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Effect of Water Absorption on Tribological Properties of Thermoplastics Matrix Composites Reinforced with Glass Fibres

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ABSTRACT

The present work investigated the water absorption of thermoplastic matrix composites and their effect on tribological behaviour. Four thermoplastic composites were researched based on Polyamide 6 and Polyamide 66 matrix reinforced with glass fibres. The composites fabricated using the injection moulding technique were immersed in distilled water at room temperature for a water absorption test for 14 days. Dry sliding wear was conducted using a ball-on-disc trbiotester. The coefficient of friction (COF) and the wear rate (K) was determined. The sliding trace was analyzed using a scanning electron microscope (SEM) to reveal the sliding wear mechanism of composites. Studies have shown that polyamide PA6 based composites are less prone to absorb water than PA66 matrix. In addition, the composites richer in fibreglass exhibit lower water absorption. Tribological results indicated that polymer composites showed higher COF and K after water absorption testing. Mean COF and K were in the range of 0.071÷0.321 and $2.51\cdot10^{-6}\div1.81\cdot10^{-4}$ mm^{3}N^{-1}m^{-1}, respectively. Wear traces SEM analysis revealed that untreated samples are characterized by less intense abrasive and adhesive wear mode than the hydrated polymers. Besides, the degradation process took place primarily at the polymer matrix-fibreglass interfaces.

Keywords: sliding wear, tribology, friction coefficient, water absorption, polymer composites, glass fibres, wear rate, polyamide.

INTRODUCTION

The tribological performance of thermoplastics is a severe problem in all branches of the mechanical industry [1]. One of the most general ideas of sliding wear investigation relies on pin-on-disc or ball-on-disc tribotester and testing procedure enablest to estimate the wear resistance of different material systems such as metals [2], ceramics [3], and composites [4]. Wear due to abrasive solid particles or sliding counterbody action, especially in humid operational environments, deteriorates the components made of polymer matrix composites [5]. Good lubricity and low weight, and new manufacturing technologies being developed favours the application of polymers as an alternative to metallic materials [6]. Polymers are lightweight have good specific strength. Abrasive wear is one of the dominant deterioration processes in polymer tribology [7]. Machine parts such as chute bushings, roller guides, automotive reciprocating parts, agricultural equipment, cams and clutch components, etc., can undergo severe wear [1]. Therefore, there is a demand for composites displaying high strength and good tribological performance. The application of composite materials could fulfil these requirements.

Research into the tribological properties of composites provides helpful information for increasing the service life of manufactured components in industrial applications: aerospace, automotive, marine and engineering structures. Polymer composite foam materials and natural and synthetic fibres are mainly used in these applications. Therefore, analyses of tribological performance taking into account the operating environment such as dry, wet, dust conditions is an important stage of material selection for fabrication of specific components [9]. The wear resistance of polymer materials depends not only on the mechanical and structural properties but also on the operational conditions, appropriate selection of friction pair materials [7, 9] and the top layer preparation and surface integrity (structural discontinuities, roughness) [10–12]. In addition, elements manufactured from thermoplastics materials are prone to UV radiation, moisture, variable mechanical loads and destruction associated with polymer matrix ageing processes, which can accelerate the overall component degradation [13, 14].

The wear mechanism of polymers differs from those reported for polymer composites, e.g. reinforced with solid particles such as glass fibre. In the case of tribological testing of polymer composite, the counterpart randomly hooks on the fibres, breaks and affects their foundation, and finally removes fibres with a portion of the polymer matrix. Moreover, the wear of reinforced material usually initiates while fibres on the top surface damage due to fibre failure, then matrix cracking and fibre kinking [15].

