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THE EFFECT OF GRAPHITE ADDITION ON THE FRICTION COEFFICIENT AND WEAR BEHAVIOR OF GLASS FIBER REINFORCED COMPOSITES

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Abstract: The use of fillers in fiber-reinforced epoxy matrix composites to enhance the wear performance of the composite is a widely employed method nowadays. In this study, the effect of incorporating graphite filler into a glass fiber-reinforced composite structure on the tribological properties of the composite was investigated. Composite materials produced using the hand lay-up method with three different levels of graphite filler were compared to unfilled composites in terms of wear behavior under different loads (7 N, 10 N, 15 N) and sliding distances (200 m, 400 m). The influence of load, filler content, and sliding distance on the friction coefficient and wear rate was discussed. When the results are examined, the significant effects of graphite filler on wear volume and friction coefficient are clearly observed. In the composite containing 12% graphite, the wear volume has decreased by almost 96%; this ratio has been around 93% for the composite with 4% graphite filler. As the reinforcement of graphite and force increase, the friction coefficient decreases, whereas with the increase in sliding distance, the friction coefficient declines. Microstructural analysis revealed that the filled composites exhibited less abrasion compared to the unfilled composites, and the surface porosity and craters were shallower.

Keywords: Graphite, Wear, Glass Fiber, Composite

Grafit ilavesinin cam elyaf takviyeli kompozitlerin sürtünme katsayısı ve aşınma davranışları üzerine etkisi

Öz: Dolgu malzemelerinin lif takviyeli epoksi matrisli kompozitlerde aşınma performansının arttırılması amacıyla kullanılması günümüzde oldukça sık uygulanan bir yöntemdir. Bu çalışmada grafit dolgusunun cam elyaf takviyeli kompozit yapıya dahil edilmesinin kompozitin tribolojik özellikleri üzerindeki etkisi araştırılmıştır. 3 farklı oranda grafit dolgusu kullanılarak el yatırma yöntemiyle üretilen kompozit malzemelerin farklı yük (7 N, 10 N, 15 N) ve kayma mesafelerinde (200 m, 400 m) aşınma davranışları dolgusuz kompozit ile karşılaştırılmıştır. Yükün, dolgu miktarının ve kayma mesafesinin sürtünme katsayısı ve aşınma oranı üzerindeki tartışılmıştır. Sonuçlar incelendiğinde, grafit dolgusunun aşınma hacmi ve sürtünme katsayısı üzerindeki belirgin etkileri açıkça görülmektedir. %12 grafit içeren kompozitte aşınma hacmi neredeyse %96 oranında azalmıştır; bu oran %4 grafit dolgusunda ise yaklaşık %93 civarında olmuştur. Grafit takviyesinin ve kuvvetin artmasıyla sürtünme katsayısı düşerken, kayma mesafesinin artmasıyla sürtünme katsayısı düşmüştür. Mikroyapısal analiz, dolgulu kompozitlerin dolgusuz kompozitlere göre daha az aşınma sergilediğini, yüzey gözenekliliğinin ve kraterlerin daha sığ olduğunu ortaya çıkarmıştır.

Anahtar Kelimeler: Grafit, Aşınma, Cam Elyaf, Kompozit

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1. INTRODUCTION

Vinyl ester, polyester, and epoxy resins reinforced with glass, carbon, and aramid fibers, due to their low cost, ease of production, and superior mechanical and tribological properties, have found extensive applications in various industries such as aviation, automotive, and marine. (Asi, 2010; Kumar et al., 2020) Fiber reinforcements enhance the mechanical properties of the polymer matrix such as toughness, strength, and impact resistance, while fillers improve the tribological behavior by reducing surface tension and increasing adhesion (Ramesh and Suresha, 2014). Moreover, the advantages of fiber-reinforced composites include lightweight, high corrosion resistance, and effective damping (Çetkin et al., 2022). Numerous studies have demonstrated that various filler additions like B_4C, SiC, graphene, graphite, SiO_2, and Al_2O_3 enhance the strength, wear resistance, and physical properties of composite materials through the reinforcement of fibers (Borrego et al., 2014; Fathy et al., 2017; Suresha et al., 2008; Agarwal et al., 2013; Akram et al.,2013). In order to enhance these properties, it is essential to achieve a homogeneous distribution of the added filler material between the matrix and fibers, along with ensuring a strong matrix-filler-fiber adhesion.

