3, and 5) N, rotational speeds (100, 250, and 450) rpm, and sliding times (5, 10, and 15) minutes. The obtained results show that the wear rate of the PTFE can be mitigated with the existence of the Al. However, it increases with the applied load, sliding distance, and rubbing velocities. It was also noted that the wear rate of the different layers decreases as the weight fraction of Aluminium increases due to the increase of the material hardness. Scanning electron microscope (SEM) with Energy Dispersive X-ray spectrometry (EDS) is used to analyse the worn surfaces. The SEM with EDS analysis showed that the predominant wear of the different functionally graded materials and their layers is an abrasive as a result of the wear debris and score formation.

Keywords: dry sliding wear, FGMs, composite materials, SEM, EDS, PTFE

List of Symbols/Acronyms

FGM- Functionally graded material
K- specific wear rate [mm^3/Nm]
m- the mass [g]
PTFE- Polytetrafluoroethylene
V- the removed material volume [mm^3]
W- the applied load [N]
S-the sliding distance [m]
f- friction coefficient
F_r- the friction force [N]
W- the applied load [N]
ρ- the density [g/cm^3]

1. INTRODUCTION

An increased demand for high-performance materials has led to the development of a wide range of materials with enhanced strength, decreased density, improved wear resistance, and other properties. Functionally graded materials, regarded as advanced composite materials, are one of such materials [1]. They are used in different industrial applications, such as pressure tanks, spacecraft, machine parts, and biomaterials [2,3]. Several techniques were used for synthesizing functionally graded materials, such as spray deposition [4, 7], and centrifugal casting [8,9]. However, powder compaction (PC) is an effective technique for producing gradients free of defects [10,11]. Polytetrafluoroethylene (PTFE) is an organic compound that can withstand temperatures up to 250°C continuously or 400°C momentarily possesses advantageous properties that make it used in a variety of applications, such as bearings, surface coatings, and chemical processing equipment [12]. It was used to increase Aluminium powder's microscale oxidation activity, which could boost its use in energetic materials [13,14]. The wear features of PTFE reinforced with 25% and 30% carbon fibre and Aluminium 6061 alloy were studied experimentally using a pin-on-disc wear test machine [15]. Pressure and temperature effects on the wear rate have been also investigated numerically. According to the results, the PTFE reinforced with 35% carbon fibre has a higher wear resistance than that with. 25% carbon fibre-filled PTFE. The mechanical and tribological properties of the epoxy reinforced with the dust of the cement kiln and its graded material produced by the vertical centrifugal casting technique have been discussed in [16]. The mechanical characteristics of the filled

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epoxy composite were evaluated and compared with those of the FGM. The speed, load, and sliding distance effects on the wear rate of such materials have been studied. It was observed that the epoxy reinforced with cement kiln dust has enhanced tribological properties compared to the graded material. Taguchi's design of the experiment was used to investigate the mechanical, and wear characteristics of the epoxy reinforced with TiO_2 particles functionally graded composite materials [17]. The wear behaviour of the material was studied under different loads, rotational speeds, and sliding distances. SEM micrographs indicated that the TiO_2 nanoparticles were peeled off in inhomogeneous composites forming holes while they remained intact in the matrix of the graded composite materials under the same experimental conditions. The mechanical and tribological characteristics of CuSn-Ni/Al_2O_3 metal matrix functionally graded composite synthesized by horizontal centrifugal casting have been evaluated in [18]. The mechanical properties were investigated utilizing tensile tests. The wear behaviour of this material was examined using a pin-on-disc wear test machine under various rotational speeds, applied loads, and sliding distances. The findings suggest the possibility of using the fabricated FGM for the bearing applications comparatively to the leaded bearing material because of its superior wear characteristics. The applied load, rotational speed, and sliding distance effects on the wear behaviour of homogeneous polyester strengthened with short glass fibre composites, and their functionally graded material produced by centrifugal was studied in [19]. The morphological properties of the worn composite specimens have been analysed using the scanning electron microscope to better understand the wear mechanisms. Also, Homogeneous composites show increased tensile modulus while the FGMs show decreased tensile modulus compared to that of the neat polyester. The key benefit of Polytetrafluoroethylene is the low coefficient of friction, which allows easy rotation, insolubility in most solvents, wide thermal stability range, hydrophobicity, low surface energy stability, good mechanical properties, and high chemical resistance. Due to these properties, the material can be used in harsh chemical and thermal environments, such as in the oil and gas industry or engine applications [20]. According to [21], polymer-based functionally graded materials (FGMs) have unusual features since their attributes vary in specific ways to satisfy different purposes. These composites, which have gained popularity in material science, are synthesized from two different materials that maintain the qualities of the parent components. It was found that the graded composites are reliable options to achieve improved tribological and thermal properties. A polymer-based functionally graded material using epoxy reinforced with Cu particles was developed in [22]. The effects of various curing conditions on the behaviour of such material were investigated. It was found that the higher curing condition of 60°C enhanced the mechanical and erosion resistance. In another work [23] a pin-on-disc tribometer to explore was used to discuss the tribological features of epoxy reinforced with Aluminium and copper particles FGMs developed by a hand lay-up technique. The tribological properties, including the wear and friction for each layer under various loadings, have been investigated. The obtained results indicated that the samples with Cu additive exhibited a lower coefficient of friction, which indicates Cu particles' effectiveness in reducing friction. The hardness and wear performance of synthesized epoxy-Al_2O_3-graded materials under different loads and rotational speeds have been studied in [24]. A wear rate enhancement of about 87.7% for the functionally graded samples in comparison with the neat epoxy when loaded from the alumina-rich side has been observed. Based on actual microstructures, A simulation of the Al/PTFE composite mechanical properties was implemented in [25]. The experimental results were effectively used to verify the simulated results obtained from solving the mathematical model. According to experimental findings, both simulated and real microstructure models with microscale modelling provide accurate forecasts of elastic modulus and yield stress. Gaydamaka et al. [26] studied the function and the wear behaviour of the intermediate gear teeth in a vertical gearbox. The work was implemented by monitoring the hardness of the intermediate gear in the workshop operating conditions. It was observed that contact fatigue, adhesive wear, and plastic deformation are the main wear modes at the teeth surface. Abdulaziz et al.[27] experimentally investigated the effect of the fibre orientation on the mechanical behaviour of a multilayer composite material composed of five layers. It was concluded that the orientation of the fibre in the different layers affects the mechanical properties of such material. The survey of the related works performed above shows that the tribological properties of PTFE-Al composite material have been studied experimentally. However, the PTFE-Al functionally graded materials have not been studied previously in the manner of the present work. The current study examines the dry sliding wear characteristics of PTFE-Al FGMs with different numbers of layers (three, four, and five layers) synthesized by powder metallurgy. The effects of different rotational speeds, loads, and sliding distances on such materials' wear rate and friction have been studied experimentally. It was expected that this type of material could be used as a bearing material for different bearings applications because of the excellent friction property of the PTFE material, which can enhance the friction coefficient of the Aluminium and the good thermal properties of the Al. However, the hardness of the PTFE material can be enhanced by the existence of the Al, which highly enhances its wear rate which limits the uses of such material in different loading and speeds.

