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TRIBOLOGICAL BEHAVIOURS OF ABS AND PA6 POLYMER-METAL SLIDING COMBINATIONS UNDER DRY FRICTION, WATER ABSORBED AND ELECTROPLATED CONDITIONS

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Abstract

The friction and wear properties of polyamide 6 (PA6) and poly-Acrylonitrile Butadiene Styrene (ABS) sliding against metal under dry sliding, water absorption and electroplated (EP) conditions were studied by using a pin-on-disc tribometer. The effect of applied load and sliding speed on the tribological behaviours of the polymer–metal sliding combinations under dry sliding, water absorbed and EP conditions were also investigated. The worn surfaces were examined by using Scanning Electron Microscope (SEM). Experimental results showed that ABS samples under water absorbed conditions showed higher wear loss compared to normal samples and the EP samples had exhibited lower wear loss compared to the water absorbed samples. Similarly EP-PA6 samples exhibited excellent wear resistance when compared with EP-ABS samples. Further, it was observed that the frictional heat produced on account of sliding action had a significant effect on the tribological behaviours of samples under dry sliding and water absorbed conditions.

Keywords: Dry friction, Wear, Tribology, Frictional heat, Water absorption, Electroplating, PA6, ABS.

Nomenclatures

K	Wear rate, mm^3/ N-m
Δm	Weight loss, g
L	Sliding distance, m
P	Applied load, N
Ra	Surface roughness, µm
V	Sliding speed, m/s
Q	Heat generated, N-m/s

Greek Symbols

ρ	Density of polymers, g/cm^3
$\varnothing$	Diameter, mm

Abbreviations

ABS	Poly-Acrylonitrile Butadiene Styrene
PA6	Polyamide 6
EP	Electroplated
SEM	Scanning Electron Microscopy
SAN	Styrene-acrylonitrile copolymer
COW	Coefficient of Wear
RH	Relative humidity
EP-PA6	Electroplated Polyamide6
EP-ABS	Electroplated ABS

1. Introduction

Due to the recent developments in production technology and resin development systems, there has been a substitution of metals from plastics in a wide range of applications. The volume of polymer consumed each year is already greater than that of steel [1]. According to ASTM D883 80C, polymers are divided into two groups with regard to their chemical and technological behaviours [1, 2]: thermosetting and thermoplastic [3]. The main benefits of plastics over metals are ease of fabrication, one stage moulding of parts, greater design flexibility and weight savings [4, 5]. Plastics are being used in development of gears, cams and bearings. Many of these are produced by either injection moulding or compression moulding or by extrusion. Therefore, looking at the applications and to obtain better properties like, longer life, reduced friction and wear, better strength, etc., of the products produced in lesser time, both tribological and processing conditions must be examined [6] and sometimes it becomes extremely important to study polymers and polymer-based composites in different conditions like dry friction and lubricated conditions to obtain the combination of good mechanical and tribological properties [7-12]. According to Kalácska [13], the effect of friction on the wear of engineering polymers is a complex and intricate consequence of the micro and macroscopic interactions of surfaces move against one another. Friction and the resulting wear are not material properties of plastics; therefore, they cannot be reduced to tabular data of material characteristics that can be found in relevant manuals. Determining friction and the resulting wear involves more complex examination because they are characteristics of a frictional contact system where the effects of the entire system are manifested. Precise knowledge of system conditions is essential to evaluate the friction and resulting wear [14].

In recent years, researchers have focused on developing surface-modified engineering polymers and nano-composites because of new technology that enhances the tribological behaviour by changing the molecular or matrix structure to change the surface or bulk properties [15-17]. Plastics are often reinforced with fillers, additives, binders, and very recently researchers have shed light on adopting electroplating as a technique for enhancing the strength of materials. Electroplating has been previously used for purposes, such as electromagnetic shielding, weight reduction, electrical conductivity, formability enhancements, high impact resistance and weatherproofing [18]. Many of the plastics like ABS, Polycarbonate, Polyphenylene, Teflon, etc., are being plated today for giving properties like high thermal resistance, durability and metallic properties to the plastic surfaces [18-20]. Kulkarni et al. [18], Chandrasekhar et al. [21], Kannan and Senthilkumaran [22], Raju et al. [23], have shown how electroplating enhances the strength of a plastics under consideration. ABS and PAs are the two most important thermoplastics used in a variety of industrial applications like textiles, Automotives, carpet and sportswear [24].

ABS is made by a combination of styrene-acrylonitrile copolymer (SAN), which is brittle in nature with polybutadiene; it makes ABS tougher. Upon the combination polybutadiene produces two forms: a graft terpolymer and a small rubber spheres which is dispersed in the terpolymer and SAN matrix. ABS is an amorphous material. It is tough, stiff, and abrasion resistant; it is widely used in casing boat shells and food containers [3]. Some plastic materials absorb certain quantities of moisture and change their mechanical properties with the quantity of absorbed moisture. Also the dimensions of such materials change with the quantity of absorbed moisture. However, in case of ABS, the absorbed moisture does not affect the properties of the finished item as well as the dimensional stability. Moisture absorption in case of ABS plastics is less than one percent [25].