Wear can be defined as the damage that occurs due to the relative motion between two solid surfaces in contact, resulting in material loss in one or both of the materials involved. Just as in metals, polymer materials are also susceptible to wear damage. In polymer matrix composites reinforced with fibers, various lubricants or hard fillers are employed to enhance the wear resistance of components subjected to wear (Zhang et al., 2009; Wang et al., 2010).

Numerous studies have demonstrated the significant impact of different fillers used in various investigations on the wear behavior of materials. Suresha et al. determined that by modifying carbon fiber-reinforced polymer composites with graphite, both tensile strength and hardness were enhanced. Furthermore, they emphasized an improvement in the wear behavior of the material with the addition of graphite filler (Suresha et al., 2010;) In another study that investigated the effect of graphite, SiO_2, and short carbon fiber fillers on the wear behavior of polymer matrix composites, it was observed that all three types of fillers were effective in reducing the coefficient of friction (COF) of the polymer matrix. The lowest COF, 0.18 μ, was achieved with 10% graphite, 10% short carbon fiber, and 3% SiO_2 reinforcements. The addition of SiO_2 was found to decrease the wear resistance of the matrix (Zhang et al., 2009). It has been determined that in a polymer matrix composite using nano Si_3N_4, short carbon fibers, and graphite reinforcements, the best wear performance was achieved when short carbon fibers and graphite were used together in the composite. Additionally, it was observed that as the load increased, the COF and wear rate (WR) decreased. The decrease in WR due to the increase in load was attributed to the new wear debris surface formed on the worn surface being more cohesive and fine in nature (Wang et al., 2010). When investigating the combined use of SiC and graphite fillers in glass fiber-reinforced composites, it has been observed that a low content of SiC reinforcement has a more positive impact on wear resistance. Furthermore, an increase in sliding velocity led to an increase in WR. With an increased load, the wear resistance of the unfilled composite decreased up to a certain point, after which it started to increase. The detachment of SiC and graphite particles from the surface was found to create a transfer film layer that reduced matrix and fiber damage, resulting in a decrease in WR (Basavarajappa and Ellangovan, 2012) Basavarajappa et al. investigated the impact of graphite filler on mass loss in unfilled, 5%, and 10% graphite-filled composites by producing different specimens under varying sliding velocities, sliding distances, and loads. They observed an increase in mass loss in both filled and unfilled composites with higher sliding velocities and loads. The authors indicated an improvement in the wear resistance of the composites with an increase in graphite filler content. They explained this phenomenon by the formation of a uniform film layer and the reduction of wear loss due to lubricating particles. (Basavarajappa, et al., 2009)

In this study, the aim was to enhance the wear resistance of glass fiber-reinforced polymer matrix composites by incorporating different ratios (4%, 8%, 12%) of graphite filler. The effects of filler ratios, applied load, and sliding distance on the COF and wear behavior of the composite were investigated.

2. MATERIAL AND METHODS

2.1. Composites production

ARC 152 laminating epoxy resin matrix material has been utilized in the production of composites. ARC-152 type epoxy has been chosen due to its excellent compatibility with fiberglass, providing a convenient working environment by offering a slow cure of the hardener, and its versatility in bonding various types of woven fabrics. These resins are commonly employed as structural adhesives in diverse fields such as the automotive industry, ship components, or aerospace applications. The epoxy/hardener ratio has been applied at 4:1 in accordance with the catalog directives. As reinforcement material, plain woven glass fiber weighing 220 g/m² was purchased from Carbomid company. Graphite particles were obtained commercially from Ege Nanotek company. The epoxy, hardener, glass fiber fabric, and graphite filler to be used in composite production were meticulously weighed according to pre-determined quantities on a precise balance. To ensure the homogeneous dispersion of graphite particles added to the epoxy resin, the mixture was stirred for 10 minutes at 1500 revolutions per minute, following which the hardener was introduced into the blend.

Fabric pieces, cut to dimensions of 100 mm x 100 mm, were placed on a flat surface, and the epoxy mixture was applied to each fabric layer using a roller to allow for impregnation into the fabric, resulting in the production of 10-layered plates. To prevent the formation of air bubbles and to remove excess epoxy, weights were placed on the composite plates. For both filled and unfilled plates produced using the hand lay-up method, the composite materials were left at room temperature for 24 hours for curing.

