

Comparison of Tribological Performance of Polyoxymethylene/Graphite Composite and Pure Polyoxymethylene Polymer

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Abstract

The friction and wear characteristics of engineered thermoplastics, namely unfilled polyoxymethylene (POM) and 10% graphite-filled polyoxymethylene (POM+10%Gr), sliding on steel under dry conditions were investigated using a pin-on-disc tribometer. The influence of applied load and sliding speed on the tribological properties of POM and POM+10%Gr on a steel counterface under dry sliding conditions was examined. Experimental results showed that the coefficient of friction (COF) of the POM and POM+10%Gr polymers decreased with increasing applied load. In addition, the wear rate (WR) values of the POM and POM+10%Gr polymers decreased with the increase in applied load. However, for all polymers, the specific wear rate values exhibited an increase with the rise in sliding speed. The best polymer material is found which is POM+10%Gr with respect to friction and wear behavior in this study. The worn surfaces of the engineering thermoplastics were investigated by optical microscope. Optical micrographs indicated that adhesive wear was the predominant wear process under dry sliding circumstances.

Keywords: Friction, Graphite, POM, Tribology, Wear.

1. Introduction

Polyoxymethylene (POM), a thermoplastic polymer, is one of the most prominent polymers with low friction and wear properties. It also provides advantages for use in different tribological areas with its good fatigue resistance properties. These characteristics have led to their widespread use as self-lubricant materials for making parts such as gears and bearings in electrical/electronic, automotive and precision equipment [1-3]. POM polymer has a typical spiral chain structure consisting of alternating carbon-hydrogen bonds. It has exceptional solvent resistance and self-lubricating characteristics owing to the high degree of uniformity in its molecular structure [4]. Certain additives are included in polymers to enhance their mechanical, thermal, tribological, or electrical characteristics. Choosing the right additives and the right manufacturing process is essential to achieve the desired performance, especially in tribological

applications. Polymer compounds made with various additives and/or strength enhancers have widespread industrial applications. Polymers incorporating solid lubricants have been extensively studied for industrial and military applications, with a notable increase in research activity in recent years. Some solid lubricants such as molybdenum disulfide (MoS₂), graphite (Gr) and polytetrafluoroethylene (PTFE) have excellent wear rate (WR) and low friction properties. Such solid lubricants are widely used to solve tribological problems in applications where liquid lubricants are difficult or inadequate to use in production. Solid lubricants, originally developed for aerospace applications, are now used in many industries [5-6]. Graphite is one of the solid lubricants used in polymer composites to reduce the material's coefficient of friction (COF) while increasing WR. The basal graphitic planes (hexagonal layers resulting from sp² hybridization) held together by weak van der Waals forces are easily broken during sliding, resulting in low COF [7]. The capacity of graphite to create a superior

film transfer on the counter disc surface results in a reduction of the COF of the polymer composite, consequently enhancing WR [8-9]. A review of the literature reveals that the tribological dynamics of various graphite-filled polymer materials have recently garnered attention in research [10-15]. It is well known that the incorporation of graphite into polymer composite materials as a solid lubricant may result in an improvement in the tribological characteristics of these materials. Chang et al. [16] investigated the tribological properties of short carbon fiber and graphite filled and nano-TiO₂ filled polyetherimide (PEI) composites under different sliding conditions. As a consequence of their research, scientists realized that the particular wear rate of the graphite-filled PEI polymer had dramatically dropped to $7.7 \times 10^{-7} \text{ mm}^3/\text{Nm}$ when subjected to the usual test conditions. About the WR of pure PEI polymer, it was discovered that this WR was around 800 times lower. Zhang et al. [17] found that the COF and WR of polyphthalazinone-ether-sulfone-ketone (PPESK) composites gradually decreased with the addition of graphite. Moderate SWR and low COF were obtained by increasing the graphite addition of PPESK above 20 wt%. Similar results were obtained in acrylonitrile butadiene styrene-based composites and it was determined that the addition of 7.5 wt% graphite was the optimum amount in tribological terms [5]. The best tribological results were obtained with a graphite content of 20 wt% in polyamide6 polymer composites containing different concentrations of graphite (5-40 wt%) [14]. Jia et al. [18] investigated the COF and WR values of polyimide-based composites prepared by adding expanded graphite at different ratios. The results of studies showed that 15% by weight gave the best tribological results. Using ultra-high molecular weight polyethylene (UHMWPE) composites that were filled with MoS₂ and macro-sized graphite, Panin et al. [19] studied the WR qualities of these various materials. Their results demonstrated that MoS₂ and graphite added to the UHMWPE polymer increased the WR by 1.3 times. Using POM polymer and additives including PTFE, LDPE, graphite, and MoS₂, Hu et al. [20] examined the wear and friction behavior of POM blends and composites.