PAs have a crystalline structure. There are a number of common PAs like nylon 6, nylon 6.6, nylon 6.10, and nylon 6.11. Nylons, in general are rigid, strong, tough, and have the ability to withstand higher melting points [3]. In general, all PAs are hygroscopic [26], i.e., they absorb water from both air and liquids. Hygroscopic property of polymers becomes an essential factor while selecting materials, designing parts, mechanical performance and optimization. It is estimated that the equilibrium moisture content of PA6 is around 2.5 wt% at 23°C, 50% RH and 9 wt% at 23°C, 100% RH [27]. Generally, it is noted that the moisture content in nylon is a prime factor affecting polymerization, compounding and moulding. It is seen affecting the mechanical, dimensional, and surface appearance when it is used in end-user products [28]. Dimensional changes of 0.7% can result in nylon parts from the "as-moulded" state to equilibrium at 50% RH environments. This change occurs in approximately 150 days for a 0.060 inch (1.5 mm) thick part [29]. The absorbed water in the layers of polymer works as a plasticizer. Since Nylon being semi crystalline material has both crystalline and amorphous phases. The moisture actually penetrates into the amorphous region, although small, water molecules take up space and displace the nylon molecules. This results in the nylon molecular matrix swelling [29]. The water molecules try to establish hydrogen-bonds with the amide group and enhance the molecular chain mobility [28], which in turn affects material properties such as modulus, yield stress, toughness, etc. [30]. The water absorption by plastics also results in alterations of dimensions and mass due to the stress and swelling that causes serious damage to the whole structure. Being dimensionally stable is very important for components used with narrow tolerances and intricate shapes [31].

A number of investigations related to the tribological performance of polymers have been carried out. The parameters that dictate the tribological performance of polymer and its composites include polymer molecular structure, processing and treatment, properties, viscoelastic behaviour, surface texture, etc., [32-36]. Watanabe et al. [37], Tanaka [38], Bahadur and Tabor [39] reported that the tribological behaviour of polyamide, high density polyethylene and their composites is generally affected by normal load, sliding speed and temperature. Pihtili and Tosun [40, 41] showed that applied load and sliding speed play a significant role on the wear behaviour of polymer and its composites. They also show that applied load has more effect on the wear than the speed for composites. Franklin [42] reports that wear behaviour of polymers under dry reciprocating sliding conditions does not always follow the generally accepted engineering rule of ‘higher sliding speed, the higher wear rate’. The influence of the normal load on the friction coefficient and wear rate of different polymer and composite materials was investigated [43] and it was found that the values of friction coefficient and wear rate are different for different materials.

From the aforementioned research works, it can be concluded that the wear coefficient of polymer materials at different normal and sliding velocity differs significantly. Even now a days, the effect of normal load and sliding velocity on wear coefficient and wear rate of polymer materials such as ABS and nylon sliding against steel surface is less understood and that too when the materials are in different conditions. This means that more research work is needed for a better understanding of wear coefficient and wear rate of these materials under normal loads and sliding velocities on steel surfaces. Therefore, in order to understand more clearly, in this study experiments are carried out to investigate the influence of normal loads and sliding velocities on wear coefficient and wear rate of ABS and PA6 in three different conditions viz., dry (normal), water absorbed and EP. An effort has been made to compare the tribological properties of the above said materials in these conditions. The authors are of the opinion that there haven’t been much tribological studies on plastics / polymers in EP conditions. Therefore this study could shed light on understanding the effects of electroplating on the tribological behaviour of plastics and thus it could be a significant contribution to studies on wear and friction of polymers.

2. Experimental Part

2.1. Materials

PA6 and ABS were used in this study. The PA6 and ABS specimens were injection moulded from pelletized materials procured from Jayalakshmi Polymers, Bengaluru, using a screw type injection moulding machine (ARBURG 170 / 90 / 200, a 20T capacity machine at shrinidhi plastics, Bengaluru).

2.2. Friction and wear tests

The friction and wear tests were conducted on a pin-on-disc type tribometer. Figures 1 and 2 provide the schematic diagram of the polymer samples and tribometer used in the study. A disc (Ø160 mm × 11.5 mm) rotating at a selected speed slid against a pin (10 mm × 10 mm × 4 mm). Before each test, a polymer pin was fixed on the tester and rubbed against a metallographic 600 grit abrasive paper placed on the rotating disc. This pre-rubbing process ensured a full contact of the pin and disc surfaces. Metal discs were cleaned with acetone and dried. The surface roughness Ra of polymer specimens was 1.815-2.12µm. All the specimens were thoroughly cleaned. The friction and wear tests were performed at room temperature (23 ± 5 ^{o}C) in atmosphere (relative humidity (RH): 50 ± 10%). Applied loads ranged from 10 N to 70 N, the rotation speeds of discs ranged from 2.5m/s to 7.5 m/s, and the sliding distance was 1000 m. The wear was measured by the weight loss of pin and disc using an analytical balance (precision: 0.001 mg). The wear rate (K, mm^3/N-m) reported in this study was calculated according to the following equation:

$$K = \frac{\Delta m}{LP\rho} \tag{1}$$

where, Δm was the weight loss (g), L the sliding distance (m), P the applied load (N) and ρ was the density of polymers (g/cm^3). The density was measured as per ASTM D792 standard, which was primarily based on Archimedes principle. For minimizing data scattering, three replicate sliding tests were carried out in this work, the wear coefficient and wear rate were average values of three replicate test results.