Mechanical properties of thermoplastic-based materials vary enormously on environmental conditions, thus their performance on humidity and temperature [16, 17]. Moisture and water absorption is essential when selecting fibre-reinforced composites for outdoor structures [18]. As shown in the papers [19–21], materials with high water absorption swell in all dimensions, and the absorbed water molecules adversely affect the interaction of the polymer matrix with fibres which can stimulate the growth of bacteria. In turn, polyamides applied for sliding purposes are designed in unmodified and reinforced structures. The reinforcement, which has mainly a powder of fibrous morphology, usually facilitates dimensional stability and allows you to reduce water absorption.

Therefore, this paper aimed to assess the impact of water absorption on the tribological behaviour of polyamide matrix composite reinforced with glass fibre.

MATERIALS AND TEST METHODS

Materials

Current research investigates four thermoplastic composites based on Polyamide 6 (PA6) and Polyamide 66 (PA66). Composites were reinforced with glass fibres. Three samples were manufactured by Grupa Azoty S.A. (Tarnów, Poland), and the fourth specimen was made by BASF The Chemical Company (Ludwigshafen, Germany). The specification of the tested samples is given in Table 1. Bulk materials used in the research were commercially fabricated using the injection moulding technique, see Figure 1. Specimens dedicated to water adsorption and tribological tests were machined to obtain 22× 22×4 mm (L×W×D) rectangular dimensions.

Water absorption test

The composite samples were dried at 50 ± 2 °C for 24 hours in a Binder MKFT climate

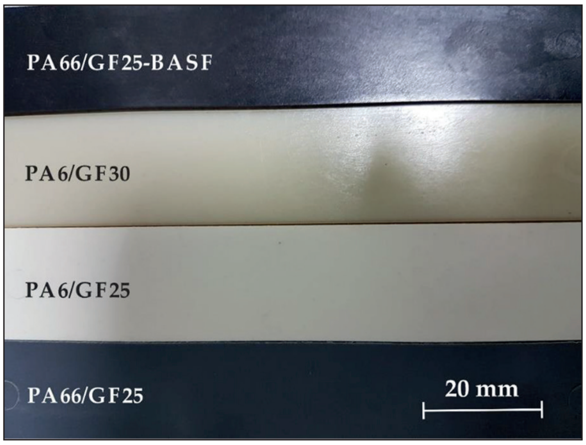

Fig. 1. Thermoplastics matrix reinforced using glass fibres manufactured using the injection moulding technique

Table 1. Characteristics and samples codes of the investigated materials

Sample codes	Trade mark	Matrix type	Content of glass fibres (wt. %)	Manufacturer
PA6/GF25	Tarnamid®	PA6	25	Grupa Azoty S. A.
PA6/GF30	Tarnamid®	PA6	30	
PA66/GF25	Tarnamid® A	PA66	25	
PA66/GF25-BASF	Ultramid® A3XZG5	PA66	25	BASF The Chemical Company

chamber (Binder, Germany) and then immersed in a vessel filled with distilled water. Five repetitions were done to obtain statistical accuracy. The samples were weighed with an electronic balance WAS220/X (Radwag, Poland) with an accuracy of ±0.1 mg. Samples were immersed for 14 days in distilled water (pH = 6.5) at 23±2 °C. Water absorption (WA) of polymer composites was calculated using the following equation (1):

$$\mathrm{WA}(\%) = \frac{W_t - W_i}{W_t} \times 100 \tag{1}$$

where: W_t represents the weight of the specimen at a certain immersion time t and W_i represents the initial weight of the specimen before soaking in water.

Sliding wear test

The coefficient of friction (COF) and wear factor (K) were characterized on a ball-on-disc tribotester (Fig. 2) (CSM Instruments, Switzerland) at room temperature of 22 °C. Calibrated balls with a diameter of ø6 mm made of 100Cr6 bearing steel were used as counter balls. The tribological tests were carried out under a load of 25 N; a linear speed of 0.1 m /s, and a sliding radius of 3 mm. The friction coefficient fluctuations were recorded during the sliding distance, which was equal to 300 m. The volume loss of the sample was measured using the Dektak 150 contact profilometer (Veeco Instruments, United States). The profilometer probel radius tip was 2 µm. The volume loss was estimated at the wear trace circumference cross-sections (in 12 locations). Next, the so-called wear factor (wear rate) K was determined according to equation (2) [22]. This formula combines the sliding load, material loss and the sliding distance.

$$K(mm^3N^{-1}m^{-1}) = \\ = \frac{Wear\ volume}{Applied\ force \times sliding\ distance} \tag{2}$$

Wear traces morphology and sliding wear mechanism were analyzed using the scanning electron microscope (SEM, Phenom-World, Waltham, MA, USA).