Samples measuring 50 mm x 25 mm were cut from the plates for use in wear testing. Figure 1 illustrates the steps involved in the production of composites, while Table 1 displays the quantities of components used in the manufactured composites. Table 2 and Table 3 show technical properties of glass fiber and catalog information of graphite particles, respectively.

Table 1. Composite specimens designation

Specimen	Epoxy (%)	Glass fabric (%)	Graphite Filler (%)
No filler (Neat)	50	50	0
4 % Gr Filler (G4)	48	50	2
8 % Gr Filler (G8)	46	50	4
12 % Gr Filler (G12)	44	50	6

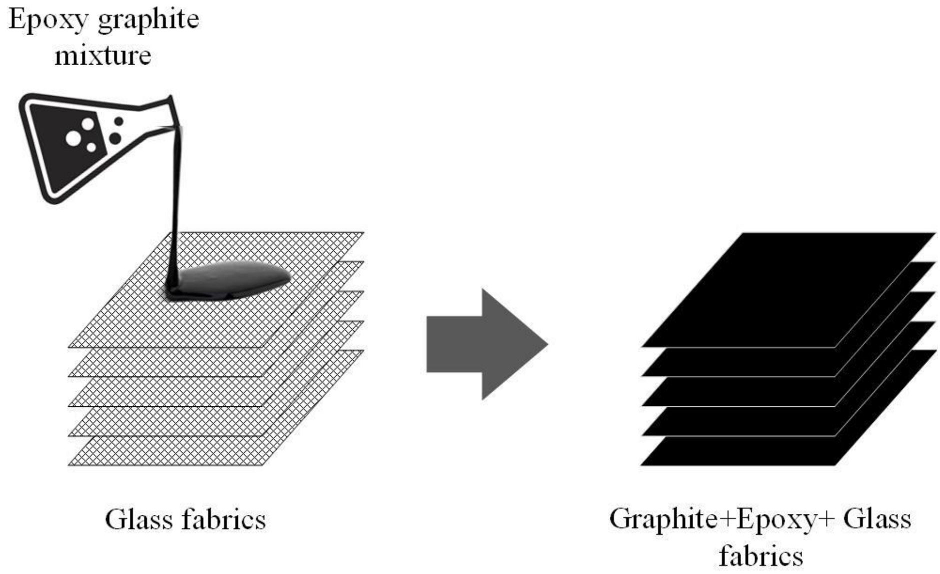

Figure 1:
Composites production stages

Table 2. Technical properties of glass fiber

Glass Fiber Type	Weight(gr/cm^2)	Thickness (mm)	Tensile Strength (MPa)	Elasticity Modul (GPa)	Weave	Thread Count (fd/cm)	
						Warp	Weft
CM 220	220	0.35 mm	1280 MPa	65	Mesh	1.8	1.8

Table 3. Catalog information of graphite particles

Particle Size	325 mesh
Purity (%)	99.9
Density (gr/cm^3)	2.09-2.23
Color	Grayish black

2.2. Wear Test

Abrasive wear tests were conducted on the TURKYUS (Figure 2) branded pin-on-disk apparatus in accordance with ASTM-G99 standards under dry sliding conditions. The test specimens were secured onto the rotating disk using screws, and the rotational speed was set to a constant 350 revolutions per minute. Subsequently, the applied load was determined by placing it on the application arm, followed by adjusting the sliding distance and time from the control panel of the wear testing apparatus. For each test parameter, 2 experiments were performed and the results obtained were averaged.

For the abrasive wear tests, three different loads (7 N, 10 N, 15 N) and two distinct sliding distances (200 m, 400 m) were applied.

