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Research Article

Tribological performance of polyamide 6/wax blend for rolling bearing, bushing and gear applications

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ABSTRACT

In this experimental study, polyamide6 polymer, which is among the engineering plastics used in rolling bearings, gears, rollers and bushings, was used. In addition, PA6 polymer blends with 6% wax solid lubricant were produced to increase wear resistance and their tribological performances were investigated. The polyamide 6/wax blend was first produced in granule form in twin screw extruder by compound production method. Then, test specimens were injection molded using the granules. AISI 316L stainless steel was used as a counter-disc in tribology tests. The tests were carried out under dry sliding conditions and at room temperature. Wear tests were carried out on a pin-disc wear tester at two different loads and four different sliding speeds. The coefficient of friction (CoF) and specific wear rate (SWR) of the materials were determined. According to the test results, an increase in the CoF and SWR of both PA6 polymer and PA6/6% wax blend was observed with increasing sliding speed. At the load and speed ranges studied, the CoF of pure PA6 polymer varied between 0.25 and 0.36, while the CoF of PA6/6% wax blend varied between 0.10 and 0.13. The SWR of PA6 polymer was obtained in the range of 1.2-12x10^{-4} mm^3/N^{-1}m^{-1}, while the SWR of PA6/6% wax blend was obtained in the range of 1.2-3.0x10^{-5} mm^3/N^{-1}m^{-1}. The addition of 6% wax to PA6 polymer caused a significant decrease in both CoF and SWR and contact surface temperature.

Keywords: Polyamide 6, tribology, wax, wear, polymer.

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ÖZ

Bu deneysel çalışmada, rulmanlı yataklar, dişli, makara ve burç yapımında kullanılan mühendislik plastikleri arasında yer alan poliamit6 polimeri (PA6) kullanılmıştır. Buna ilaveten aşınma direncini artırmak için %6 oranında vaks katkılı PA6 polimer karışımları (PA6/%6vaks) üretilmiş ve tribolojik performansları araştırılmıştır. Poliamit6/vaks karışımı önce kompound üretim yöntemi ile çift vidalı ekstruderde granül formda üretilmiştir. Sonrasında ise granüller kullanılarak test numuneleri enjeksiyonla kalıplanmıştır. Triboloji testlerinde karşı disk olarak AISI 316L paslanmaz çelik kullanılmıştır. Deneyler kuru kayma şartlarında ve oda sıcaklığında yapılmıştır. Deneyler iki farklı yükte ve dört farklı kayma hızında pim-disk aşınma test cihazında gerçekleştirilmiştir. Aşınma testlerinde malzemelerin sürtünme katsayısı ve spesifik aşınma hızı belirlenmiştir. Test sonuçlarına göre, kayma hızının artmasına bağlı olarak hem PA6 polimeri hem de PA6/vaks karışımının sürtünme katsayısı (SK) ve spesifik aşınma hızında artış gözlenmiştir. Çalışılan yük ve hız aralıklarında SK, saf PA6 polimeri için 0.25-0.36 arasında iken PA6/vaks karışımı için 0.10-0.13 arasında değişim göstermiştir. PA6 polimerinin aşınma hızı 1.2-12x10^{-4} mm^3/N^{-1}m^{-1} aralığında elde edilirken PA6/vaks karışımının aşınma hızı ise 1.2-3x10^{-5} mm^3/N^{-1}m^{-1} aralığında elde edilmiştir. %6 oranındaki vaks PA6/6Vaks kompozitin hem sürtünme katsayısında ve aşınma hızında hem de temas yüzey sıcaklığında önemli azalmaya sebep olmuştur.

Anahtar Kelimeler: Poliamit 6, triboloji, vaks, aşınma, polimer.