RESULTS AND DISCUSSION

Water absorption behaviour

The water absorption (WA) results are presented in Figure 3. It can be noted that the polyamide PA6 matrix composites present a lower tendency to absorb water compared to polyamide PA66 matrix composites. Besides, increase in the ratio of fibreglass from 25 wt.% to 30 wt.% decreased water absorption by c.a. 13.3%. Additionally, a composite made of Polyamide PA66 has more favourably WA than the products of Grupa Azoty S.A. In general, the absorption of water by polymer composites reinforced with fibres occurs due to diffusion, capillary, and transport of water molecules [18]. In addition, diffusion takes place within microseals in polymer structure [23]. Capillary transport occurs in the gaps and structural discontinuities - mainly at the fibre-matrix phase

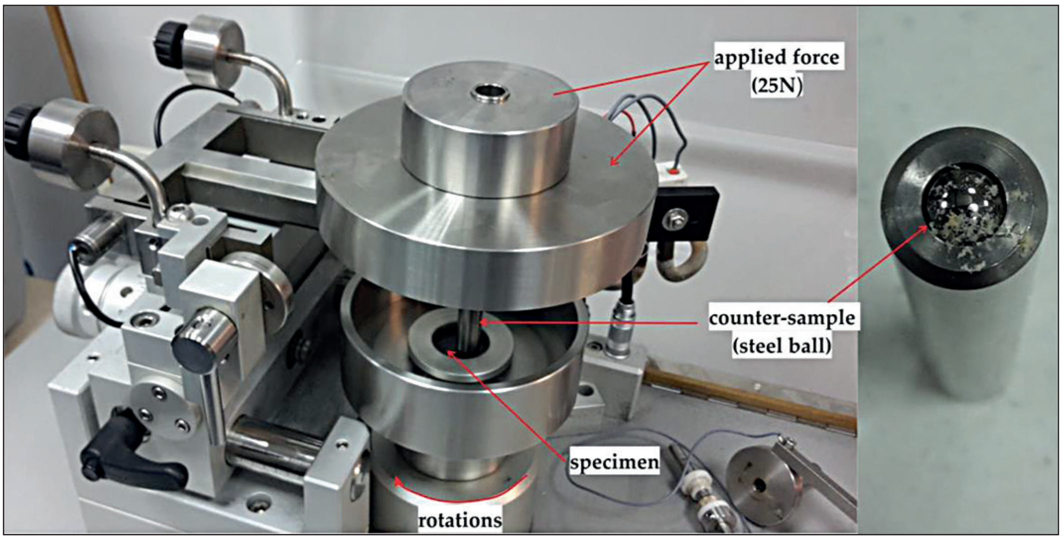

Fig. 2. View of the ball-on-disc rig used for tribological testing

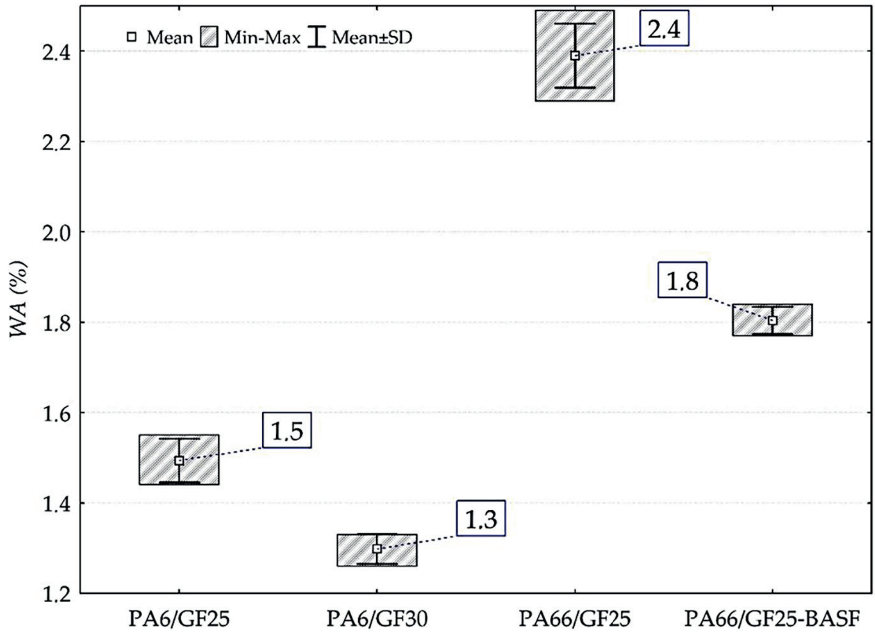

Fig. 3. Results of water absorption test of investigated polymer composites