2. EXPERIMENTAL DETAILS

In this study, PTFE-Al functionally graded materials with different layers have been produced by adding Al powder with different percentages (0, 25, 50, 75and 100) to the PTFE powder using the powder metallurgy technique. The dry sliding wear properties of these materials were investigated using a pin-on-disc tribometer. The effect of the weight percentages of the materials, the applied load (1, 3, and 5) N, the rotational speed (50, 250, and 450) rpm, the sliding time (5, 15, 30) minutes, and the number of layers (1, 3,4 and 5) on the wear behaviour of such materials have been discussed.

2.1. Sample preparation

Figure 1 shows the steps required to synthesize the layers and the functionally graded materials studied in the present work. The Al and PTFE powders with 25µm and 200nm particle sizes, respectively, were used to synthesize the different FGMs and their layers. The Al and PTFE particles were characterized using XRD and SEM micrographs. The powders were weighted using a high-precision scale balance according to the required weight percentages. The powders with suitable weight percentages were then mixed using a ball blender. The mixture of the powders was then pressed in a cylindrical die manufactured for this purpose to produce the required layers. The layers were then stacked with each other using a 6-ton force to produce the FGMs, which were sintered in an inert atmosphere furnace by raising the temperature to 150 °C at a rate of 3 °C/min, where they were left at this temperature for 30 minutes. The samples were then heated to 290 °C with the same temperature rate and left at this temperature for 210 minutes. The samples are then cooled to ambient temperature and prepared for the required tests. For more details about the synthesizing of the functionally graded materials and their layers, one can refer to [28].

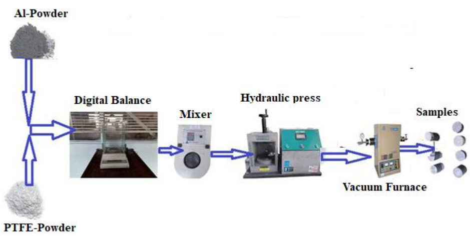


Fig. 1. Steps followed to synthesize FGMs wear testing samples

2.2. Wear characterization

The wear tests for the PTFE-Al FGMs and their layers were performed as stated by the ASTM G-99 standard using the pin-on-disc tribometer type MT/60/NI/HT/L shown in Figure 2. In the wear test, the disc material wears out during the testing process, and the amount of material lost is measured to determine the wear rate. The impact of speeds, applied loads, sliding times, and the number of layers on the tribological properties of the produced PTFE-Al FGMs has been examined experimentally. Wear and friction experiments were accomplished at an ambient temperature (Lab. temperature) and 30-40% relative humidity. The wear test was performed by first washing the head of the pin and the samples with alcohol and then drying them before each experiment. During sliding, the FGM disc's surface is in touch with the entire pin's surface, and machine markings are visible on the disc. Then the load and the rotational speed were applied for the specified required time. After the wear test had been performed, the mass loss from the disc was determined by the difference between the disc's pre-test and post-test masses using a precision balance with four-digit resolution. The wear rate was determined by calculating the wear volume using the profiles acquired from the wear track cross-section according to the following equation:[29]

$$K = \frac{V}{WS} \quad (1)$$

The removed material volume was calculated as:

$$V = \frac{m}{\rho} \quad (2)$$

The friction coefficient can be calculated as:

$$f = \frac{F_r}{W} \quad (3)$$

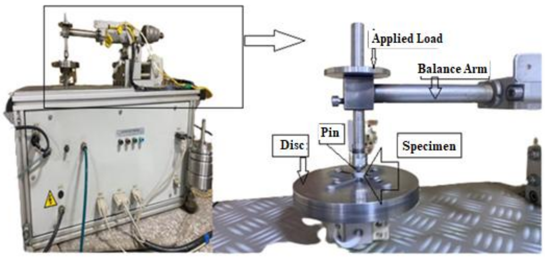


Fig. 2. Pin on disc tribometer

3. DISCUSSION OF THE EXPERIMENTAL RESULTS

The obtained experimental wear results of the different graded materials and their layers will be presented in the following sections.