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1. INTRODUCTION

Polyamide 6 (PA6) polymer is a semi-crystalline engineering polymer with high mechanical properties and high crystallinity. With these properties, it is an engineering polymer that is widely used in the production of engineering products in many sectors such as the automotive sector, the electrical/electronics sector and the packaging sector. However, the use of PA6 polymer in wider applications limited due to its properties such as low impact strength at low temperatures, low thermal degradation temperature, poor dimensional stability and high wear under dry sliding conditions.[1-4] Although there are different ways to improve the mechanical and thermal properties of PA6 polymer, one of the simplest and most preferred methods is the incorporation of filler materials such as glass fibers (GF), carbon fibers (CF) and aramid fibers (AF) into the polymer. There are some studies on fiber reinforced polyamide based polymer composites in the literature. Among these, Nuruzzaman et al.[5] investigated the tensile and impact properties of GF (5-20% by weight) reinforced PA6 polymer composites. Their results showed that the modulus of elasticity, the yield strengths, tensile strength and fractural strength increased by 329%, 230%, 113% and 159%, respectively. They stated that the elongation at break decreased by 1300% by increasing the GF ratio in the polymer matrix from 5% to 20%. Hyo Jin et al.[6] investigated the mechanical and thermal properties of long CF reinforced with PA6 polymer composites. They demonstrated that the tensile strength of the unfilled PA6 polymer was 38.7 MPa, while 110.3 MPa was obtained for the PA6/18% long carbon fibre (LCF) polymer composite. The tensile modulus increased from 0.52 GPa to 6.49 GPa. At the same time, elongation at break decreased from 38.7% to 21.0%. They also reported that while the melting temperature (T_m) and thermal decomposition temperature of the PA6 composite were not affected by the CF addition, the addition of the CF had an effect of the crystallization temperature (Tc). Li et al.[7] investigated the heat deflection temperature (HDT) properties of PA6-based composites, the properties of fibre type (carbon or glass) and ratio (0-5% by weight) on mechanical and thermal conductivity. Their results showed that the thermal conductivity of the composites increased with the increasing CF ratio, while it decreased slightly with the increment of GF ratio. However, they demonstrated that the tensile modulus and heat deflection temperature of PA6-based composites can be achieved with increasing fibre content. Yi-Lan et al.[8] studied the effect of 0%-25% GF to PA6 polymer on tribological properties. It has been stated that the addition of 15% GF to the polymer matrix reduces the CoF and SWR by 92% and 95%, respectively. Kumar and Panneerselvam[9] investigated the mechanical and abrasive wear properties of pure PA6 and GF filled PA6 composites. The study was carried out under atmospheric conditions at a sliding distance of 500 m. The effects of applied load (5, 10, 15 and 20 N) and GF ratio (0, 10, 20 and 30 wt%) on wear were analysed. The results demonstrated that while the SWR decreased with the increase in GF ratio, the lowest wear rate was obtained in 30wt.% GF reinforced PA6 composite. As a result of the analysis, the abrasive wear loss increased with the increase in applied load. The tribological properties of polymer materials are significantly affected by environmental and process conditions. The effects of test conditions such as applied load, sliding speed, sliding distance, contact geometry and environmental conditions (dry or wet) on the friction and wear properties of PA6 polymer have been extensively studied. Various studies demonstrated that the CoF of polymers decreases with increasing sliding speed and load.[10-13] Kumar and Kanagaraj[13], Umesh[14], Lakshmi[15], Kumar and Kanagaraj[12] found that SWR increased with increasing load while Kumar and Kanagaraj[13], and Umesh[14] stated that SWR increased with increasing sliding speed.

Solid lubricants such as poly-tetra-fluoro-ethylene (PTFE), graphite, paraffin wax, ultra high molecular weight polyethylene (UHMWPE) and molybdenum-di-sulphide (MoS_2) are widely used to improve the friction and wear properties of PA6 polymer.[16-21] Li et al.[19] investigated the effects of PTFE, graphite, UHMWPE and their combinations on the mechanical and tribological properties of PA6/15%GF composite. While the tensile strength of PA6/15%GF composite increased with the addition of graphite filler, the graphite/UHMWPE combination significantly increased the impact strength of PA6/15%GF composite. In addition, it was stated that the CoF decreased at the maximum ratio with the addition of 5wt.% PTFE filler, and PTFE/UHMWPE combination solid lubricant would be the best choice to increase both the friction and wear performance of the PA6/15%GF composite. Demirci et al.[22] studied the effects of sliding speed, contact pressure and temperature on the wear loss of PA66, PA66+30%GF and PA66+25%GF+3%MoS_2 composites. They showed that the transfer film layer formed between the contact surfaces due to the presence of MoS_2 solid lubricant improves the wear resistance of PA66 polymer. Among solid lubricants, paraffin wax is chemically inert, non-corrosive, long-lasting, inexpensive, ecologically harmless and non-toxic.[23] Paraffin waxes show stable behaviour up to 250°C and therefore do not boil even at high temperatures.[24] Paraffin wax is one of the potential candidate materials as solid lubricant filler for polymer composites with these properties. Unal et al.[25] examined the effect of wax solid lubricant on the electrical, thermal and tribological properties of graphite filled PA6 composites. The results of the study showed that the CoF and SWR of PA6 composite is reduced with the addition of wax to the 15wt.% graphite/PA6 polymer. However, it has been stated that glass transition (T_g) and melting temperature (T_e) are not affected by the wax lubricant ratio. It was also reported that optimum friction and wear performance