interfaces. Such a phenomenon is related to wettability and refers to incomplete impregnation of the reinforcement by a polymer matrix during production [24]. In addition, moisture absorption may increase the specific volume of the polymer composite, leading to mismatches in the dimensions of the finally manufactured part [18].

Sliding wear

Analysis of tribological results showed an increase of the coefficient of friction (COF) for composites after water absorption tests (Fig. 4). However, weaker statistical importance was observed for the PA6/GF30 specimen. The top layer of composites, due to the steel ball abrasive action, especially with absorbed water, is subject to severe degradation resulting in glass filler detachment and transfer through the wear trace. Therefore, it leads to an increase in COF. Tribological deterioration is supported by water absorption. Structural discontinuities and fibre-matrix interfaces are crucial for separating glass fibres from the matrix. Moreover,

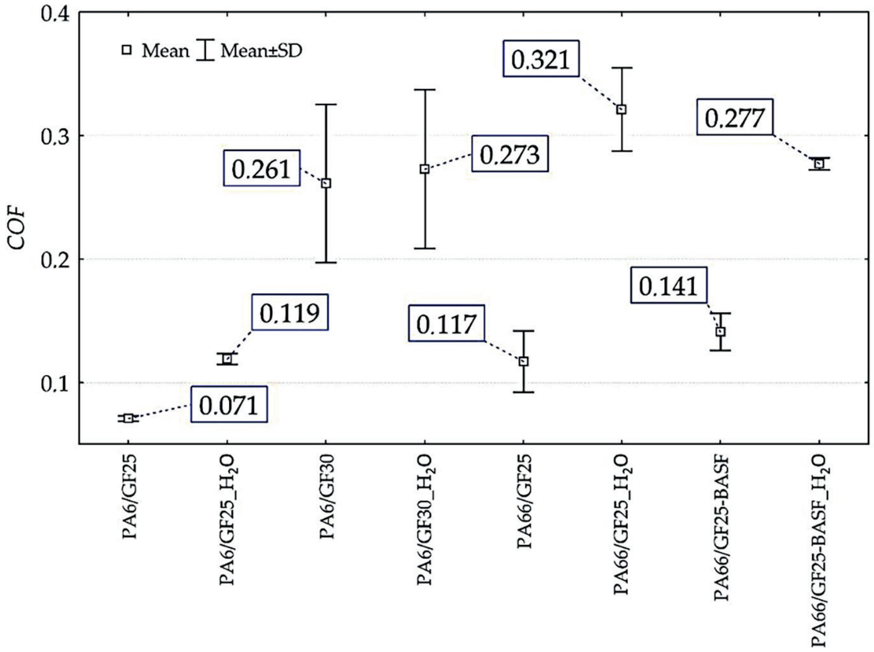

Fig. 4. Comparison COF of thermoplastic matrix composites sliding wear investigated before and after water absorption