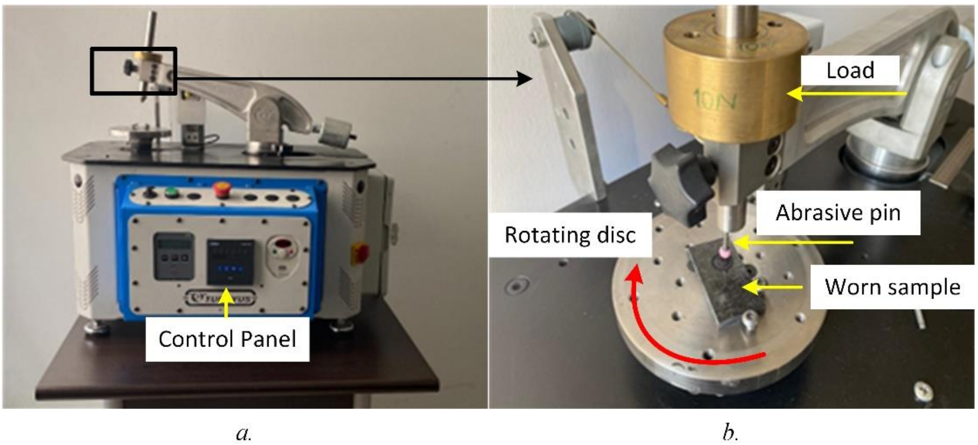

Figure 2:
a. *Wear device* ***b.*** *A close-up view of the abrasion region.*

After the completion of the tests, the data obtained from the apparatus was transferred to a computer environment, and the data was transformed into graphical representations. The width of the wear track was taken as the basis for determining the wear volume. Following the conclusion of the test, the width of the wear track on the worn specimens was measured at four different points under a microscope, and the average was calculated. The equation utilized for the calculation of the wear volume is provided below:

$$V = 2\pi R\left[r^2 \sin^{-1}\left(\frac{d}{2r}\right) - \left(\frac{d}{4}\right)\sqrt{4r^2 - d^2} \right] \tag{1}$$

Where V is volume loss in mm^3, R is diameter of wear trace, r is abrasive pink grinding radius and d is wear trace width

3. RESULTS AND DISCUSSION

Figure 3 displays the temporal evolution of the COF of unfilled and graphite-filled composites under a 7 N load and 200 m sliding distance.

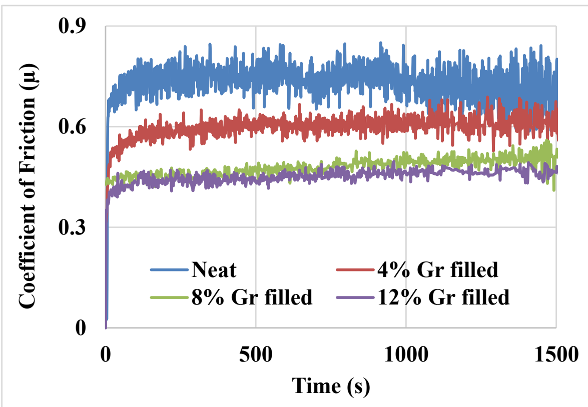

Figure 3:
Variation in COF with Filler Ratio

The highest and lowest COFs were obtained for the neat composite and the composite with a 12% graphite filler content, respectively. In the friction graph of the neat composite, it can be observed that higher wavelengths emerge due to an increase in surface roughness caused by wear. In the case of filled composites, the lubricating property of graphite contributes to a lower COF.

Furthermore, with an increase in wear duration in both neat and filled composites, it was observed that as the abrasive pin removed more material from the epoxy surface and reached the underlying glass fiber layer, causing more surface degradation, the wavelengths increased towards the end of the test. At a 4% filler ratio, lower degradation of the surface integrity led to a smoother wavelength trend. In the case of 8% and 12% filled composites, the fluctuation of COF followed a similar trend, suggesting that the composite becomes saturated with graphite at 8% and above. These observations are validated by the surface morphology of the worn surface, depicted in Figure 4 and Figure 5.

Table 2. Coefficient of friction values depanding filler ratio (μ)

Sliding Distance and Load	Neat	4%Gr filled	8% Gr filled	12% Gr filled
200m 7N	0.73	0.6	0.48	0.45
200m 10N	0.65	0.58	0.45	0.43
200m 15N	0.67	0.67	0.46	0.36
400m 7N	0.93	0.57	0.55	0.51
400m 10N	0.85	0.55	0.52	0.45
400m 15N	0.77	0.46	0.46	0.39