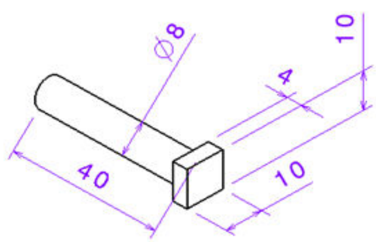


Fig. 1. Dimensions of wear specimen used in the study.

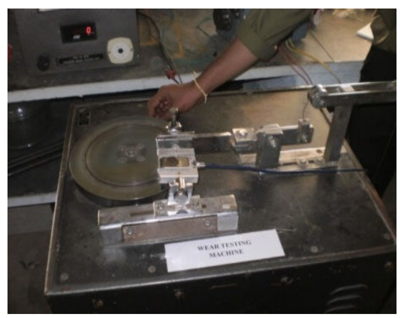


Fig. 2. Pin-on-disc type tribometer used in the study.

2.3. Worn surface analysis

The worn surfaces of ABS and PA6 were cleaned thoroughly. The samples were sputter coated with gold-palladium coating of 10nm thickness. It was noted that samples were nonconducting and could not be subjected directly for SEM studies and therefore samples had been coated with gold-palladium coating which offered the required conductivity for SEM studies. These sputter coated samples were then subjected to SEM (Jeol 6390LV, SAIF, STIC, Kochi, India) study, to expose the wear mechanisms.

3. Results and Discussions

3.1. Friction and wear properties

The wear coefficients of PA6–metal and ABS-metal sliding combinations under dry friction (Normal), 24 hours water absorbed and EP conditions are given in Fig. 3. The thermal and mechanical properties of the polymer specimens are listed in Table 1. Under dry friction conditions, the wear coefficient of PA6 is higher and the recorded value is about 23.8 % higher than ABS. The wear coefficient of ABS–metal combinations under water absorbed conditions is higher and is about 92.3 % higher in comparison with PA6. The EP samples show the same wear coefficient in both ABS and PA6 samples and the values are lower than dry friction and water absorbed conditions.

The specific wear rates of PA6 and ABS samples under dry friction, 24 hours water absorbed and EP conditions are shown in Fig. 4. It is interesting to note that wear rate of ABS samples are higher under dry sliding and 24 hours water absorbed conditions when it is compared with PA6 samples. But the wear rate of both ABS and PA6 are found to be the same under EP conditions. The wear rate of PA6 normal sample is not observed in Fig. 4, since the wear rate is as small as less than 10^{-5} mm^3/N-m. Moreover from the Table 1 it is understood that the hardness and surface roughness values of water absorbed samples have not shown an appreciable increase and from the literature survey it is understood that polymer samples in the water absorbed state lose their mechanical strength and this causes enhanced coefficient of wear (COW) and wear rate in the water absorbed samples. The SEM study conducted on these samples in section 3.2 provides the evidence for the same. The EP samples exhibit enhanced hardness and the Ra values indicate smooth surface i.e., reduced roughness as compared with dry and water absorbed samples. The smooth surface of the EP samples causes them to slide over the metal counter surface. Thus reduced COW and wear rates are observed with EP samples.

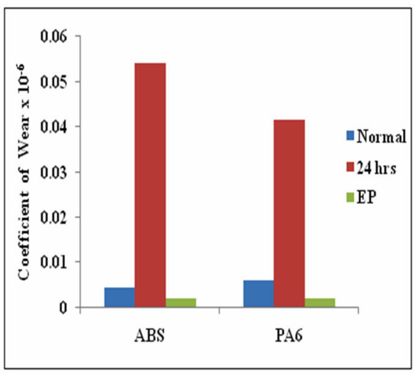


Fig. 3. Wear coefficients of polymer samples under dry sliding (normal sample), 24 hours water absorbed and EP conditions (applied load: 10 N, sliding speed: 2.5 m/s, sliding distance: 1000 m).

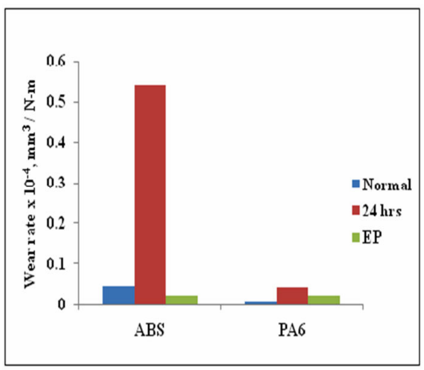


Fig. 4. Wear rates of polymer samples under dry sliding, 24 hours water absorbed and EP conditions (applied load: 10 N, sliding speed: 2.5 m/s, sliding distance: 1000 m).