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were obtained in 6wt.% of wax contents. Jozwik et al.[26] also examined the tribological characteristics of the wax filled PA6, M_oS_2 filled PA6, aluminium filled poly-oxy-methylene (POM), PTFE filled polyethylene terephthalate (PET), bronze filled PTFE and graphite filled PTFE composites. Their results showed that one of the most important factors affecting the tribological characteristics is the filler type and the best tribological performance was obtained in the case wax added PA6 mixture. It has been stated that the CoF of all materials tested with increasing load is reduced.

There are limited studies on this material in the literature. Therefore, the aim of this study was to examine the tribological performances of polyamide 6 and PA6/6wt.% wax polymer composites, which is among the high -performance engineering plastics, under dry sliding conditions against the AISI 316L stainless steel disc. Wear tests were performed on Pin-on-Disc test device. This study was carried out to understand the tribological problems that may occur in materials such as bearings, gears, bushings and rollers. The study was carried out at different sliding speeds (0.5-1.0-1.5-2.0 m/s^{-1}) and under loads (50 N -100 N). Experimental studies were planned to a using sliding distance in 2000 m, under atmospheric conditions and in a dry sliding environment. The variation of CoF and SWR of unfilled PA6 and PA6/6%wax blend produced under the above-mentioned conditions were investigated.

2. MATERIALS AND METHODS

Polyamide 6 polymer used in wear experiments was obtained from Domopolymer as known as Domamid commercial name. The wear test samples were produced with injection moulding technique in accordance with the ASTM G99 standard. In wear experiments were performed under dry conditions using the Pin-on-Disc wear system under atmospheric conditions. The PA6 polymer and PA6/6wt.%wax polymer blend pin samples for wear tests produced by injection moulding method. Pin sample dimensions were 6 mm diameter and 50 mm length. AISI 316L stainless steel which has surface roughness of 0.32 Ra, is used as a counter-disc material. The specific wear rate (K_O) was determined with Equation 1. L; sliding distance (m), ρ; the density of the material (g/cm^{-3}) and F; applied load (N).

$$K_o = \frac{\Delta m}{L * \rho * F} \quad (1)$$

The coefficient of friction measurements of the test specimens were measured with the help of a load-cell in a wear test setup designed to have a pin on the disc. The lateral force measured by the load cell is transferred to a computer and recorded in the excell program. Approximately 65.000 data measuring the lateral load were obtained during the experimental period. This lateral load data was recorded in a column in the Excel program and then divided by the applied load to calculate the coefficient of friction. The coefficient of friction (μ) between the pin specimens used in the experiments and the opposing SS disc is the ratio of the lateral force to the normal force and is calculated by the formula given in Equation (2). In the formula, μ is the coefficient of friction, Fs is the frictional force (N) and Fn is the normal force (N).

$$\mu : Fs/Fn \quad (2)$$

Before the wear tests, the specimen and disc surfaces were smoothed with 1200 grit sandpaper and the surfaces were then cleaned with acetone.

3. RESULTS AND DISCUSSION

Table 1 shows the results of the CoF depending on the sliding speed for unfilled PA6 polymer and PA6/6%wax blend. The sliding speed-CoF graph of pure PA6 and PA6/6% wax blend are given in Figure 1. The figure shows that the CoF of unfilled PA6 polymer and PA6/6% wax blend increased with increase in sliding speed.

Table 1. Results for sliding speed-friction coefficient of unfilled PA6 and PA6/6wt.% wax blend.

Materials	Load, N	Sliding speed m s^{-1}			
		0.5	1.0	1.5	2.0
		CoF, μ			
PA 6	50	0.25	0.28	0.30	0.35
	100	0.27	0.30	0.32	0.36
PA6/6wt.%wax	50	0.10	0.11	0.12	0.13
	100	0.10	0.11	0.11	0.12