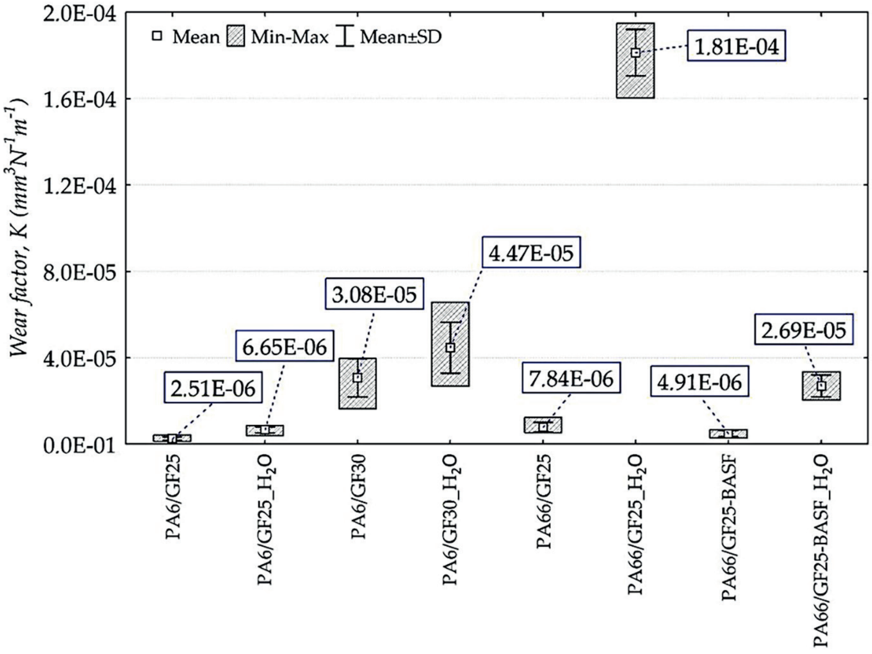

Fig. 5. Comparison wear factor (K) of thermoplastic matrix composites before and after water absorption

the presence of the wear debris hinders the steel counter ball sliding over a composite surface and consequently increases the COF. Overall, the lowest COF was recorded for polyamide PA6 based composites than those based on PA66.

The wear factor K has been employed the estimate the wear resistance (Fig. 5). Analysis of graphs (Fig. 4 and 5) indicates that samples with low COF also obtained low K-factor records. In addition, the percentage increase of reinforcement does not correlate with wear resistance, and it seems that such type of composite should not be selected for machine parts operating in friction conditions. The best wear resistance was reported for PA6/GF25 composite, which also obtained a relatively low wear factor estimated for water-absorbing treatment. In addition, comparing the PA6/GF25 composite results with the results given reported for polymers used for sliding nodes manufactured by Igus® (K = $2.78 \cdot 10^{-6} \div 1.44 \cdot 10^{-5}$ $mm^3N^{-1}m^{-1}$) [9], the wear factor for PA6/GF25 (tested in both dry and water absorbed conditions) looks exceptionally favourable. Bearing in mind the obtained COF values and the K-factor for PA6/GF25, it can be assumed that this composite would perform well in technically dry friction conditions and humid environments.

Analysis of worn composites

The SEM micrographs presented in Figure 6 shows severely damaged surfaces of polymer composites reinforced with glass fibre, which resulted from sliding wear action. Numerous delamination has been observed. In the vicinity of the fibres, the scratches and microcracks of the polymer matrix are visible. In addition, one can observe craters formed after matrix delamination and transfer of the removed material. This indicates the adhesion of polymer material to the steel ball, related to an increase in temperature in the friction area resulting in loss of solidity of the polymer matrix. The transfer of wear products by the countersample action is visualized in Figure 6. Studies [9, 25, 26] also indicate that as a result of long-term tribological processes, polymer-metal friction pair changes into polymer-polymer cooperation due to polymer film formation. At the same time, wear products enriched with detached glass fibres can determine increasing material loss and COF.