In the present study, the tribological properties of graphite filled POM have been investigated as alternatives to pure POM widely used in industry. The experiments were conducted using a wear device featuring a pin on the disc. Tribological testing was conducted with 50N and 150 N loads in dry sliding circumstances at sliding speeds ranging from 0.5 to 2.0 m/s. It was found that the solid graphite lubricant additive added to the POM polymer at a rate of 10% significantly reduced the wear rate of the composite.

2. Materials and Methods

The pure POM polymer and graphite filled POM polymer composite used in the experiments were obtained from Cleanese Co. in rod form with the commercial code Hostaform POM. The tribological tests were carried out according to dry sliding circumstances at the temperature of the surrounding environment. The experiments were conducted using the pin-disc wear device, which is illustrated in Figure 1.

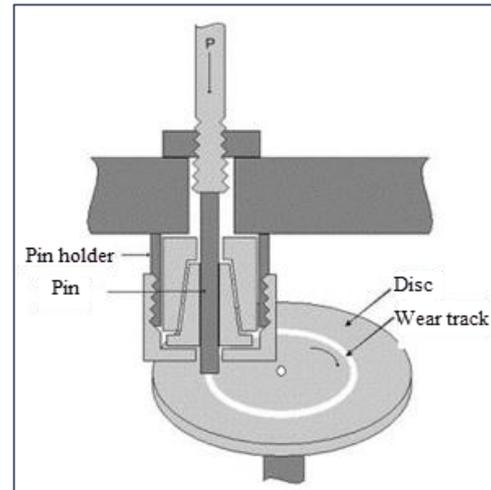


Figure 1. Schematic illustration of pin-disc wear tester.

Injection-molded pin specimens measuring 50 mm in length and 6 mm in diameter were used for tribological testing. Steel discs serve as the material for counter discs. The disc material was machined on a conventional lathe with a diameter of 90 mm and a thickness of 5 mm and then ground on a plane surface grinding machine. Before every wear test, the disc and pin surfaces were wiped with acetone and allowed to dry. Table 1 shows the wear test parameters of the materials used in the study. The specimen pin weight (m_1) before each wear test and the pin weight (m_2) after the wear test were measured and the weight loss Δm , i.e. ($m_1 - m_2$) was determined. The WR was determined using the formula presented in Equation (1). The formula uses L for the sliding distance (m), ρ for the material density (g/cm^3), and F for the applied load (N).

$$WR = \frac{\Delta m}{L * F * \rho} \quad (2.1)$$

Following is the formula for calculating the COF. In the formula, F_N is the normal load and F_s is the friction force between the steel disc and the pin measured with a load cell. In the experiments, approximately 1000 data per minute were taken during the experiment. The data were simplified to plot the COF-sliding distance graphs.

$$COF (\mu) = \frac{F_s}{F_N} \quad (2.2)$$

Table 1. Conditions for testing the experimental samples.