3.1. Wear analysis

Figure 3a-c shows the experimental results for the specific wear rate obtained from the wear test of the PTFE-Al FGMs and their layers under different rotational speeds with varying sliding times of 5, 15, and 30 minutes while the applied load was kept at 1N. Figure (3-a) shows that the wear rate for the layer with 100%wt PTFE increases with the rotational speed of the disc. The wear rate increases from 0.0175mm^3/N.m to 0.0225(mm^3/N.m) when the rotational speed increases from 50 to 450 rpm, while the sliding time is kept at 5 minutes with a percentage increase in the wear rate of 28.5%. This can be explained by the increasing sliding distance of the rubbing surfaces with the increasing rotational speeds. However, a lower specific wear rate was obtained when increasing the weight percentage of Aluminium powder used with the PTFE powder. The lowest wear rate was obtained for the layer with 75wt% Al when it becomes nearly zero with a decreasing percentage of almost 100% due to the higher hardness of such material in this case. It is also clear from this Figure that there is a nearly zero constant wear rate for the FGMs and their layers when tested at different rotational speeds. Figure 3-b illustrates that the wear rate of the PTFE layer increases from 0.03 to 0.045 as the rotational speeds increase from 50 rpm to 450 rpm, respectively, when the sliding time is kept at 10 minutes. This Figure also depicts that the wearing out of the pure PTFE layer increases as the sliding time increases to 10 min while maintaining the applied load at 1N. It can be observed that the wear rate decreases with the increasing percentages of Al in the functionally

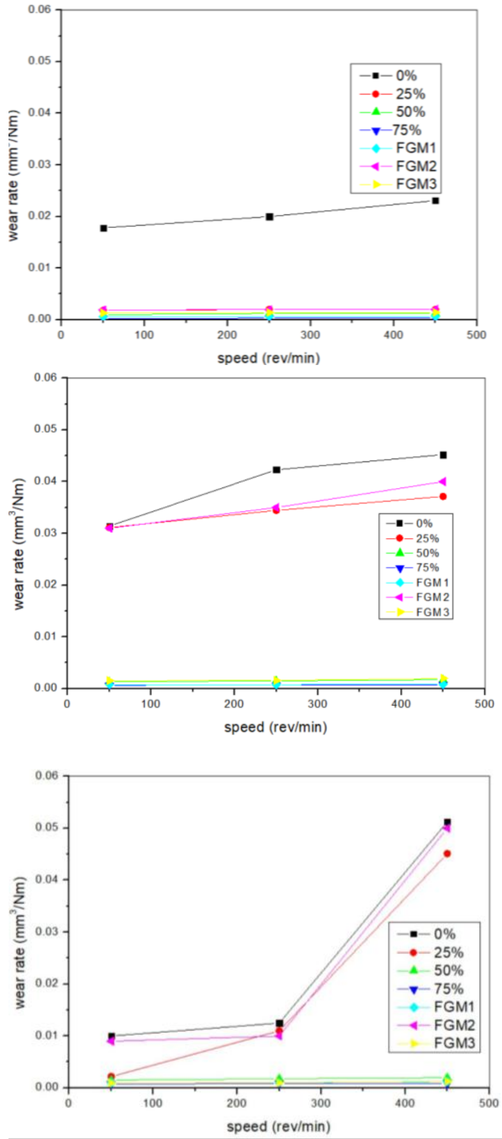


Fig. 3. Effect of rotational speed on specific wear rate of different FGMs and their layers under the applied load of 1N (a) sliding time 5minutes, (b)10min, (c)15min

graded material. The different functionally graded material samples (FGM3 and FGM1) show a constant nearly zero wear rate, while (FGM2) shows a comparable wear rate to the layer with 75wt%PTFE and 25wt%Al. The PTFE layer shows a lower abrasion at rotational speeds of (50 and 250) rpm; after that, severe wear is produced at the rotational speed of 450 rpm, as can be seen in Fig (3-c), because of the increasing sliding distance.

It can be depicted from Figure 3 that the wear rate of the functionally graded coating is much lower than that of the composite layers.

The wear rate behaviour of the different FGMs can be explained by referring to Figure 4, which shows the hardness of those materials measured at thicknesses of 3mm,7mm, and 11mm. This Figure depicts that FGM1(graded material with five layers) has the highest hardness at a material thickness of 11mm when it reaches 53.1 HV in comparison with 50.32 HV for the graded material with three layers (FGM3) and 6.3HV for the graded material with four layers (FGM2). So, FGM1 shows the lowest wear rate, followed by FGM3 and FGM2, respectively as a fact that the wear rate of the materials is inversely proportional to their hardness. Figure 5 demonstrates the applied load effect on the wear rate of different layers when the rotational speed was fixed at 450 rpm.

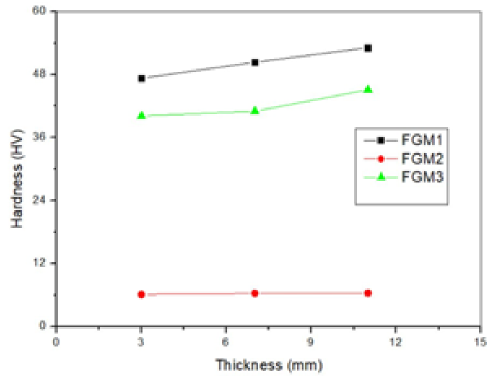


Fig. 4. The hardness of the FGMs at different thicknesses

It can be noted that the material rate of abrasion decreases with the increasing percentages of Al powder until it reaches nearly zero for the layers with (50 and 75) wt% Al due to the increasing hardness of the material in this case. However, it can be observed that the wearing out of each layer increases with the increasing applied load as a result of the higher contact area between the two rubbing surfaces.

Figure 6 shows the impact of the applied load on the different FGMs when the rotational speed was *fixed at 450 rpm. This Figure depicts that the functionally graded FGM1 and FGM3 show a negligible wear rate at different applied loads. However, the functionally graded material with four layers shows a comparable wear rate to that of 75wt%PTFE-25wt% Al layer when subjected to different applied loads. The decreased wear rate shown by FGM1 and FGM3 can be explained by the higher hardness of such materials in comparison with that of FGM2. Figure 7 illustrates the effect of the rotational speed on the wear rate of various graded materials when the applied load is 5N and the sliding time 15min. The increase of the FGM wear rate with the rotational speeds is depicted in this Figure. The increasing rubbing velocity of the disc surfaces can explain this. However, the graded materials with five and three layers show a lower wear rate than those with the four layers. This Figure also shows that the abrasion rate of FGM3 is slightly higher than that of FGM1 due to the lower hardness of the FGM3 compared with that of the FGM1, as mentioned before.