Besides, the wear traces analysis indicates that all types of composites wear relates to abrasive and adhesive wear modes. In addition, the fatigue wear mechanism facilitated the overall damage of composites. It relies on cyclic deformation, leading to the growth and propagation of microcracks in the matrix. SEM images (Fig. 7) shows that samples previously tested for water absorption were much more seriously damaged, and additionally, numerous delaminations and severe material loss are observed in the wear trace.

Following the results given in works [24, 27], it can be claimed that the water absorbability of composites can be sped up by the loads applied in

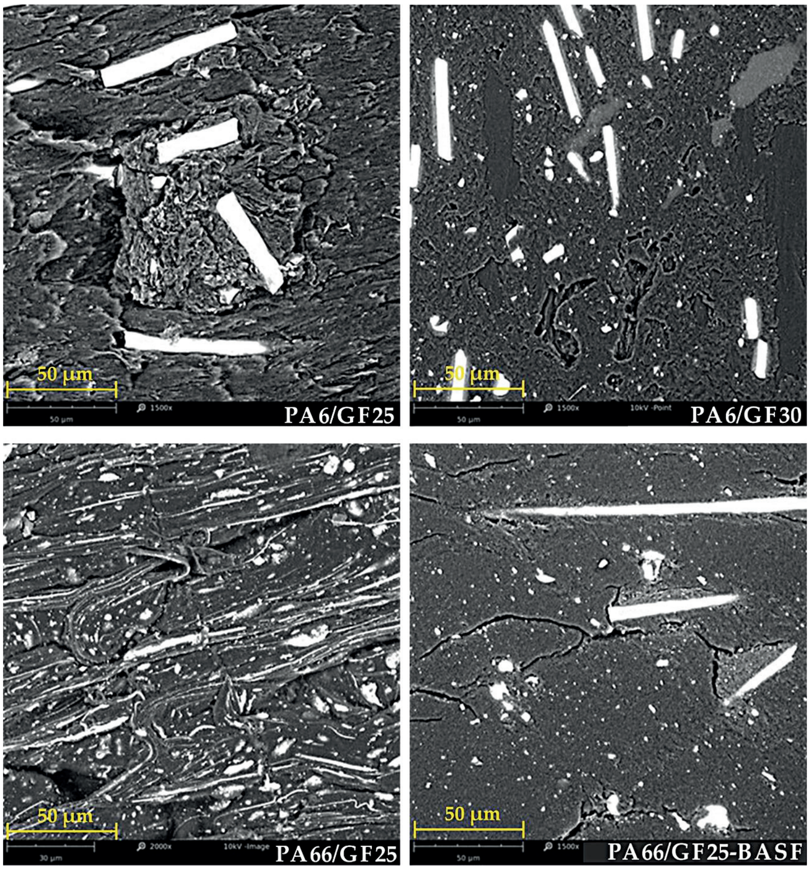

Fig. 6. Worn surfaces of composites tested in a dry state (before water absorption test)