Table 1. Thermal and mechanical properties of the polymer specimens.

Properties	*ABS*	*PA6*	*ABS*	*PA6*	*ABS*	*PA6*
Tensile Strength (MPa)	38.5	41.3	32.5	25.7	27.4	50.1
Hardness (HRR)	97.9	90.9	93	87	112	105
Melting point (^{o}C)	107	222	-	-	-	-
Surface roughness, Ra	1.815	2.12	1.9	2.18	0.03	0.18
Condition of samples	**Dry**		**Water absorbed**		**Electroplated**	

3.1.1. Applied load effect on friction and wear

Figure 5 indicates the variation of the wear coefficient with applied load for ABS–metal sliding combinations under dry friction, 24 hours water absorbed and EP conditions. The results in Fig. 5 reveal that the wear coefficients of all sliding combinations increase with the increasing applied load for dry friction, water absorbed and EP conditions for ABS samples. A higher COW is observed with water absorbed samples (Fig. 5) and this means, the samples tend to offer some amount of resistance for rubbing but at the same time the absorbed water in the layers of ABS weakens the mechanical strength of the samples. Also, as the load increases the wear resistance tends to increase, and the resistance causes a rise in temperature which further supports wearing of the samples as seen from Fig. 14. The decrease in COW of normal and water absorbed samples indicate that samples are free to move over the counter surface and the possible reason for decrease in the COW and wear rate (Fig. 7) can be attributed to matrix softening due to the rise in temperature with increased load, this helps in smoothening of surface layers that are in contact with the counter surface. The smooth layers help in easy sliding and reduced wear rate of the samples subjected to dry sliding. The EP samples have metal layers (nickel and copper) that helps in exhibiting enhanced wear resistance and also the surface roughness of these samples is too low which exhibits extreme smoothness as compared to dry and water absorbed samples. The SEM analysis of these samples is carried out to make a note of peeling of these metal layers and has been discussed under section 3.2.

While from Fig. 6 it is understood that the wear coefficient of PA6 increases with increase in applied loads for dry sliding, whereas the wear coefficients are independent of applied loads for water absorbed and EP conditions. Figure 8 shows the variation of specific wear rates of PA6 samples with applied load for the above said conditions. The wear loss of PA6 samples increases sharply with the increasing applied load under all sliding conditions. It is also interesting to note that PA6 samples which absorb more water when compared to ABS have shown reduced COW and wear rate. It is learnt from previous literatures that PA6 samples have been used in many tribological related applications like in gears, fittings, and bearings, in the automotive industry for under-the-hood parts, as a material for power tools housings and for automobile fuel tanks [44] and all these are due to its excellent wear resistance. It is also seen that the water absorbed and EP curves crisscross each other between 10 N and 30 N loads. This could be due to the low friction force and load at the beginning of the sliding, as the load increases the EP sample tends to get rid of the EP layers. However it is not very clear that at what load the base material would come in contact with the counter surface. Hence, a small study had to be carried out to select the upper load limit wherein the sample subjected to sliding at a load with the coating material still exists. Also the results of the research have been ascertained using SEM analysis. It is understood from Fig. 8 that with the increase in load the EP samples tend to undergo ploughing effect, trapped wear particles between the contacting surfaces tend to increase the wear rate [32]. The samples subjected to dry sliding shows enhanced wear loss but is comparatively lesser to ABS samples. The reason for the increment in wear loss is due to effects of the rise in temperature as observed in Fig. 16, as there is a steep rise in COW values with the increase in *PV* value.

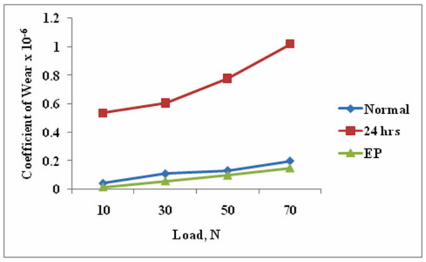


Fig. 5. Effect of applied load on wear coefficients under dry sliding, 24 hours water absorbed and EP conditions of ABS samples (sliding speed: 2.5 m/s and sliding distance; 1000 m).

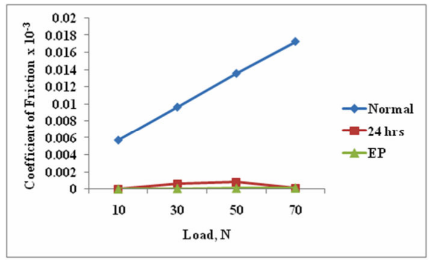


Fig. 6. Effect of applied load on wear coefficients under dry sliding, 24 hours water absorbed and EP conditions of PA6 samples (sliding speed: 2.5 m/s and sliding distance; 1000 m).