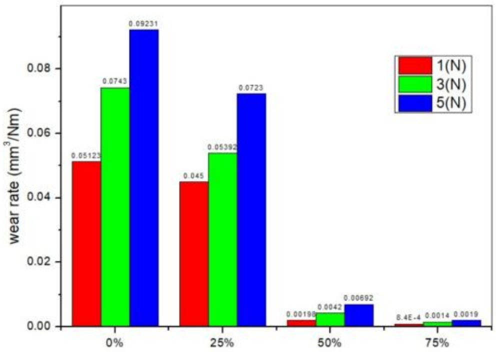


Fig. 5. Applied load effect on the wear rate of the layers, N=450rpm

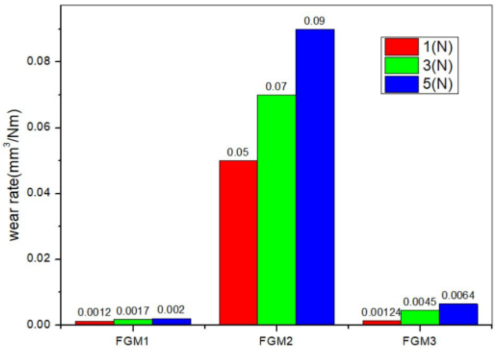


Fig. 6. Applied load effect on the wear rate of the different FGMs, N=450rpm

The highest wear rate was observed in the four-layer graded material (FGM2) due to the lowest hardness of such material.

Figures 8 and 9 show the sliding time effect on the specific wear rate of the FGMs and their layers. Figure 8 shows the impact of the sliding time on the specific wear rate of different layers. This Figure depicts that the wear rate increases with the sliding time due to the increasing sliding distance and, hence the contact between the rubbing surfaces. It can also be noted from this Figure that the wear rate of pure PTFE is higher than that of Al-PTFE composite material. It can be noticed that the wear rate decreases to nearly zero for the materials with 50% and 75% weight percentages of Al. The decrease in wear rate can be attributed to the increase in the PTFE-Al composite material hardness.

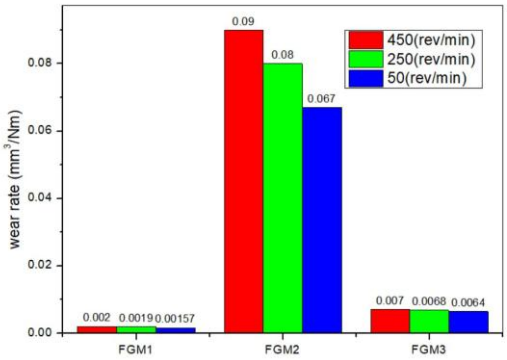


Fig. 7. The effect of the rotational speed on the wear rate of different FGMs

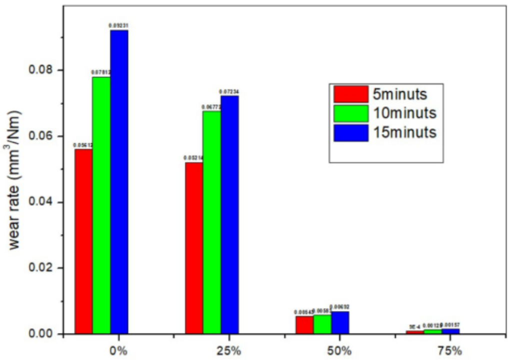


Fig. 8. Sliding time vs. wear rate of different layers. W=5N N= 450rpm

Figure 9 shows the sliding time impact on the specific wear of different FGMs while keeping the applied load 5N and the rotational speed at 450rpm. It can be noticed from this Figure that the wear rate increases with the increasing sliding time as a result of the longer sliding distance of the rubbing surfaces. The FGM2 shows a higher specific wear rate than FGM1 and FGM3. It can be observed that FGM3 suffers from severe wear when the sliding time increases to 15 minutes.

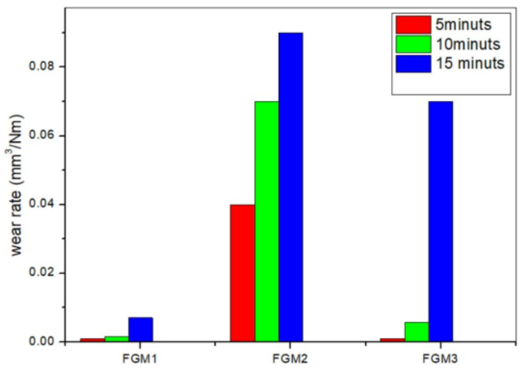
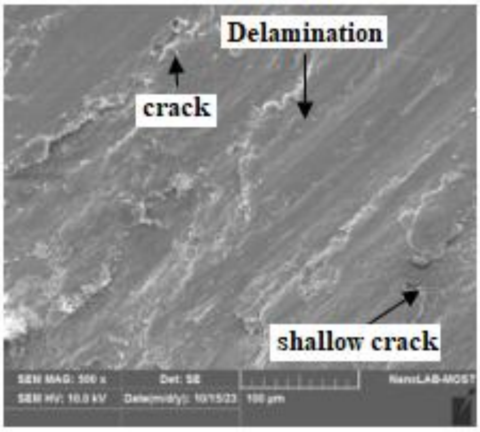


