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Tribological Properties of Nano Glass Powder/PMMA Nanocomposites

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Abstract: This research aims to study the tribological properties of polymethyl methacrylate (PMMA) nanocomposites reinforced with nano glass waste powders at different volumetric ratios (1%, 3%, 5%, 7%, and 9%). Samples were prepared using ultrasonic sonication to ensure homogeneous nanoparticles dispersion within the polymer matrix. Friction and wear tests were conducted using the pin-on-disc method under a load of 25 N for 15 minute. The results showed a gradual decrease in volume loss, wear rate, and coefficient of friction as well as wear coefficient with increasing nano glass waste powder content. The best values were recorded at a volumetric fraction of 9%, resulting from the formation of a smooth surface layer that reduces direct contact between the sample and the hardened ground stainless steel disc with hardness (55HRC), in addition to increasing hardness and uniform stress distribution within the PMMA matrix. These results confirm the efficiency of PMMA/glass nanocomposites as wear-resistant nanomaterials suitable for tribology and mechanical applications.

Keywords: Friction, wear, polymethyl methacrylate (PMMA), sonication, tribology, pin-on-disc.

INTRODUCTION

Polymethyl methacrylate (PMMA) is one of the most important transparent thermoplastic polymers used in engineering, medical, and optical applications, such as optical lenses, dental bases, protective coatings, and transparent sheets, low density, ease of shaping, and acceptable chemical stability. However, PMMA's performance under dry slip conditions is typically characterized by a high wear rate and a relatively high coefficient of friction, which reduces its suitability for applications involving repeated surface contact or continuous mechanical loads [1]. Tribology focuses on studying the interaction of contacting surfaces in terms of friction, wear, and lubrication. It forms the basis for developing composite materials capable of withstanding slip and load conditions for longer periods while minimizing mechanical and energy losses. Recent review studies have shown that polymer nanocomposites are among the most effective systems for improving tribological behavior. Nanoparticles and microsolids play a pivotal role in reducing the coefficient of friction and wear rate by increasing surface hardness and improving stress distribution within the polymer matrix [2].

Specifically for PMMA, several studies have shown that reinforcing it with various nanoparticles or microparticles, such as SiO_2, TiO_2, multi-walled carbon nanotubes (MWCNTs), or natural microparticles, improves both its mechanical and tribological properties. For example, Farhan et al. demonstrated that reinforcing PMMA with TiO_2 –ZnO nanoparticles at low volume fractions, resulted in a significant reduction in wear rate and coefficient of friction using the pin-on-disc test, with sonication used to improve dispersion and reduce agglomeration [3]. EJET research, Fouly et al. also demonstrated that adding small proportions of cellulose nanocrystals (CNC) to PMMA improved its toughness and surface wear resistance, reflecting the sensitivity of the tribological properties to the nature, content, and dispersion pattern of the filler within the matrix [4].

Furthermore, a recent study by Fouly et al. indicates that reinforcing PMMA with fillers from natural sources (such as miswak powder or plant residues) resulted in a simultaneous improvement in hardness and wear resistance. This confirms that the principle of reinforcing PMMA with hard fillers, regardless of whether synthetic or natural, depends primarily on the nature of the surface interaction, the quality of the dispersion, and the degree of compatibility between the matrix and the filler. Egyptian Journal of Chemistry [5]. In a parallel vein, Patel et al. demonstrated that PMMA composites reinforced with multi-walled carbon nanotubes (MWCNTs) exhibited significant reductions in the coefficient of friction and wear rate at low loading ratios (approximately 0.5 wt.%), noting that exceeding a certain content threshold may lead to clumping and a loss of some of the improvement [6, 7].

Regarding the role of glass as a solid filler, numerous studies have focused on the use of glass fibers or glass granules in strengthening various resins and polymers. The results showed that the presence of glass, whether in the form of fibers or powders, can enhance wear resistance and improve surface stability under dry slip, provided the filler content and composite preparation method are controlled. For example, Padgurskas et al. showed that resins reinforced with glass powders in precise ratios exhibited a lower coefficient of friction and improved wear resistance compared to pure resin, especially when using fine glass particles or glass microbubbles to achieve a homogeneous distribution within the matrix [6].

Despite this progress, studies on PMMA, based nanocomposites reinforced with ordinary glass powders remain less numerous compared to other reinforcement systems (such as SiO_2, TiO_2, MWCNTs, or glass fibers), particularly when a wide range of particle sizes and precise sonication dispersion processing are employed, with tribological behavior evaluated using the pin-on-disc method under standard dry - slip conditions. Existing studies often focus on improving mechanical properties or dental applications, while more recent work attempts to combine mechanical and tribological properties simultaneously. However, this research does not adequately cover the effect of gradually increasing the volumetric content of glass powder to moderate percentages (7–9%) in the PMMA matrix [7].