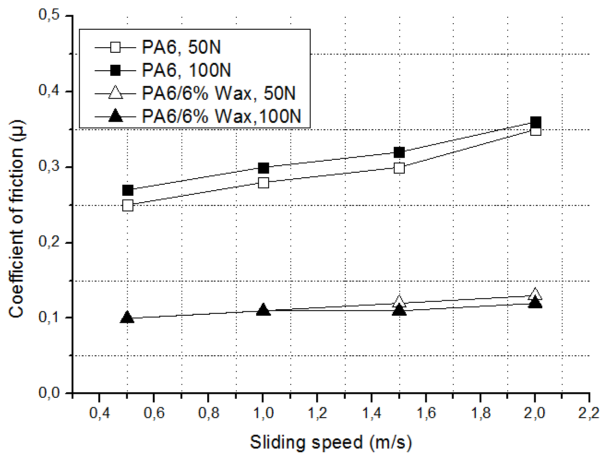

Figure 1. CoF-sliding speed graphs of PA6/6wt.% wax blend and unfilled PA6 polymers.

This increase was obtained under 50N load as 40% and 30% for unfilled PA6 and PA6/6wt.% wax blend, respectively. For 150 N load, the increase in CoF for unfilled PA6 polymer and PA6/6wt.% wax blend was

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obtained as 33.3% and 20%, with increasing sliding speed ratio with 300%. Therefore, this study demonstrates that increasing the load from 50N to 100N did not affect the CoF. For unfilled PA6 polymer, the CoF at different sliding speed decreased by an average of 6.6 %, while the CoF for PA6/6wt.% wax blend did not change. The 6wt.% wax filled into PA6 polymer played an important role in reducing the CoF in the range of sliding speed and applied load. The CoF of PA6/6wt.% wax blend under 50N and 150N loads decreased by 156 % and 183 %, respectively, compared to the pure PA6 polymer. In the experiments carried out at 50-100N load and 0.5-2.0 m/s sliding speed ranges, the highest CoF was obtained in unfilled PA6 polymer under 2.0 m/s^{-1} sliding speed and 100N load, while the lowest CoF was found at 0.5 m/s^{-1} sliding speed and under 50 and 100N loads for PA6/6wt.%wax blend.

Figure 2 shows the variation of pin and disc surface temperatures at the contact point of unfilled PA6 and PA6/6wt.% wax blend working against AISI 316L stainless steel disc depending on the sliding distance. As expected, it was determined that both pin and disc surface temperatures increased depending on the sliding distance. The initial temperature of the unfilled PA6 polymer, which was about 23°C, increased to the range of 42-44 °C depending on the sliding distance. The addition of 6wt.% wax reduced both the pin and disc surface temperature by half, and the temperature value was obtained in the range of 27-31 °C when the sliding distance was 2000 m. The most important reason for the decrease in pin material and steel disc temperatures can be explained by the high thermal conductivity of the steel disc material. The wax solid lubricant added to the polyamide 6 polymer main matrix showed high lubricant properties, causing a decrease in the CoF and a decrease in the surface temperature of the polymer pin and steel disc.

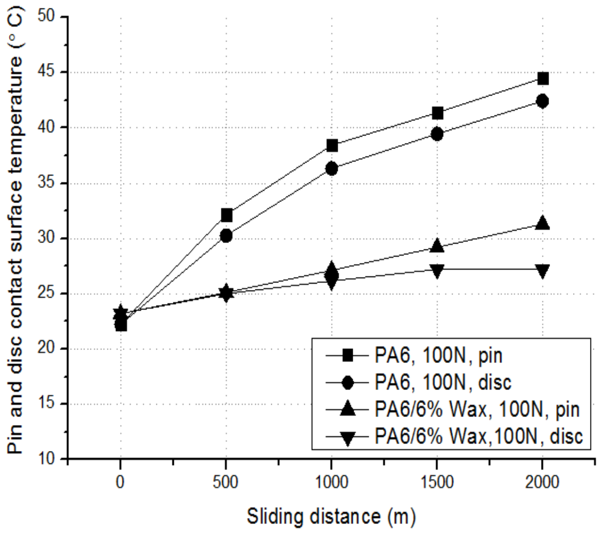

Figure 2. Variation of sliding path-pin and disc contact surface temperatures of PA6/6wt.% wax blend and unfilled PA6 polymers.

The results of the sliding speed and the SWR depending on the load for unfilled PA6 and PA6/6wt.%wax blend were presented in Table 2. The sliding speed-SWR graph is given in Figure 3. The SWR for pure PA6 polymer was obtained as 10^{-4} mm^3 N^{-1}m^{-1}. The SWR was obtained as 10^{-5} mm^3 N^{-1}m^{-1} for PA6/6wt.% wax blend. The lowest SWR was provided in the PA6/6wt.% wax blend sample with a sliding speed of 0.5 m s^{-1} and a load of 100N, with a value of 1.20x10^{-5} mm^3 N^{-1}m^{-1}.