Materials	Density (g cm ⁻³)	Test Temperature (°C)	Sliding Distance (m)	Humidity (%)	Speed (m s ⁻¹)	Load (MPa)
POM	1.42	18±2	2000	23±3	0.5	50
POM+10%Gr	1.35	15±2			1.0	
					1.5	150
					2.0	

2. Results and Discussion

Within the context of the applied load and sliding velocity, the COF for pure POM and POM+10%Gr composites are shown in Table 2. Figure 2 demonstrates the sliding distance versus COF curve for POM and POM+10%Gr composites under 50 and 150 N at 0.5 m/s sliding speed.

Table 2. Test conditions of the experimental samples.

Materials	Load (MPa)	Speed (m/s)			
		0.5	1.0	1.5	2.0
		Coefficient of friction (μ)			
POM	50	0.2594	0.2459	0.2486	0.1896
	150	0.2203	0.2247	0.2284	0.1652
POM+10%Gr	50	0.1284	0.1492	0.1484	0.1564
	150	0.1181	0.1308	0.1335	0.1422

There are two distinct phases to the COF: the running-in phase and the steady-state phase. The COF became stable after equilibrium was reached between the transfer film layer (TFL) formed on the disc surface and the removal of this layer from the disc surface. The COF measured during the running-in phase is often greater than the one measured during the steady state [15]. This occurs because, during the running-in period, the polymer pin and disc surfaces exhibit surface roughness. Now that the pin and disc surfaces are touching, the COF is increased [14]. There have been reports that indicate the following: during the running-in period of POM composites that were fortified with polytetrafluoroethylene (PTFE), a high COF was obtained in direct contact between the sliding block and the steel ring. After a certain amount of time (1000 seconds), the COF stabilized [4]. There is a connection between this and the TFL that is created on the surface of the disk. As can be seen in the figure, the steady-state period was obtained around 800-900 m under a 50 N load, while the steady-state period was obtained at a distance of approximately 600-650 m under a 150 N load. The TFL established on the counter disc surface has been shown to considerably decrease the transition distance to the steady state phase. The weak Vander Waals bonds present in the layered structure of graphite allow for the easy disruption of the graphite arrangement when subjected to shear forces during sliding conditions. The distribution of graphite flakes on the sliding surface is symmetrical, effectively minimizing direct contact between the composites and the steel disc [5]. Perego et al. [21] indicated that samples exhibiting higher crystallinity demonstrated

improved heat resistance, resulting in the POM/particle system having enhanced tolerance to temperature increases, alongside a reduction in both the COF and volumetric wear rate.

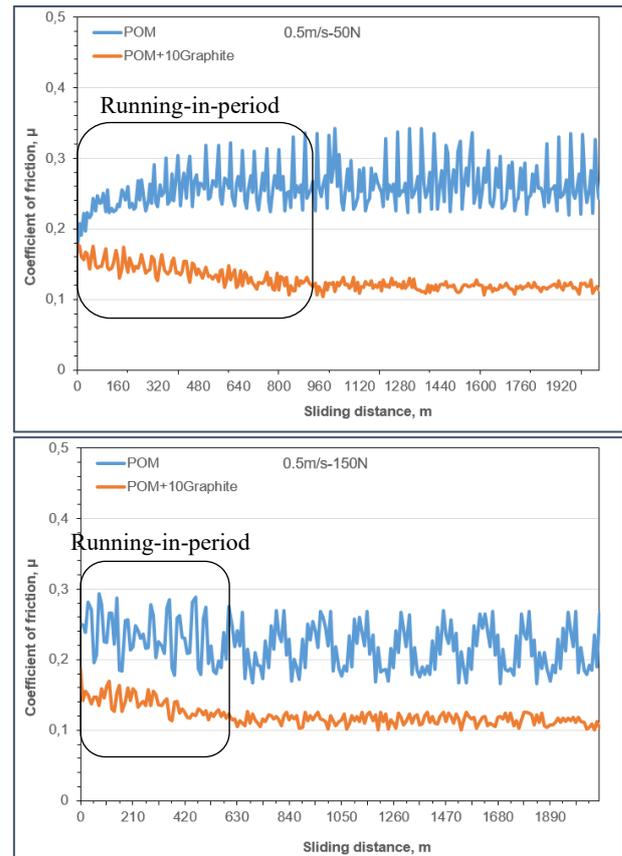


Figure 2. COF-sliding distance relationship of POM and POM+10%Gr composites.