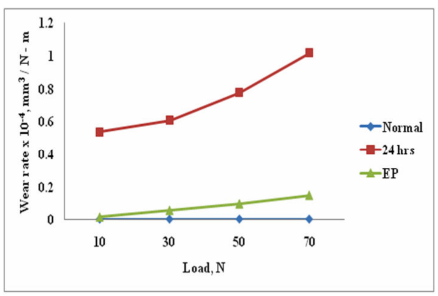


Fig. 7. Effect of applied load on wear rate of ABS samples under dry sliding, 24 hours water absorbed and EP conditions (sliding speed: 2.5 m/s, sliding distance: 1000 m).

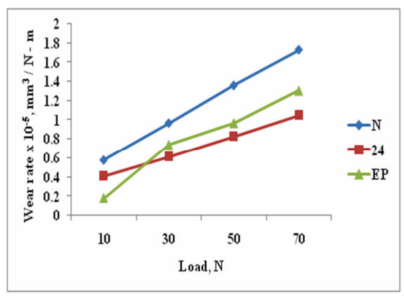


Fig. 8. Effect of applied load on wear rate of PA6 samples under dry sliding, 24 hours water absorbed and EP conditions (sliding speed: 2.5 m/s, sliding distance 1000 m).

3.1.2. Sliding speed effect on friction and wear

The effect of sliding speed on wear coefficients of ABS sliding combinations under dry sliding, 24 hours water absorbed and EP conditions is presented in Fig. 9. As seen from Fig. 9, the wear coefficient of ABS-metal combination under dry friction condition increases to the maximum value when the sliding speed is 5 m/s; after that, the wear coefficient decreases with the increasing sliding speed; the wear coefficient of ABS samples under water absorbed conditions indicates drastic reduction in wear rate with the increase in sliding speed.

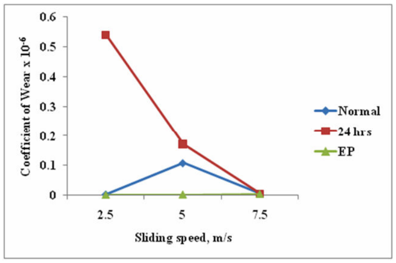


Fig. 9. Effect of sliding speed on wear coefficients under dry sliding, 24 hours water absorbed and EP conditions (applied load: 10 N, sliding distance:1000 m).

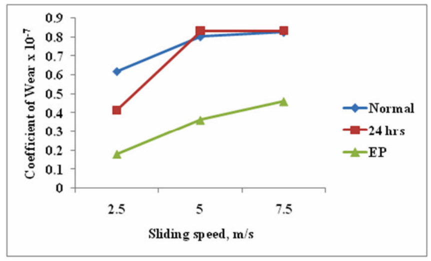


Fig. 10. Effect of sliding speed on wear coefficients under dry sliding, 24 hours water absorbed and EP conditions (applied load: 10 N, sliding distance:1000 m).

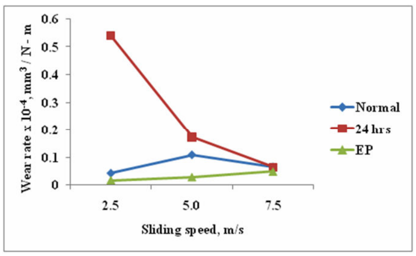


Fig. 11. Effect of sliding speed on wear rates of ABS samples under dry sliding, 24 hours water absorbed and EP conditions (applied load: 10 N, sliding distance:1000 m).

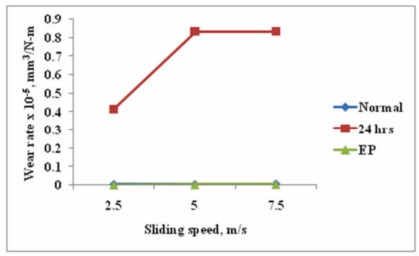


Fig. 12. Effect of sliding speed on wear rates of PA6 samples under dry sliding, 24 hours water absorbed and EP conditions (applied load: 10 N, sliding distance: 1000 m).

As seen from Fig. 10 dry sliding and water absorbed PA6 samples show higher wear coefficient in comparison with EP samples. The values of all samples under all conditions increase till 5 m/s and thereafter EP samples show a slight increase with increasing speed whereas normal/dry sliding and water absorbed samples do not vary with increasing speed.

The effect of sliding speed on the specific wear rates of ABS and PA6 samples under dry sliding, 24 hours water absorbed and EP conditions are given in Figs. 11 and 12. The specific wear rate of water absorbed PA6 sample increases till 5 m/s and after that attains a stagnation point, i.e., specific wear rate does not vary with increase in speed after 5 m/s rubbing speed, but the normal sample on the other hand does not show any variation in wear rate between 2.5 m/s and 5 m/s rubbing speed and increases beyond 5 m/s. This is not visible in Fig. 12 as the specific wear rate values are as less as 10^{-6} mm^3/N-m for normal and EP conditions. The EP values show an increasing trend with the increase in sliding speed.