Table 2 shows the effect of load and sliding distance on COF's values of neat and graphite-filled composites. Upon analyzing the graph, it becomes evident that an increase in load leads to a reduction in the COF for both filled and neat composite types. It can be seen that while the COF for neat composite is 0.73 at 200 m and 7 N load, it decreases to 0.67 at 15 N load. As the load increases, the temperature of the polymer increases, causing a thin film layer to form between the abrasive counter surface and the worn material, resulting in a decrease in COF. Similar studies conducted with graphite-filled composites have also indicated that an increase in load leads to a decrease in the COF, and consistent results have been obtained with this study (Zhang et al., 2009; Wang et al., 2010). Shivamurthy et al. have indicated that the decrease in the coefficient of friction with an increase in load in graphite-filled composites is attributed to the graphite particles separating from the sample surface and acting as a lubricant by getting trapped between the abrasive and the worn piece (Shivamurthy et al., 2013). The lowest COF, 0.37, was observed in the 12% graphite-filled composite material at a sliding distance of 200 m and a load of 15 N. On the other hand, the highest COF, 0.93, was found in the neat composite at a sliding distance of 400 m and a load of 7 N.

Table 2 revealed that when the sliding distance of the 8% graphite filled composite for a 7 N load was increased from 200 m to 400 m, the friction coefficient increased by 14%, from 0.48 to 0.55. It is apparent that an increase in sliding distance causes to an increase in the COF.

The addition of graphite filler to the glass fiber-reinforced composite leads to a significant decrease in the COF. Graphite acts as a solid lubricating material, contributing to the reduction in the COF (Akram et al., 2013;). At a sliding distance of 200 m and a load of 10 N, the addition of 4% graphite to the unfilled composite reduced the friction coefficient of the composite by 10%, from 0.65 μ to 0.58 μ. It is understood that as the graphite filling ratio increases, the friction coefficient of the composite gradually decreases. The most dramatic friction coefficient decrease occurred in the 4% filled composite at 400 m sliding distance and 7 N load. It is believed that the graphite filler forms a lubricating graphite film on the abrasive surface, leading to a reduction in the COF. This phenomenon has been addressed in a study by Alajmi et al. (2020), where they discussed this effect.

Table 3. Wear volume values depanding filler ratio (mm^3)

Sliding Distance and Load	Neat	4%Gr filled	8% Gr filled	12% Gr filled
200m 7N	2.65	0.23	0.12	0.09
200m 10N	4.29	0.38	0.30	0.27
200m 15N	10.19	0.67	0.46	0.36
400m 7N	6.51	0.86	0.47	0.56
400m 10N	7	1.14	0.66	0.79
400m 15N	20.72	1.68	0.86	1.11

Table 3 illustrate the change in wear volume of neat and graphite-filled composites with varying loads and sliding distances in abrasive wear tests. It is evident that the increase in graphite filler content and filler ratio in the composite significantly contribute to reducing the wear volume. The lowest wear volume was obtained in the 12% graphite-filled composite at all loads and sliding distances, while the highest was observed in the neat composite. For a sliding distance of 200 m and a load of 15 N, the wear volume of the neat composite was 10.19 mm^3, whereas it reduced to 0.67 mm^3 in the 4% graphite-filled composite. Increasing the filler ratio from 4% to 8% at the same load and sliding distance resulted in a 31% reduction in wear loss. Graphite is a material where carbon atoms are arranged in a hexagonal pattern. The layers in the structure of graphite are bonded to each other through weak van der Waals bonds, while the atoms within the rings are bonded by strong covalent bonds. The presence of two different bond structures allows the crystal structure of graphite to move in different directions. Moreover, the weak van der Waals bonds between the layers enable them to slide over each other, thus assuming the role of a solid lubricant and enhancing wear resistance (Suresha et al., 2007). The examination of Table 3 reveals that in the case of a 4% graphite-filled composite, with a 200 m sliding distance and a 7N load, the wear volume decreased by 91%, dropping from 2.65 mm^3 to 0.23 mm^3. Upon increasing the graphite content to 12%, the WR further decreased to 0.09 mm^3 under the same load and sliding distance conditions. The most dramatic reduction in wear volume occurred with the addition of 4% graphite in the neat composite. A similar study has highlighted that both an increase in load and sliding distance are important factors contributing to an increase in wear volume (Suresha et al., 2010). When the impact of load on wear volume is examined, increasing the load has led to an increase in wear volume. For a 200 m sliding distance, elevating the load from 7N to 15N resulted in an escalation of wear volume from 2.65 mm^3 to 10.19 mm^3 in the neat composite, and from 0.09 mm^3 to 0.36 mm^3 in the 12% graphite-filled composite.