Figure 3 shows the COF variations of POM+10%Gr composite with pure POM polymer under 50 N and 150 N loads at 0.5, 1.0, 1.5 and 2.0 m/s sliding speeds. When the graphs are analyzed, the COF decreased with increasing the applied load from 50 N to 150 N. When sliding at speeds of 0.5, 1.0, 1.5, and 2.0 meters per second, respectively, the COF of the pure POM polymer decreased by 15.07%, 8.62%, 8.12%, and 12.86% on average. When the COF results of the POM+10%Gr composite are evaluated, the reduction in COF is found as 8.02%, 12.33%, 10.04% and 9.07% for sliding speeds of 0.5, 1.0, 1.5 and 2.0 m/s respectively. The results of the sliding speed and COF changes of pure POM and POM+10%Gr composite demonstrate that the COF of pure POM polymer decreased significantly due to increasing sliding speed, while that of POM+10%Gr

composite increased. When the sliding speed was raised from 0.5 m/s to 2.0 m/s, the pure POM polymer's COF dropped by an average of 25%. The COF of the POM+10%Gr composite increased by 21% depending on the sliding speed. Under dry friction conditions, an increase in pin surface temperature due to the frictional heat accumulated at the contact point leads to an increase in adhesive friction. Polymer pin specimens sliding against a steel disk exhibit adhesive-induced-friction component that are directly proportional to the contact area and shear strength of the polymer, as is well known. It is common for the frictional heat to raise

the contact temperature between the polymer pin and the steel disc as the load increases. The COF has two opposing impacts as a result of this. While the decrease in shear strength reduces the COF, the modulus of elasticity of the composite decreases due to increasing temperature. As a consequence, this results in an increase in the contact area, which eventually leads to an increase in the COF. As the applied load increases, the TFL is easily formed due to the increase in adhesion force between the polymer pin and the steel disc. This results in lower COF and lower WR due to the reduced degree of wear [15].