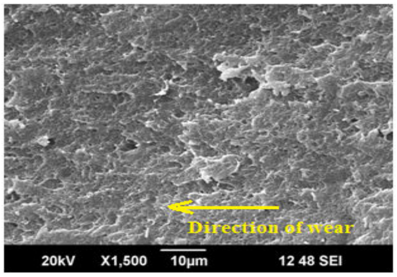
It appears that EP samples are independent of the increase in sliding speed. It is understood that after the running-in process for certain duration, surface roughness and other parameters reach to a steady state value and for this reason, there is no change in friction with time. These findings are in agreement with the findings of Chowdhury et al. [32] and Chowdhury and Helali [45].

3.2. SEM observation of worn surfaces

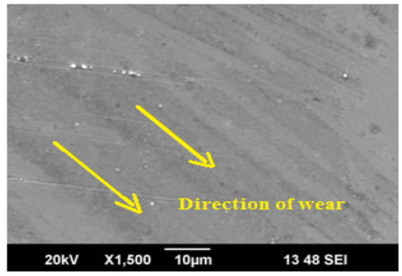
The SEM micrographs of worn surfaces of ABS and PA6 under dry friction, 24 hours water absorbed and EP conditions are given in Fig. 13. It is observed that the worn surface of PA6 under dry friction condition is smooth, and no debris is observed in this case. As for 24 hrs water absorbed condition, there is much debris on the worn surface as observed from Fig. 13(d), the surface of PA6 is noted to have obviously and deeply frictional marks. The previously discussed experimental results found that the wear rate of PA6 under water absorbed condition was greater than that under normal condition (Fig. 3). The SEM-EDX analysis of EP-PA6 indicates the erosion of nickel layer and the presence of the conductive paint layer (Ag) *[Nylon's electroplating procedure involves the conductive painting of PA6 surface and then subjecting the painted PA6 sample to copper and Nickel electroplating procedure]* and copper layer, thus it could be understood that the sample has resisted wear loss to a much greater extent as compared to normal and water absorbed conditions. The EP-PA6 sample's worn surface indicates a smoother surface as compared with 24 hrs water absorbed SEM images.

Similarly, the worn surface of ABS sample shows the formation of flake like surface as observed from Fig. 13 (a). The samples subjected to water absorption studies indicate larger flakes, and are characterized by no debris formation on the worn surface. The enlargement in the size of the flakes indicates the increase in the COW and wear rate and this is also observed in Fig. 3 where ABS under water absorbed condition shows more wear loss than any other samples under study. The SEM-EDX analysis of EP-ABS samples indicates the erosion of nickel layer, this causes reduced wear loss and the worn surface to appear smoother than normal and the water absorbed samples, Fig. 13(e). From Fig. 3 it is also understood that PA6 sample's hardness values are lesser than ABS samples and thus makes it to undergo lesser wear loss when compared to ABS samples under dry condition, also the reason for increased wear in the water absorbed samples can be deduced from the fact that water diffuses into PA6 and ABS surface from micro cracks and micro pores on polymer surfaces, which induces the reduction in mechanical strength under water absorbed condition and this is seen as a fact from Table 1, wherein the tensile strength of the material has decreased in water absorbed state and also there isn't much improvement in hardness values and therefore higher wear rate can be observed under water absorbed condition.

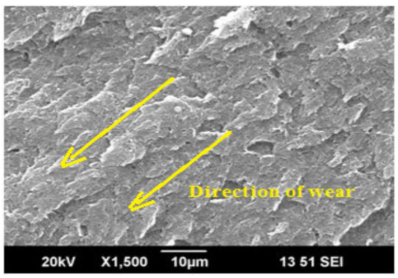
Also from Fig.14 it is observed that EP-ABS and EP-PA6 samples subjected to a load of 30N experiences a little higher wear loss. It is understood that higher load leads to ploughing effect which helps in trapping of the wear particles this increases the wear rate. From Fig. 15 it is observed that water absorbed PA-6 samples undergo delamination and hence peeling of layers with the increase in speed (5 m/s), this is quite different from what is observed at 2.5 m/s rubbing speed. But, water absorbed samples even at higher load of 70N and higher speed of 5 m/s and have not undergone delamination.