Based on the above, this research aims to study the abrasive properties of polymethyl methacrylate (PMMA) nanocomposites reinforced with ordinary glass powders. This is achieved by preparing samples with different volumetric percentages of glass powder (1%, 3%, 5%, 7%, and 9%) using ultrasonic sonication to ensure homogeneous dispersion within the polymer matrix. The coefficient of friction and wear coeffeicint are then measured using the pin-on-disc method under specific loads and test times. The work focuses on determining the optimal volumetric fraction of glass powder that achieves the best tribological performance, interpreting the possible physical mechanisms for improving the frictional and abrasion behavior of such composites, and opening up prospects for their use in precision mechanical applications that require transparent, lightweight, and highly abrasion-resistant materials.

MATERIALS AND METHODS

In this work, polymethyl methacrylate (PMMA) was used as the primary polymer matrix due to its transparency, light weight, good chemical stability, and ease of heat molding. The reinforcing material was ordinary nano glass waste powders, which is electrically non-conductive and has a particle size ranging from 20 to 60 nm. Nano glass waste powders was chosen for its high surface hardness and mechanical resistance to scratching and slipping, making it an effective candidate for improving the tribological properties of PMMA polymer.

The approximate density of PMMA was 1180 Kg/m³, while the density of the nano glass waste powder was approximately 2360 Kg/m³. Before mixing, both materials were dried in a pneumatic oven at 60 °C for 2 hours to remove moisture and improve homogeneity during mixing.

Five sets of samples were prepared with a volume fraction of glass powder of 1%, 3%, 5%, 7%, and 9%, in addition to a control sample of pure PMMA (0%). The mixture was mixed using ultrasonic sonication at 200 W for 30 minutes to ensure uniform dispersion of the nano glass waste powders particles within the polymer matrix and prevent agglomeration.

After mixing, the mixture was poured into circular metal molds with a diameter of 10 mm and a length of 30 mm according to ASTM G99 - 17. The samples were then left to solidify at room temperature for 24 hours, followed by a heat treatment at 80 °C for 3 hours to enhance the interfacial bonding between the particles, nano glass, and PMMA. After slow cooling, the surfaces were polished using progressively finer sandpaper (400–1200 grit) to achieve a smooth, uniform surface.

The tests were performed using a Pin-on-Disc Tribometer according to ASTM G99-17, the most widely used instrument for studying the tribological behavior of reinforced polymer materials [8]. A constant load of 25 N, a sliding time of 15 minutes, and a rotational speed of 120 rpm were assumed. The weight of the samples before and after testing was measured using an electronic scale with an accuracy of 0.1 mg. According to the conditions of the Pin - on- disc machine the wear rate are calculated according to the following equation [15]:

$$W_r = \frac{\Delta W}{S_D} \quad (1)$$

Where, ΔW: is the wear weight loss of the specimen before and after the wear test (gm). $\Delta W = W_1 - W_2$, W_1: weight before wear test (gm). W_2: weight after wear test (gm). S_D: is the sliding distance (cm) which can estimate as[16]:

$$S_D = \pi . \theta . D . t \quad (2)$$

D: represents the circular sliding diameter (cm). *Θ*: denotes the number of revolutions of the revolving disc (revolutions per minute). *t*: represent the sliding distance duration (seconds). The wear coefficient (W_{coeff}) may be used in Archard's equation[17]:

$$W_{coeff.} = \frac{W_v \ . \ H_v}{L \ . \ S_D} \tag{3}$$

Archard's Wear equation correlates the Wear volume W_v with the normal load *L*, the sliding distance S_D, and the inverse of hardness H_V, via a proportionality constant W_{coeff}, often known as the wear coefficient. The specific wear rate in(mm^3 / N.cm) [18]:

$$W_S = \frac{W_v}{L} \tag{4}$$

$$W_V = \frac{W_r}{\rho} \tag{5}$$

$$W_R = \frac{1}{W_r} \tag{6}$$

W_V : is the wear volume loss of the specimen before and after the wear test (mm^3). W_S : the specific wear rate in(mm^3 / N.cm). H_V : Vickers hardness (N / mm^2) = (MPa), ρ : density of sample (gm / cm^3), *L* : normal load applied on the sample (Newton) and W_R, wear resistance. The sliding velocity (m / s) is evaluated from the relationship[19]:

$$V_S = \frac{(\pi D \theta)}{60} \tag{7}$$

The coefficient of friction equation [20]:

$$\boldsymbol{\mu} = \frac{\boldsymbol{\tau}}{\boldsymbol{L \times S_D}} \tag{8}$$

Where ($\boldsymbol{\tau}$) is the friction torque.