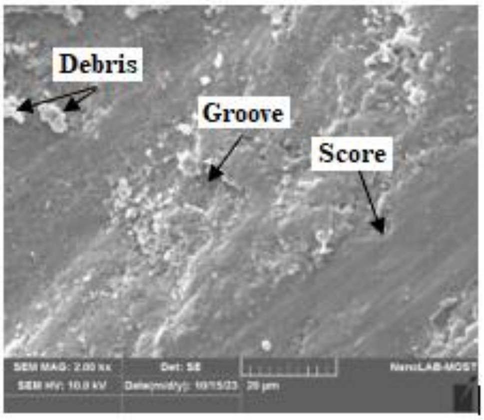
Fig. 9. Sliding time effect on the wear rate of different FGMs W= 5N and N= 450rpm

3.2. SEM micrographs of the worn surfaces

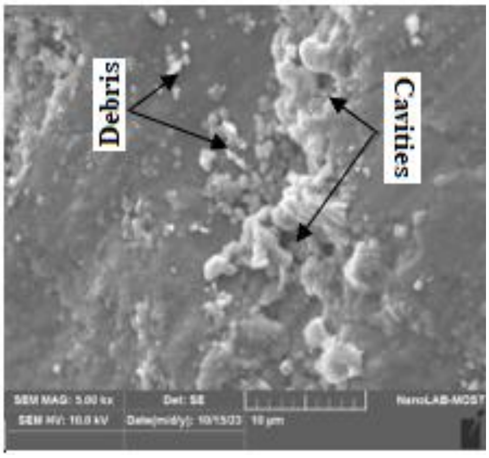
The worn surfaces of the PTFE-Al samples were tested using an Electron microscope (SEM) with EDS. Figure 10 shows the micrographs obtained by the scanning electron microscope for the worn surfaces of the composite material layer composed of 75wt% Al and 25wt% PTFE powders. It can be observed from this Figure that the material suffers from mild abrasive wear with explicit wear scores at the disc surface. It seems that this layer had the minimum wear compared to the other layers, confirming that the abrasion rate of the composite material becomes lower as the percentage of Al powder increases. Cracks, scoring, and wear debris were observed at the wear tracks of the specimen. The abrasive wear was noted at the surface of this material as indicated by the wear debris formation as shown in Figure 10b and Figure 10c.



(a) 100μm



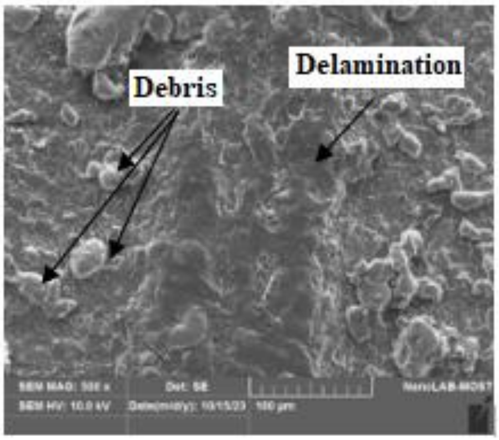
(b) 20μm



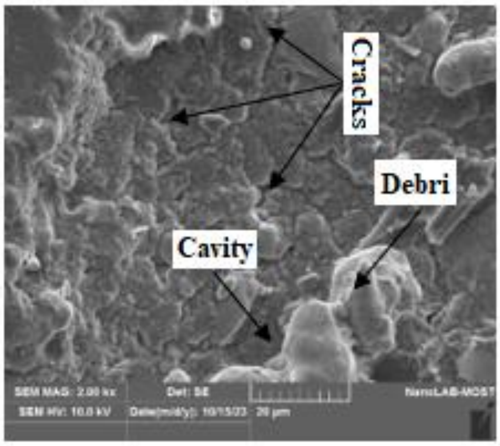
(c) 10μm

Fig. 10. SEM micrographs for the layer with 75wt%Al and 25wt%PTFE

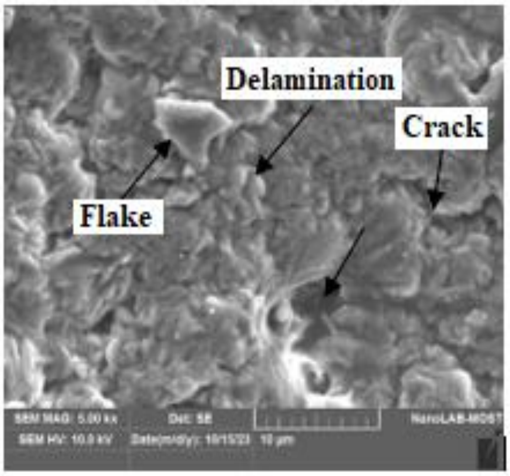
Increasing wear debris and micro-cracks have been observed for the layers with lower Al contents (50wt%Al and 25wt%Al), as shown in Figure 11 and Figure 12. This can be attributed to the low hardness of the material.