Table 2. Results of sliding speed-SWR of unfilled PA6 and PA6/6wt.% wax blend.

Materials	Load, N	Sliding speed, m s^{-1} 0.5	1.0	1.5	2.0
		Specific wear rate, mm^3 N^{-1}m^{-1}			
PA 6	50	1.20 E^{-04}	1.26 E^{-04}	1.32 E^{-04}	1.37 E^{-04}
	100	8.00 E^{-04}	9.00 E^{-04}	9.1 E^{-04}	1.20 E^{-03}
PA6/6wt.%wax	50	1.50 E^{-05}	2.20 E^{-05}	2.60 E^{-05}	3.00 E^{-05}
	100	1.20 E^{-05}	1.40 E^{-05}	1.50 E^{-05}	1.80 E^{-05}

The highest SWR was obtained in unfilled PA6 polymer with a sliding speed of 2.0 m s^{-1} and a load of 50 N, with a value of 1.37x10^{-4} mm^3 N^{-1}m^{-1}. It was observed that the SWR increased with the increase in sliding speed. By increasing the sliding speed by 300%, the SWR of unfilled PA6 polymer increased by 14.1% under 50 N load and 50% under 100 N load. For PA6/6wt.%wax composite, the specific wear rate increased by 100% and 50%, respectively, under 50 N and 100 N loads, depending on the sliding speed. The addition of 6wt.%wax played a much more effective role in reducing the SWR. For example, under 2.0 m s^{-1} sliding speed and 50 N load, the SWR of PA6/6wt.% wax blend decreased by 356.6% compared to unfilled PA6 polymer.

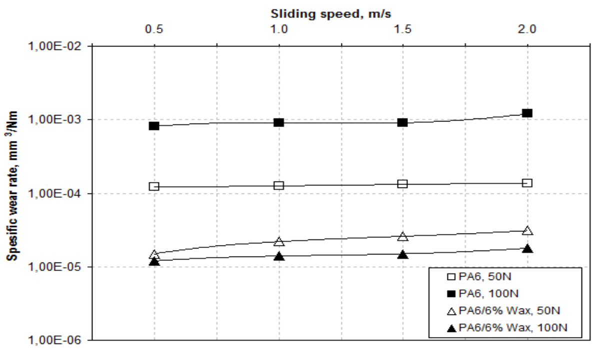

Figure 3. SWR-sliding speed graph of unfilled PA6 polymer and PA6/6wt.%wax blend.

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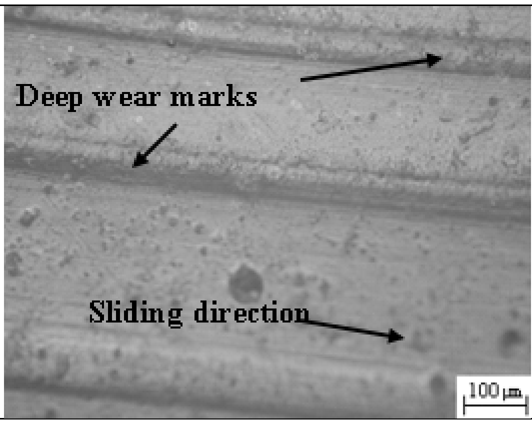
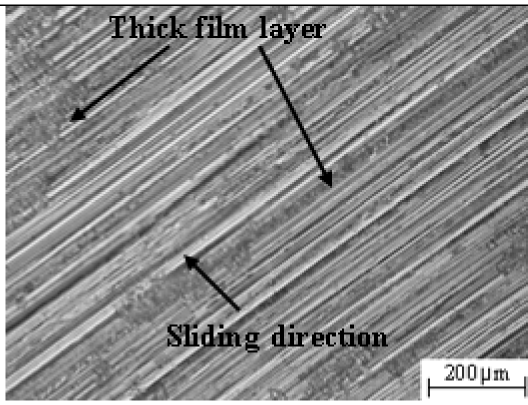
Pin