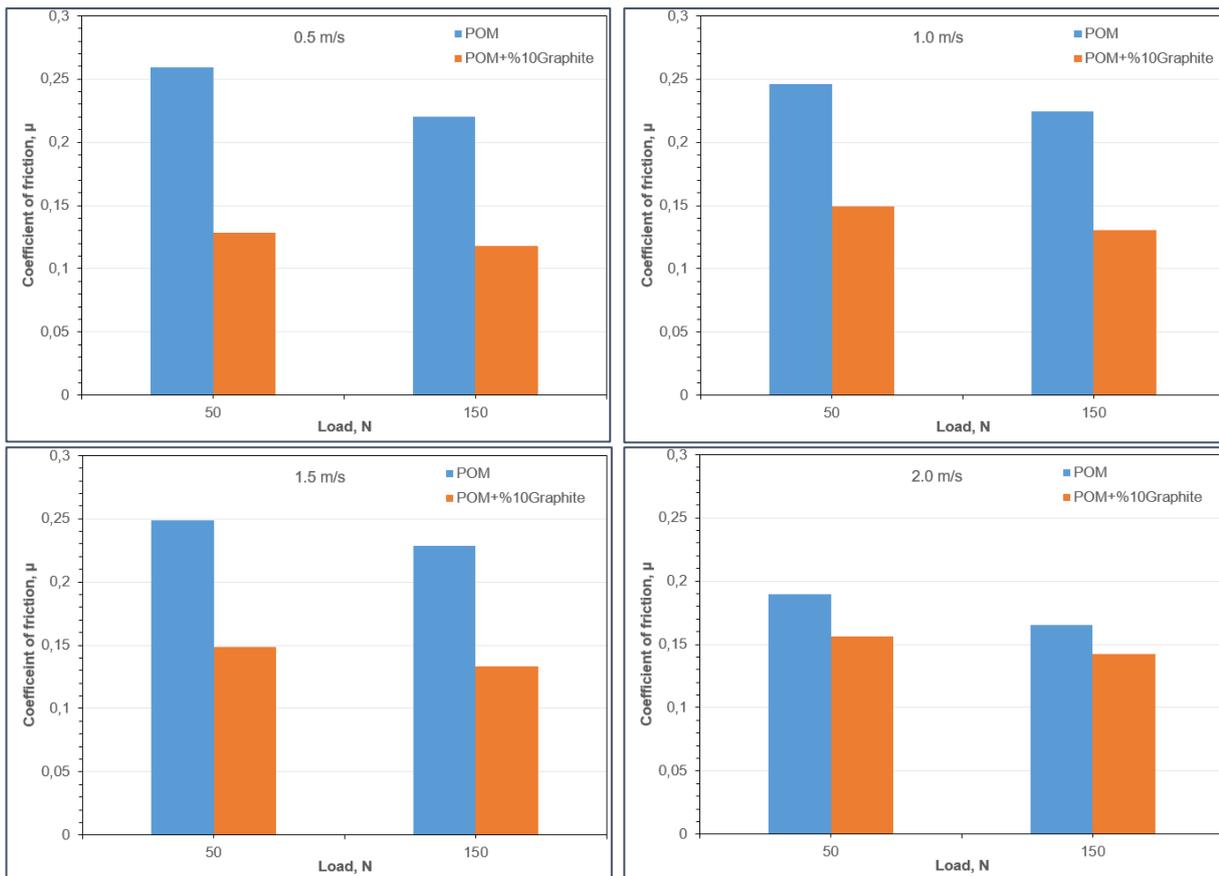


Figure 3. The correlation between the COF and load for POM polymer and POM+10%Gr composites.

When compared to pure POM polymer, the effect of sliding speed on the COF for the POM+10%Gr composite was found to be much more pronounced when the load was increased. For the POM+10%Gr composite, the reduction in contact area with increasing sliding speed played an important role in the formation of the TFL. The COF for the pure POM polymer was measured between 0.16 and 0.25, varying with sliding speed and load, whereas the COF for the POM composite containing 10% graphite showed a notable decrease. The COF ranged from 0.11 to 0.15, contingent upon the weight and sliding velocity. Compared to the COF of POM polymer without additives, the COF of the POM+10%Gr composite was reduced by approximately 40%. The lowest COF with a value of 0.11 was obtained in the POM+10%Gr composite under 0.5 m/s sliding

speed and 150 N load. Similar results were obtained in studies investigating the wear and friction properties of graphite filled Polyamide 6 (PA6) and Polyimide (PI)/glass fiber composites [14-15]. This can be attributed to the good dispersion of small solid lubricants in the polymer matrix, which acts as a lubricant [15, 22]. The assessment of the impacts of sliding speed, applied load, and graphite doping indicated that graphite doping was more effective in reducing the COF.

Table 3 shows the WR values of pure POM polymer and POM+10%Gr composite depending on the applied load and sliding speed. Figure 4 illustrates the variations in WR for pure POM polymer and POM+10%Gr composite subjected to loads of 50 N and 150 N at

sliding speeds of 0.5, 1.0, 1.5, and 2.0 m/s. The findings indicated that elevating the applied load from 50 N to 150 N diminished the WR, whilst augmenting the sliding speed from 0.5 m/s to 2.0 m/s escalated the WR. The WR of pure POM polymer declined by 34.4% as the load increased. This reduction was 23.7% for POM+10%Gr composite. The increase in the quantity of graphite particles that get separated from the polymer matrix as a consequence of plastic deformation brought about by the impact of the applied force and the creation of a tribo-film at the sliding contact is the cause of the reduction in WR that occurs as the load increases [23]. This TFL reduces the hardness of the counter surface and prevents further mass loss from the composite, resulting in increased wear resistance. Adhesive wear becomes dominant with increasing applied load. When the polymer pin was in contact with the steel disc during the abrasion test, the contact surface of the sample experienced both a rise in temperature and abrasion. The sliding contact between the pin and the disc results in the creation of heat on the surfaces, which thus leads to a rise in temperature [24].