(a) 100μm



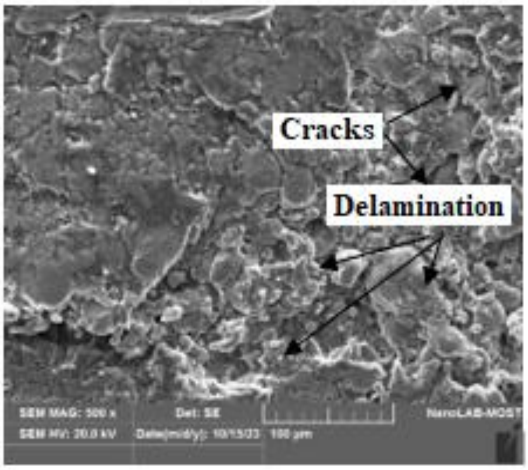
(b) 20μm



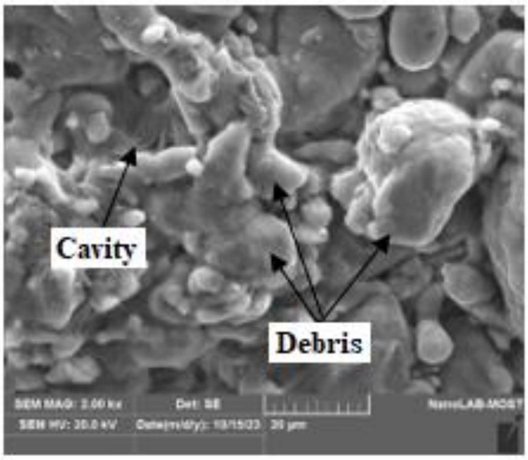
(c) 10μm

Fig. 11. SEM micrographs for the layer with 50wt%Al and 50wt%PTFE

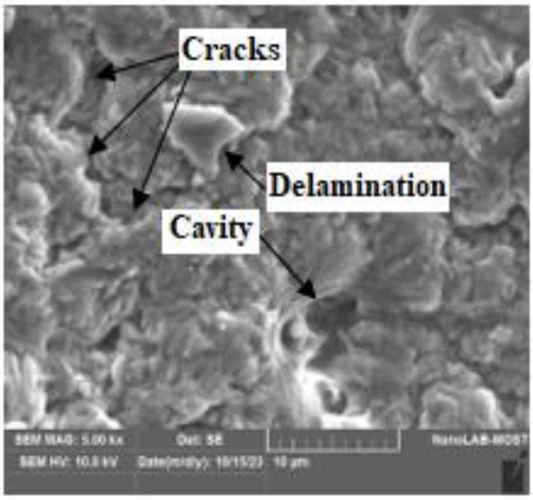
Figure 13 shows the morphological property of the worn surface for the layer with 100wt% PTFE. This Figure depicts the severe abrasive wear with a higher wear rate of the sample observed as flakes, cracks, scores, and delamination. Cavities have been noticed at the surface of the sample when using a higher magnification(5000X).



(a) 100µm

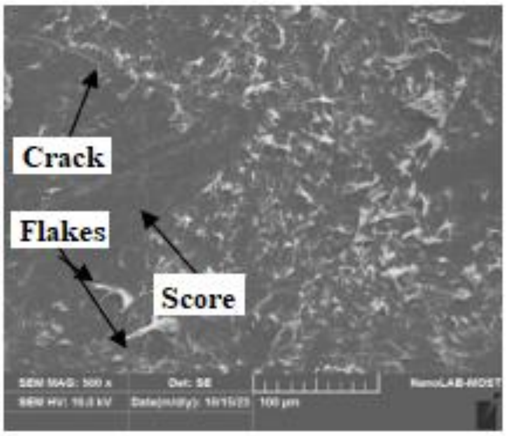


(b) 20µm

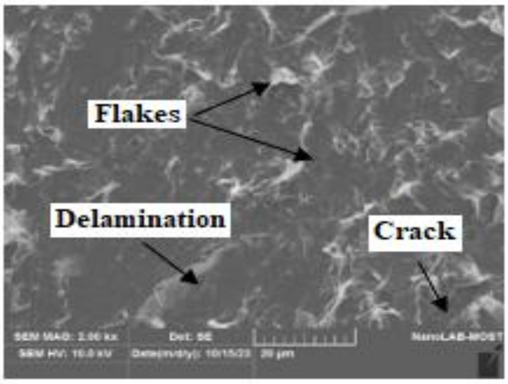


(c) 10µm
Fig. 12. SEM micrographs for the layer with 75wt%Al and 25wt%PTFE

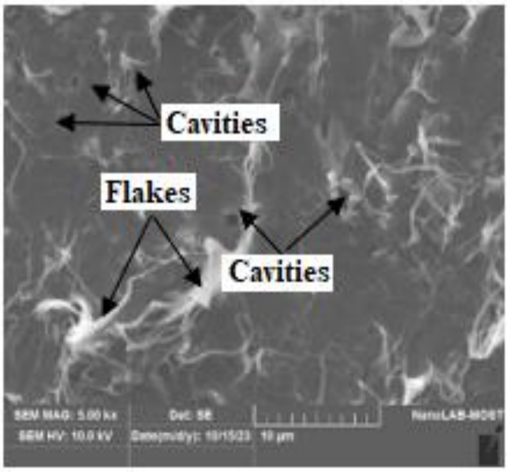
Figure 14 shows the surface morphology of the FGM's worn surfaces. Figure 14a shows the SEM micrograph for FGM1 (five layers of functionally graded material). The material's wear rate can be observed due to the presence of different delamination r egions, scores, and wear debris.



(a) 100µm

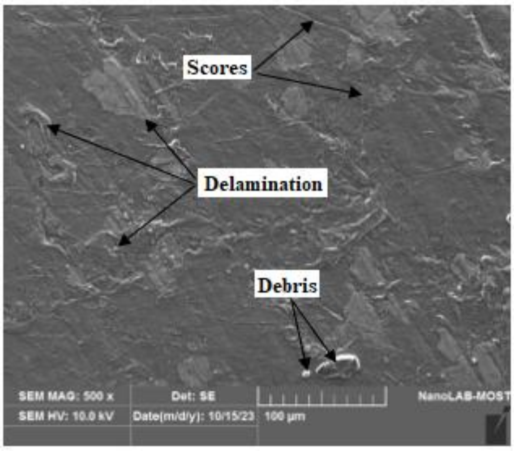


(b)20µm

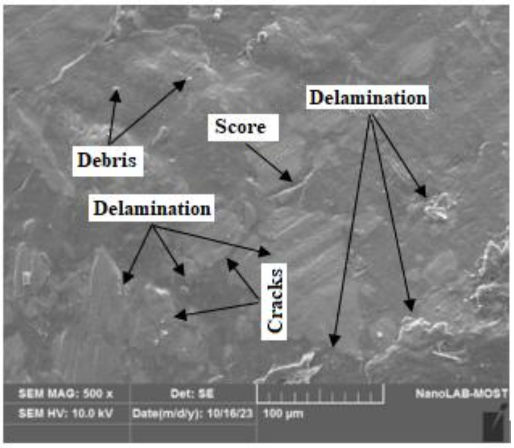


(c) 10µm
Fig. 13. SEM micrographs for 100wt% PTFE

Figure 14b shows more delamination, cracks, and shallow grooves at the surface of the FGM2. This can be attributed to the lower hardness of this material, as mentioned before. However, many shallow grooves (scores) and material delamination have been observed at the worn surface of the FGM3, as presented in Figure 14c. Energy Dispersive X-ray spectrometry (EDS) for the different FGMs has been obtained using an electron beam with an energy of 10kV, which allows a significant amount of Al and PTFE at different thicknesses to be detected in the spectrum, as can be shown in Figures 15-17.