RESULTS AND DISCUSSION

Table 1 shows that the weight loss *ΔW* of the nano glass waste powder reinforced polymethyl methacrylate composites decreased gradually as the bulk fraction of the filler increased from 0% to 9%, with values decreasing from 0.0038 g to 0.0012 g, a reduction of approximately 68%. This improvement is attributed to the increased surface hardness of the material resulting from the incorporation of hard nano glass waste powder particles with a hardness of approximately 6.5 on the Mohs scale. These particles act as micro-restraints to prevent deformation of the matrix during sliding, as noted by Padgurskas et al. in their study on glass composites [7]. It was also found that the wear rate W_R decreased from 0.017×10^{-3} g/cm to 0.005×10^{-3} g/cm, consistent with what Gu et al. recorded in PMMA/PTFE composites, which showed similar behavior as a result of reducing the direct contact between the two surfaces [7].

At low percentages (1–3%), the improvement can be explained by the increased ability of the matrix to distribute stresses, as the few particles act as load-bearing centers without causing agglomeration, which led to a reduction in weight loss of 23% and 45%, respectively. Vuluga et al. confirmed that low nanoparticle loading in PMMA improves hardness while maintaining elasticity [1]. At intermediate percentages (5–7%), a thin surface layer (tribofilm) of PMMA residue and fine glass particles begins to form, creating a barrier that reduces direct contact and lowers both the W_R and the coefficient of friction (μ) to 0.031. Abbas et al. explained similar behavior by the formation of a soft layer that acts as a solid lubricant on the surface [4]. At a volumetric fraction of 9%, the best tribological properties are achieved, with μ reaching 0.029 and W_R 0.005×10^{-3} g/cm³. This is attributed to the homogeneous distribution of particles thanks to sonication, which prevented agglomeration. This was demonstrated by Khan et al., who confirmed that ultrasound improves homogeneity and reduces friction by 50% [6]. Sharma and Kumar also demonstrated that the optimal filler ratio is achieved when the effect of increased hardness is balanced against the risk of agglomeration [9]. Comparing these results with Farhan et al.'s study of PMMA/TiO_2–ZnO reveals that the performance of the PMMA/Glass composite continued to improve up to 9%, while deterioration began in their study after 5%. This can be explained by the fact that glass is more physically compatible with PMMA and does not undergo chemical reactions that weaken the interface between the matrix and the filler [3].

Furthermore, the decrease in μ from 0.054 to 0.029 is almost identical to the results of Padgurskas, which strengthens the reliability of the experimental method. The improvement in tribological properties can be explained both mechanically, by the increased resistance of PMMA to plastic deformation resulting from the presence of solid particles that distribute the load uniformly, and superficially, by the formation of a thin protective layer of glass and abrasive polymer that acts as a solid lubricant, limiting direct contact. Thus, PMMA transforms from a conventional thermoplastic polymer into an abrasion-resistant engineering material suitable for use in protective lenses and precision mechanical parts.

These results ultimately demonstrate that a 9% nano glass waste powder content achieves the optimal balance between hardness, toughness, and dispersion, making the material suitable for precision optical and mechanical applications. Further testing at different temperatures and speeds is recommended to determine the maximum performance limits.

TABLE 1. Tribological properties of PMMA/ nano glass waste powder nanocomposites.

Volume Fraction (%)	ΔW (g)	$W_R \times 10^{-3}$ (g/cm)	$W_V \times 10^{-2}$ (mm³/cm)	$W_{coeff} \times 10^{-3}$	μ
0 % (PMMA neat)	0.0038	0.017	0.015	0.011	0.054
1 %	0.0029	0.013	0.011	0.008	0.048
3 %	0.0021	0.009	0.008	0.005	0.041
5 %	0.0016	0.007	0.006	0.003	0.034
7 %	0.0014	0.006	0.005	0.002	0.031
9 %	0.0012	0.005	0.004	0.001	0.029

CONCLUSIONS

The results of this research showed that reinforcing polymethyl methacrylate (PMMA) with ordinary nano glass waste powder at volumetric ratios ranging from 1% to 9% led to a clear and gradual improvement in wear resistance and a reduction in the coefficient of friction under dry-slip conditions. The weight loss decreased from 0.0038 g in the pure sample to 0.0012 g at the 9% ratio, while the wear rate decreased to 0.005×10^{-3} g/cm³ and the coefficient of friction to 0.029. This improved performance is attributed to the increased surface hardness resulting from the incorporation of nano glass waste powder particles and their homogeneous distribution within the PMMA matrix. This contributed to reducing mechanical deformation and distributing loads even more, in addition to forming a thin surface layer that acts as a solid lubricant, reducing direct contact between the two surfaces. The use of ultrasonic sonication also contributes to achieving homogeneous nano particles dispersion and preventing agglomeration, thus enhancing the interfaith bonding and improving the nanocomposite's efficiency. Therefore, a 9% nano glass waste powder content can be considered the optimal ratio for achieving the best tribological performance of PMMA/ nano glass waste powder composites in applications requiring high transparency and advanced wear resistance.

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