It is apperant that increasing the sliding distance has a detrimental effect on the wear volume in both neat and filled composites. In the neat composite, increasing the sliding distance from 200 m to 400 m at a 10 N load resulted in a 164% increase in wear volume, rising from 2.65 mm^3 to 7 mm^3. In the 8% graphite-filled composite, under the same wear parameters, the wear volume increased from 0.3 mm^3 to 0.66 mm^3.The primary reason for this difference can be attributed to the adhesion between the filler material and the matrix. Although filler materials significantly reduce wear, the wear losses due to adhesion have become proportionally higher with increasing distance and load. Suresha et al. observed that in graphite-filled fiber-reinforced composites, the wear volume increases linearly with the increasing wear distance (Suresha et al., 2009).

When all parameters are considered together, it is understood that the most effective parameter on COF and wear volume is the filler material. Taking into account the combined effect of load and sliding distance on wear volume, it is concluded that the load has a more pronounced impact on increasing wear volume.

4. WORN SURFACE EXAMINATION

Figure 4 displays microscopic images of the worn surfaces of unfilled and graphite-filled composites at a constant sliding distance of 200 m and varying loads. In Figure 5, SEM images of abraded unfilled and filled composites are presented under a 7N load and a sliding distance of 200 m.Upon examining the images, it can be observed that in graphite-filled composites, the scratches on the worn surfaces appear smoother, the outer matrix layer is less damaged, and a narrower wear path is formed. In the case of the neat composite, it is evident that there is more matrix debris generated, deeper pits, and cracks compared to the graphite-filled composite at the same load and sliding distance. Additionally, as the abrasive interacts with the composite for longer durations and at higher pressures due to increased load and sliding distance, plastic deformation intensifies, leading to a deeper and broader wear surface.

Upon closer examination of the wear surfaces, it is observed that the scratches become more distinct with increasing force. Furthermore, an increased graphite ratio is associated with the formation of non-worn areas on the surface, highlighting the pronounced lubricating property of graphite. When examining Figure 5, in the case of the unfilled composite, it is apparent that more matrix debris, deeper pits, and cracks occur compared to the graphite-filled composite under the same load and sliding distance. Additionally, the fibers under the epoxy matrix were more prominently exposed.