(a)



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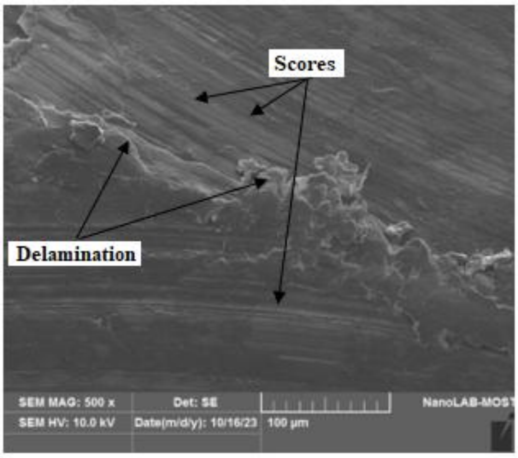
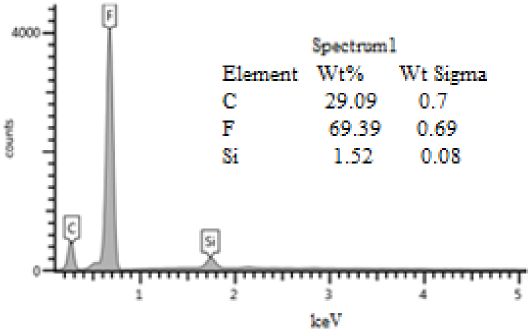


(c)

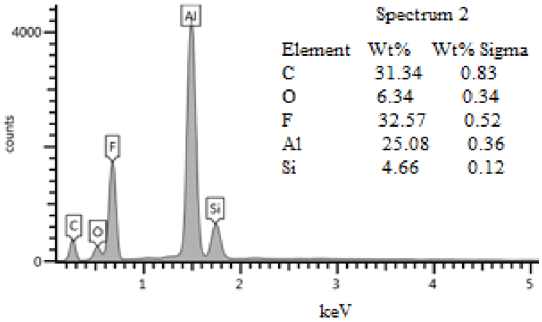
Fig. 14. SEM of FGMs 500x(a)FGM1, (b) FGM2, (c)FGM3

The EDS of the five layers of Al-PTFE functionally graded material at different thicknesses is illustrated in Figure 15. The DES micrograph shown in Figure 15(a, b) has been taken at places indicated by Spectrum 1 and Spectrum 2 in Figure 15 (c, d). This figure illustrates the distribution of the PTFE and Al in the functionally graded material. White areas in the figure indicate the PTFE particles, while the black areas show the Aluminium particles. The SEM images show the gradual changes of the materials in the FGM. These changes are also confirmed by the EDS micrographs.

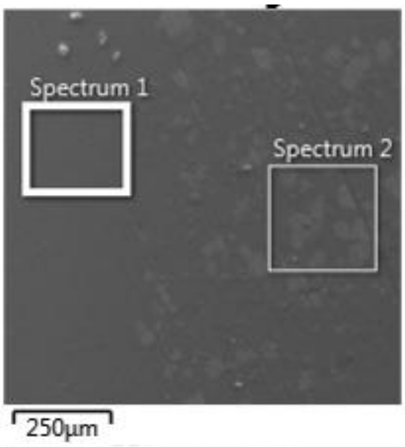
a)



b)



c)



d)

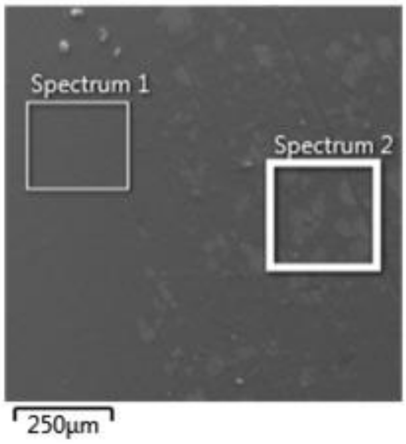


Fig. 15. EDS micrograph for the five layers FGM (FGM1) (a) EDS of the spectrum1 (b) EDS of the spectrum2 (c)Spectrum1 (d) Spectrum2

The EDS micrographs for the four and three layers are illustrated in Figure 16 and Figure 17.