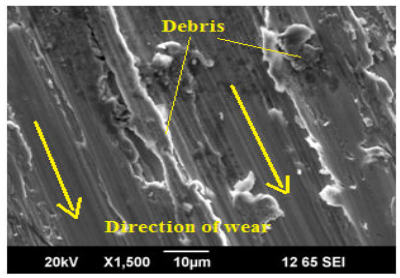
(a) Normal-ABS



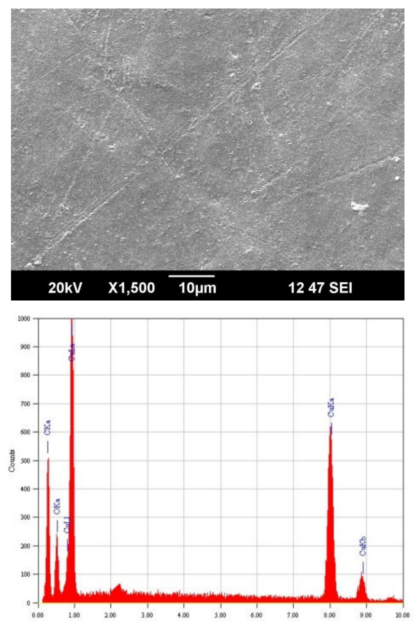
(b) Normal-PA6



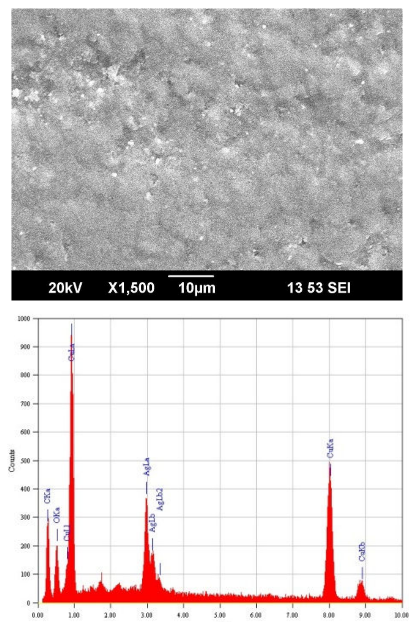
(c) 24 hours-ABS



(d) 24 hours-PA6

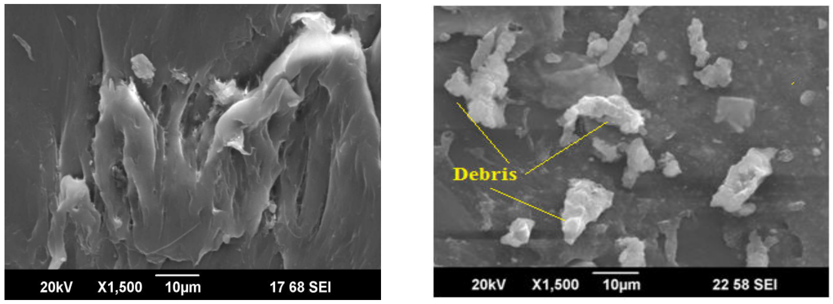


(e) EP-ABS EDX results



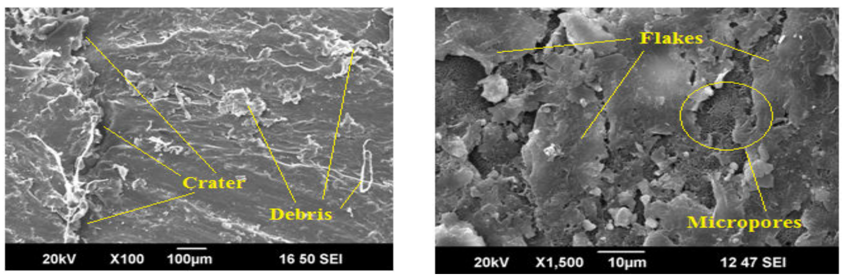
(f) EP-PA6 EDX results

Fig. 13. SEM micrographs of worn surfaces under dry sliding, 24 hours water absorbed and EP conditions (Applied load: 10 N, sliding speed: 2.5 m/s, sliding distance: 1000 m).

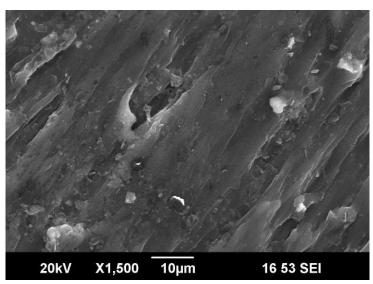


(a) EP-ABS samples subjected to 30 N. **(b) EP-PA6 samples subjected to 30 N.**

Fig. 14. SEM micrographs of worn surfaces under EP conditions (sliding speed: 2.5 m/s, sliding distance: 1000 m).



(a) 24 hours water absorbed ABS sample subjected to 70 N load, sliding speed: 2.5 m/s. **(b) 24 hours water absorbed PA6 sample subjected to 10 N load, sliding speed: 5 m/s.**



(c) 24 hours water absorbed ABS sample subjected to 10 N load, sliding speed: 5 m/s.

Fig. 15. SEM micrographs of worn surfaces under 24 hours water absorbed condition (sliding distance: 1000 m).

3.3. Discussion

According to Jia et al. [9], the rubbing between materials at all times results in heat generation due to the unevenness of the surfaces which causes a rise in the temperature between the surfaces when they come in contact or rub or slide against each other. The amount of heat generated is determined by the formula Q

= μPV [9], where μ is the friction coefficient, P the applied load, and V is the sliding speed. In the early studies, Watanabe et al. [37] has stated that the maximum friction with increasing sliding speed for nylon–metal couple is attributed to temperature effects is caused by frictional heat.