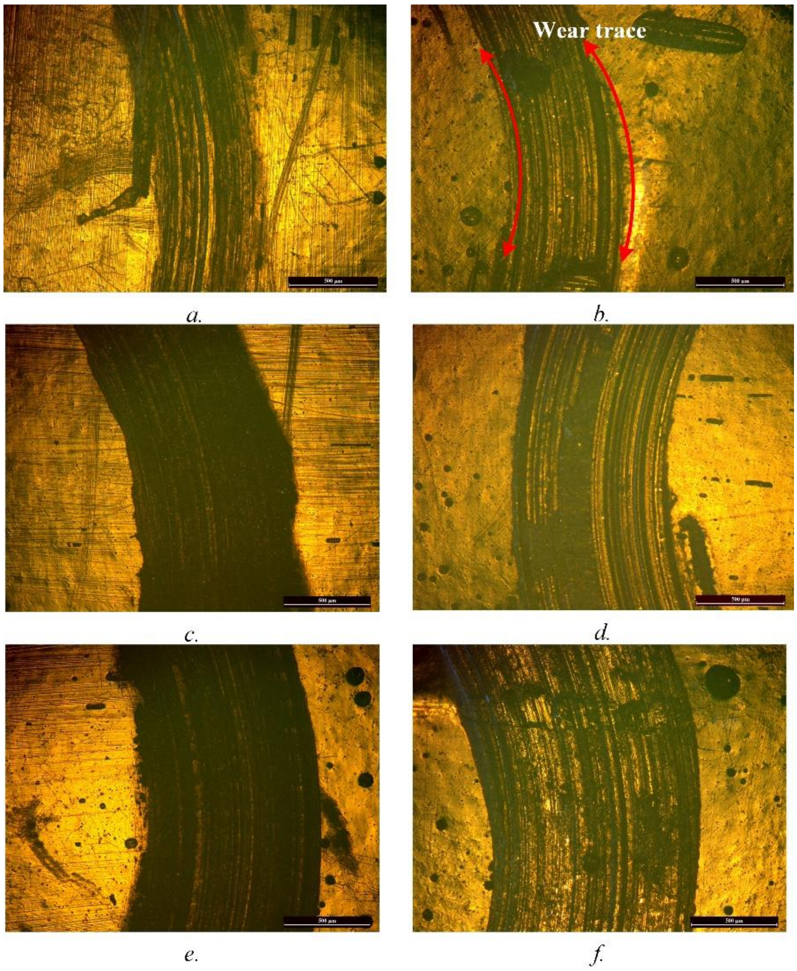

Figure 4:
*Wear change on unfilled and filled composite surface due to increasing load: **a.** Neat, 7 N **b.** 4%Gr filled, 7 N **c.** Neat, 15 N **d.** 4%Gr filled, 15 N **e.** Neat, 15 N **f.** 12%Gr filled, 15 N*

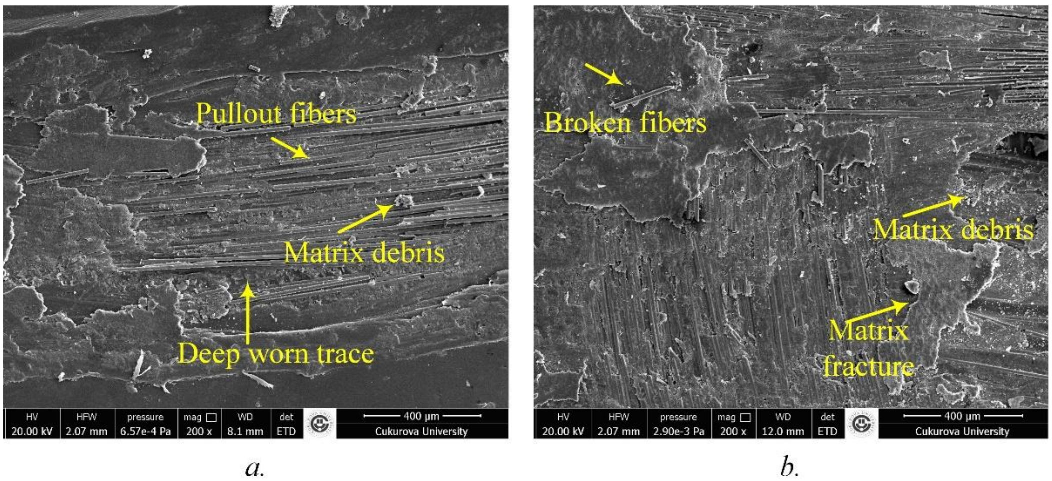

Figure 5:
*SEM image of neat and filled composite: **a.** Neat **b.** 4% Gr filled*

5. CONCLUSIONS

The results obtained from testing composite materials produced using varying ratios of graphite filler under different wear parameters are presented below.

- The COF increased inversely with the increase in load and directly with the increase in sliding distance.
- The wear volume exhibited an increasing trend with both an increase in load and sliding distance. The effect of sliding distance on wear volume was more pronounced and negative. In the neat composite, the highest wear volume was 10.19 mm^3, while the lowest was 2.65 mm^3.
- Graphite filler and increased filler content contributed to a reduction in the composite's COF. The highest COF was 0.93 μ in the unfilled composite, whereas the lowest was 0.37 μ in the composite with 12% filler.
- The addition of graphite filler significantly enhanced the wear resistance of the glass fiber-reinforced composite. The lowest wear volume was achieved with a 12% filler content, measuring 0.09 mm^3.
- Upon examining the microstructures of the worn surfaces, it is observed that the scratches in unfilled composites are wider and deeper, with more significant epoxy damage and frequent pitting. In graphite-filled composites, wear pits are shallower, wear scars are narrower, and there is less matrix debris.

CONFLICT OF INTEREST

Author(s) approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

AUTHOR CONTRIBUTION

The author Mehmet Emin DEMİR has contributed throughout all stages of the study and is responsible for every aspect of the work.

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