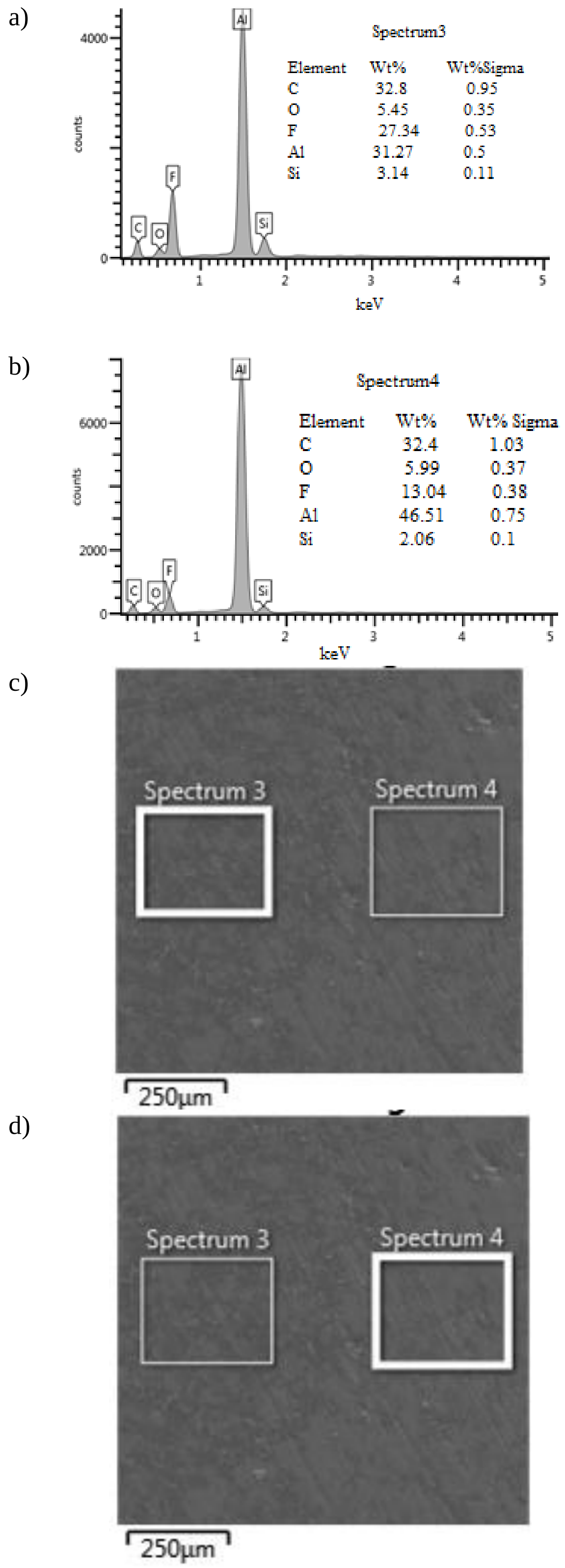


Fig. 16. EDS micrograph for the five layers FGM (FGM2) (a) EDS of the spectrum1 (b) EDS of the spectrum2 (c)Spectrum1 (d) Spectrum2

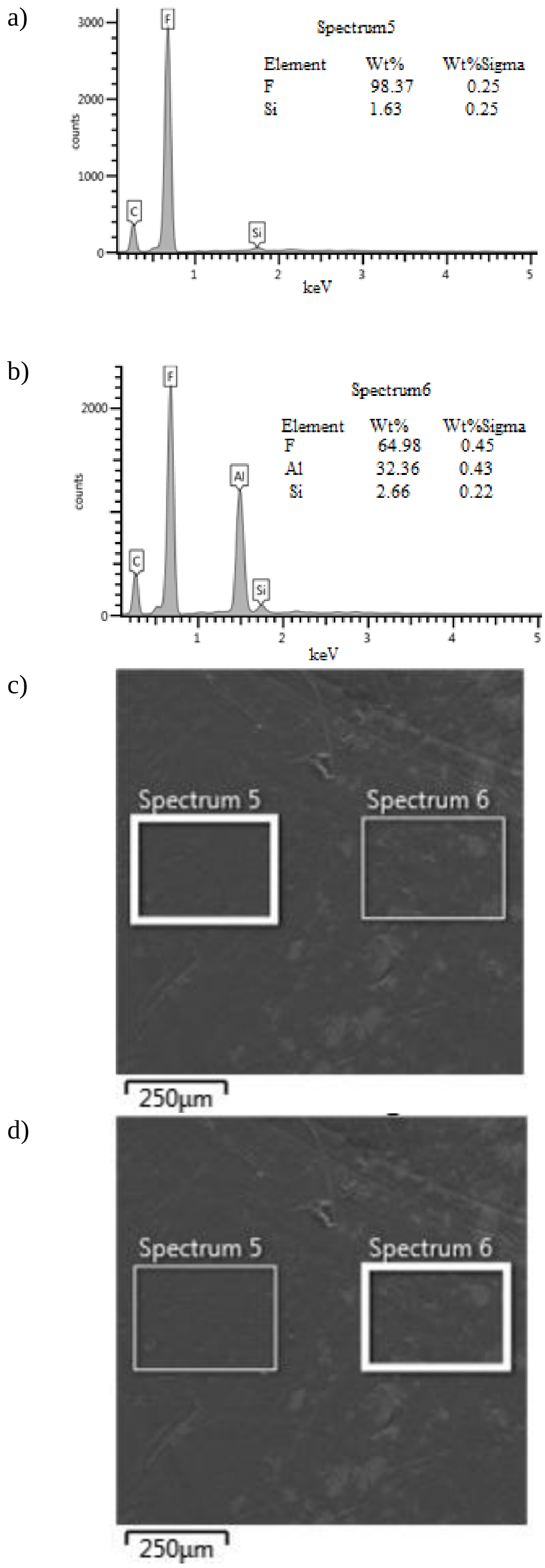


Fig. 17. EDS micrograph for the three layers FGM (FGM3) (a) EDS of the spectrum1 (b) EDS of the spectrum2 (c)Spectrum1 (d) Spectrum2

4. CONCLUSIONS

The wear behaviour of PTFE-Al functionally graded materials with different numbers of layers (three, four, and five layers) synthesized by powder compaction has been studied experimentally in the present work. The wear rate of the specimens was tested for different parameters of loads, rotational speeds, and sliding times. The following conclusions can be demonstrated from the discussion of the obtained experimental results:

1. The wear rate of the different functionally graded materials and their layers increases with the sliding velocities.
2. The functionally graded material with five layers shows a lower wear rate than three and four-layer functionally graded materials as a result of its higher hardness.
3. The PTFE-Al composite layers with a higher percentage weight of Al powder show a low wear rate due to the high hardness of the functionally graded material.
4. The wear rate of the different functionally graded materials and their layers increases with the sliding distances because of the increasing contact between the two rubbing surfaces.
5. The four-layer functionally graded material shows a higher wear rate than the other due to its lower hardness.

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