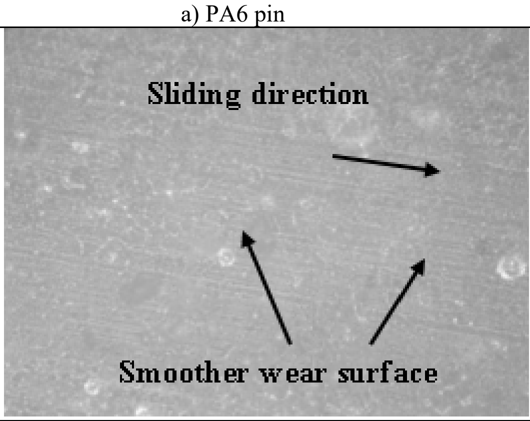


a) PA6 pin

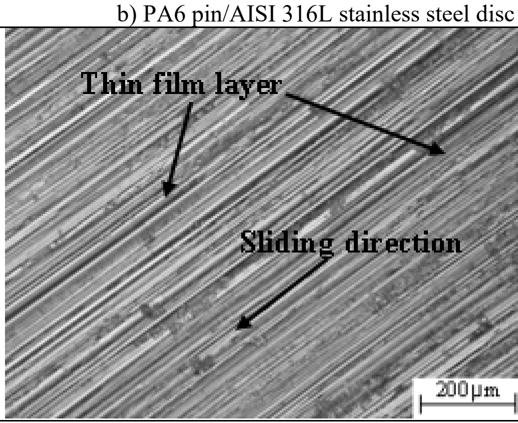
Disc



b) PA6 pin/AISI 316L stainless steel disc



c) PA6/6wt.%wax pin



d) PA6/6wt.%wax pin/AISI316L stainless steel disc

Figure 4. Optical microscope images of stainless steel disc and pin wear surface (Load:100 N, Speed: 2.0m s^{-1}).

Optical microscope images of worn unfilled PA6 polymer pin surface and PA6/6wt.wax blend pin surface against AISI 316 stainless steel disc under high sliding speed (2.0 m s^{-1}) and high load (100 N) are given in Figure 4a- Figure 4d. When Figure 4b and Figure 4d SS disc surfaces are investigated, it is observed that a transfer film layer (TFL) is formed that prevent the pin and disc contact. While the TFL formed unfilled PA 6 polymer was observed as a thicker TFL on the disc surface (see Figure 4b), it was determined that the transfer film layer was formed locally. Figure 4d shows that the TFL on the disc surface was thinner in PA6/6wt.% wax blend. When the pin surfaces of the unfilled PA6 polymer were examined, it was observed that deep and wider wear marks were formed in the sliding direction of pin material and therefore the wear mechanism can be announced abrasive wear (see Figure 4a). Moreover, it was observed that the wear marks decreased in the sliding direction on the PA6/6wt.%wax blend pin sample, while a smoother wear surface was observed (see Figure 4c). Addition of 6wt.% wax to the PA6 polymer changed the wear mechanism to an adhesive wear mechanism. This result is consistent with the reduced CoF and increased wear resistance (see Figure 1 and Figure 3).

4. CONCLUSIONS

1. The CoF of unfilled PA6 polymer increased by 12%, 20% and 40%, respectively, with the sliding speed.
2. The CoF of PA6/6wt.%wax blend slightly increased with the increase in sliding speed. As a result of increasing the sliding speed from 0.5 m s-1 to 2.0 m s^{-1}, CoF increased by 10%, 10% and 20%, respectively.
3. Compared to the CoF of unfilled PA6 polymer, the CoF of PA6/6wt.% wax blend is approximately 156% and 183% lower under 50 N and 100 N loads.
4. Pin and disc surface temperatures increased with increasing sliding speed from 0.5 m s^{-1} to 2.0 m s^{-1}. While the highest pin and disc surface

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temperature was obtained in the range of 42-44 °C for unfilled PA6 polymer, it was found to be approximately 27-31 °C for PA6/6wt.% wax blend.

5. The wear rate of unfilled PA6 polymer increased with the increase in sliding speed. The wear rate increased by 14.1% at 50 N load and 50% at 100 N load, respectively.
6. The SWR of the PA6/wax polymer blend increased slightly due to the increase in sliding speed. The SWR increased by approximately 100% at 50 N load and 50% at 100 N load.
7. Compared to unfilled PA6 polymer, the wear rate of the PA6/6wt.%wax blend was 80% lower at 50 N load and 96% reduction at 100 N load.
8. As a result, it can be stated that the use of PA6/6wt.%wax blend instead of unfilled PA6 polymer in rolling bearing, gear and bushing applications will increase the material service life by about two times.

Conflict of interests

I declare that there is no a conflict of interest with any person, institute, company, etc.

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