Table 3. The WR of POM and POM+10%Gr composites are affected by the sliding speed and the applied load.

Materials	Load (MPa)	Speed (m/s)			
		0.5	1.0	1.5	2.0
		Wear rate (m ² /N)			
POM	50	8.1E-14	1.1E-13	1.1E-13	1.2E-13
	150	5.8E-14	6.6E-14	7.2E-14	7.7E-14
POM+10%Gr	50	4.3E-14	5.6E-14	6.2E-14	6.1E-14
	150	3.6E-14	4.2E-14	4.6E-14	4.4E-14

The WR of the pure POM polymer increased by approximately 41.2% depending on the sliding speed, while the WR of the POM+10%Gr composite increased by an average of 32.8%. A considerable decrease in the WR was seen as a consequence of the incorporation of solid graphite lubricant into the pure POM polymer at a composition of 10%. When the data of the WR were compared under a sliding speed of 1.0 meters per second and a load of 100 N, the estimated wear rate fell by 35.7%. This is likely attributable to the self-lubricating characteristics of the 10% graphite additive incorporated into the pure POM polymer. When graphite particles form a strong bond with the main polymer matrix material, the applied loads are transferred from the matrix to the graphite particles. They protect the polymer sample from the severe abrasive mechanism of the steel disc due to the strong interfacial bond, which plays an important role here [14]. In addition, heat is generated, and the temperature rises on the rough surfaces of the two materials that come into contact with each other. The heat dissipation rate of POM polymer increases gradually with the

addition of graphite [25]. This heat must be evenly distributed over the contact surface. Graphite particles exhibit remarkable antifriction characteristics that effectively dissipate heat from the contact surface over time [14]. Similar results were obtained in different studies [4, 10, 26]. Within the limits of applied load and sliding speed, the POM+10%Gr composite demonstrated a good level of wear resistance and a low COF.

For the purpose of conducting wear studies on disc surfaces composed of pure POM polymer and POM+10%Gr composite, the loads applied were 50 N and 150 N, and the sliding speeds were 0.5 and 1.0 m/s. The optical images that were produced as a consequence of these experiments are shown in Figure 5. As seen in the figure, it is observed that a thin TFL is formed on all disc surfaces depending on the applied load and sliding speed. It was observed that the pure POM polymer did not form a continuous film covering the entire wear track. A limited quantity of dark-hued streaks aligned with the shear direction and a thin polymer layer formed along these streaks was seen. In the case of the POM+10%Gr composite, the surface of the disc was coated with a patchy layer of transfer film. This TFL covered the rough surfaces of the steel disc, reducing the effect of abrasive wear and promoting the adhesive wear mechanism [27]. It is possible to explain the decrease in the COF and WR by referring to the formation of a TFL on the surface of the counter steel disc. The transfer layer enables the pin to slide against the opposing surface by diminishing mechanical resistance from surface roughness or a reduction in contact force, while also mitigating mechanical locking and frictional force using solid lubricants in contact [2].

Figure 6 illustrates the morphology of the worn pin surfaces for pure POM polymer and 10%Gr filled POM composites subjected to a load of 150 N and a sliding velocity of 1.0 m/s. Figure 6-a shows the prominent wear marks typical of plastic deformation of the pure POM polymer. This is due to the rough surface of both the pin specimen and the steel disc surface at the contact point. This surface roughness will cause some heat generation and softening of the POM polymer matrix under dry sliding conditions. The hard rough protrusions on the steel disc surface will abrade the soft polymer and cause wide and deep wear marks as shown in Figure 6-a. The wear surface of the 10% graphite-filled POM composite exhibited a notable smoothness, characterized by the presence of more superficial wear marks and grooves aligned with the sliding direction. It is possible to trace this phenomenon to the production of a TFL on the surface of the steel disc, as shown in Figure 6-b. Similar results were obtained in the study investigating the tribological properties of PTFE-filled POM composites [4].