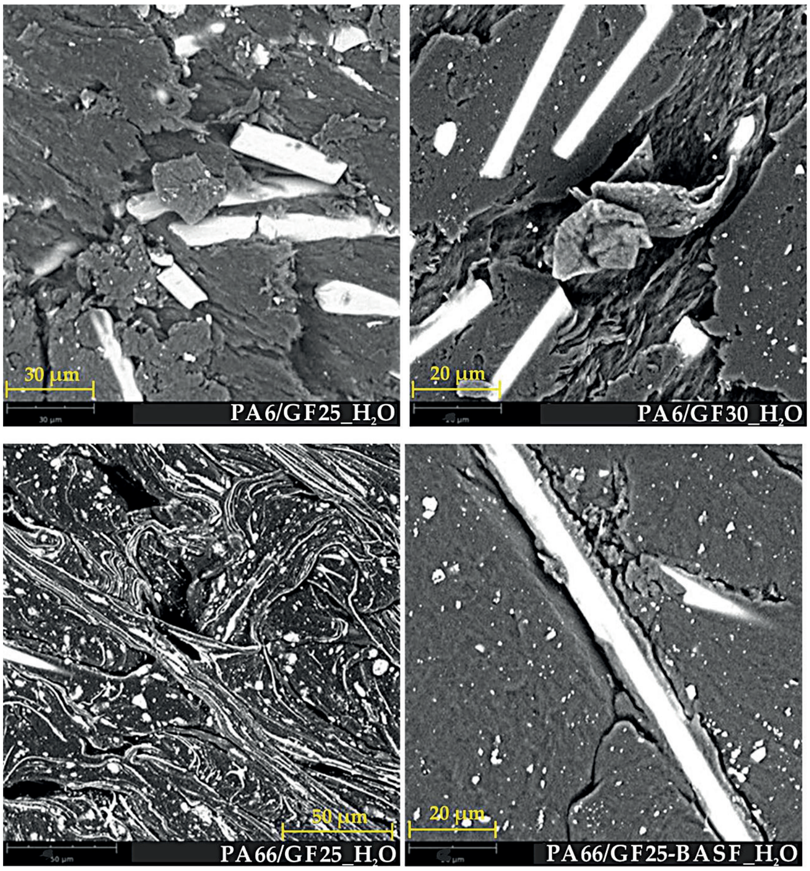

Fig. 7. Worn surfaces of composites subjected to WA test

tribological testing. The water transport mechanism takes place through matrix microcracks and relies on the swelling of the fibres as a result of water storage [23, 24]. Fibre swelling can be induced by penetrating water molecules into the matrix-fibre phase interfaces. Literature data [28] shows that such behaviour can lead to damage, formation of cracks in the bulk material and, above all, detachment at the fibre-polymer border. Furthermore, the absorbed water weakens the cohesion of the composite microstructure and, in turn, cause the fibre to detach from the matrix. Consequently, it can reduce the mechanical properties of the composites, such as tensile strength and intensify the wear of the material.

CONCLUSIONS

The experimental results of this study lead to the following conclusions:

1. The water absorption (WA) test showed that glass fibre reinforced thermoplastics matrix composites are prone to water absorption. However, Polyamide PA6 based materials present a lower tendency to absorb water than polyamide PA66 ones. In addition, an increase in the percentage content of fibreglass lowers the WA.
2. Analysis of tribological results indicates that all samples subjected to water absorption tests increased coefficient of friction (COF) and wear factor (K). Overall, the mean COF and K were in the range of $0.071 \div 0.321$ and $2.51 \cdot 10^{-6} \div 1.81 \cdot 10^{-4}$ $mm^3N^{-1}m^{-1}$, respectively. The lowest growth of wear factor was reported for Tarnamid PA6/GF25 material. Besides, PA6/GF25 anti-wear properties in a humid environment less deteriorated. Other composites, under wet conditions, present a significant deterioration and poor tribological properties.
3. Analysis of wear mechanisms indicates a predominantly abrasive and adhesive nature, followed by fatigue-related microcracking. In addition, SEM investigations showed that the samples tested after water absorption testing are characterized by more intense surface damage, i.e. numerous delaminations and larger areas of the material removal. The composite degradation process occurs primarily at the matrix-fibreglass interfaces resulting in phase decohesion.

The results of this research may be helpful for engineers involved in the selection of materials. This paper shows that using polyamide composites under wear conditions, especially operating in a humid environment, is related to the coefficient of friction increase, resulting in accelerated material wear.

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