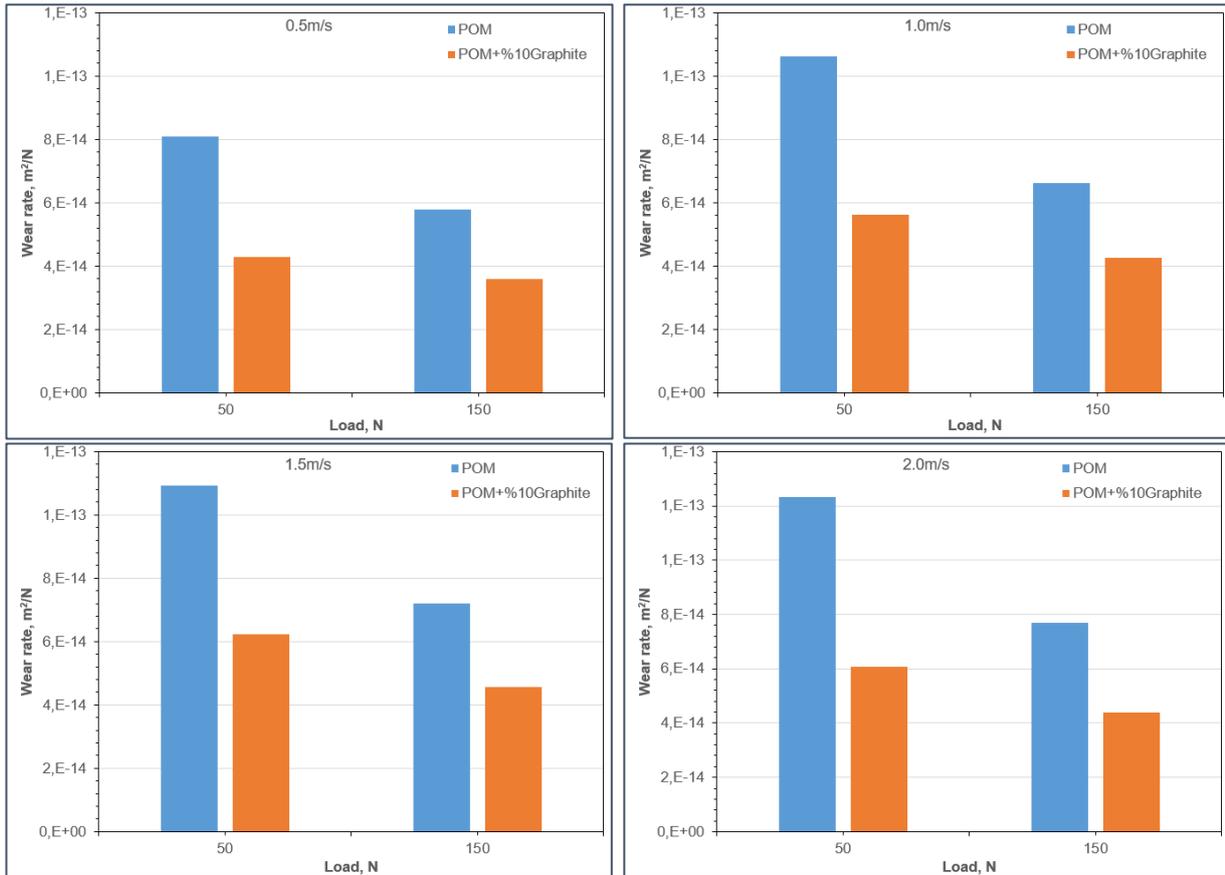


Figure 4. WR-load relationship of POM and POM+10%Gr composites.

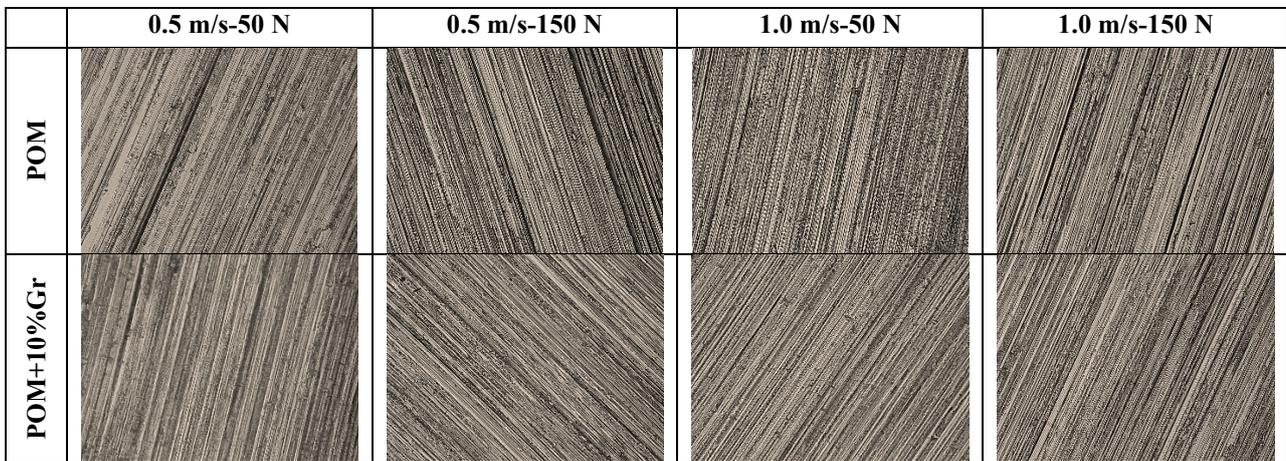


Figure 5. Optic micrographs of worn disc surfaces.

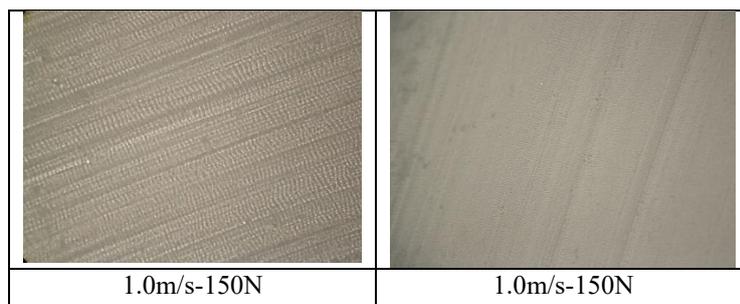


Figure 6. Optic micrographs of worn pin surfaces

3. Conclusion

As a consequence of the findings of the research in which the tribological properties of pure POM and POM composites with 10%Gr addition were investigated, the COF decreased with the increase of the applied load. When the sliding speed was increased, the COF of pure POM polymer dropped due to the increased sliding speed. However, the COF of POM+10%Gr composite increased. The addition of 10% graphite doping to the pure POM polymer base matrix reduced the COF of the composite by approximately 40%. The WR decreased as the applied load increased, whereas it increased with greater sliding speed. Although it varies with sliding speed, the WR of the pure POM polymer increased by approximately 41.2%, while the wear rate of the POM+10%Gr composite increased by approximately 32.8%. The graphite TFL on the steel disc's surface decreased wear by creating a thin film, so rendering the adhesive wear mechanism predominant.

Author's Contributions

Hüseyin ÜNAL: Assisted in analysis on the structure, supervised the experiment's progress, result interpretation and helped in manuscript preparation.

Salih Hakan YETGİN: Drafted and wrote the manuscript, performed the experiment and result analysis.

Sinan KÖSE: Drafted and wrote the manuscript, performed the experiment and result analysis.

Ethics

There are no ethical issues after the publication of this manuscript.

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