As it is known that the effect of applied load P and sliding speed V leads to the rising of temperature on worn surfaces under sliding conditions [9], the relationship between wear coefficient and PV value under dry sliding and the water absorbed conditions for ABS and PA6 samples is exhibited in Fig. 16 and 17, which is on the basis of the results shown in Figs. 3 to 10. It is recognized from Fig. 16 that the wear coefficient increases with the increasing PV value for the ABS samples; with the increase in wear coefficient the specific wear rate also increases. The water absorbed samples show higher wear coefficient and hence higher specific wear rate than normal and EP samples. The possible reason for this increase in wear coefficient and wear rate may be due to the various molecular motions [9] of ABS sliding surface. Also ABS samples absorb a little water due to which the water in ABS weakens the ABS matrix and decreases the mechanical strength. Therefore, an increase in heat generation takes place and leads to higher COW and wear loss. But in case of PA6 the water acts as a lubricant and reduces the wear loss and COW as observed from Fig. 17. PA6 samples are more rigid than ABS and hence under dry sliding create more friction and due to which more heat and more wear loss with an increase in PV value.

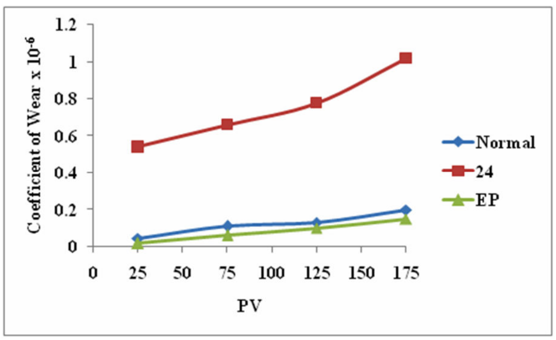


Fig. 16. Relationship between wear coefficient of ABS-metal combination and *PV* value for dry sliding, water absorbed and EP condition.

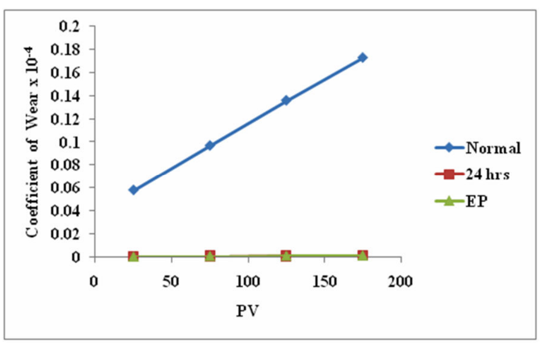


Fig. 17. Relationship between wear coefficient of PA6-metal combination and *PV* value for dry sliding, water absorbed and EP condition.

The possible rise and fall of COW and wear rate of ABS and PA6 values under various conditions can be attributed to the reason that, when the *PV* value is small, the thermal motion of PA6 and ABS molecules is weak because the frictional heat is relatively low, then the deformation of PA6 and ABS molecule cannot respond to external forces, so the wear coefficient and the wear rate are relatively high. As the frictional heat gradually increases, the amount of PA6 and ABS molecules in movement gradually increases, then the deformation of PA6 and ABS molecules can respond to external forces, so the corresponding wear coefficient and the wear rate of PA6 and ABS gradually decrease. With the increasing frictional heat, the molecular segments of PA6 and ABS are likely to move, so the friction and wear of PA6 and ABS increase with increasing frictional heat, because PA6 and ABS molecules can easily entangle or interpenetrate into each other in this state. When the frictional heat increases with the increasing *PV* value, the PA6 and ABS main molecules can move freely, and the molten sliding surface forms a low shear-strength interfacial layer which behaves as a lubricant, so the wear coefficient decreases. Furthermore, the PA6 and ABS sliding surface can melt flow under external forces, so the wear rate of PA6 and ABS increases sharply.

4. Conclusions

The following are the conclusions drawn from the tribological studies on the ABS and PA6 samples subjected to various test conditions.

- The higher wear loss of PA6 under dry sliding and ABS in the water absorbed conditions is due to the reduction in mechanical strength.
- The EP-ABS and EP-PA6 samples exhibit lower wear loss and lower wear coefficient when they are compared with their counterparts in dry and water absorbed conditions.
- The friction and wear behaviours of PA6–metal combination are closely dependent on the *PV* value for the dry sliding condition, while the *PV* value has little effect on the tribological behaviours for water absorbed and EP conditions, whereas for ABS–metal combination is closely dependent on the *PV* value for the water absorbed condition, while the *PV* value has little effect on the tribological behaviours for dry sliding and EP conditions.
- The study indicates clearly that by using PA6 in the EP condition has beneficial effect for industrial applications in terms of wear resistance, hardness and strength.

References

1. Alauddin, M.; Choudhury, I.A.; El Baradie, M.A.; and Hashmi, M.S.J. (1995). Plastics and their machining: A review. *Journal of Materials Processing Technology*, 54(1), 40-46.
2. Shachelford, J.F. (2000). *Introduction to material science for engineering*. Prentice Hall, Upper Saddler River, NJ, USA.

3. Aldousiri, B.; Shalwan, A.; and Chin, C.W. (2013). A review on tribological behaviour of polymeric composites and future reinforcements. *Advances in Materials Science and Engineering*, Article ID 645923, 1-8.
4. Hart, R.P. (1995). Electroplating of plastics. Nickel development institute, Technical series No 10078. Accessed December 23, 2013 from http://www.nickelinstitute.org/~/Media/Files/TechnicalLiterature/ElectroplatingonPlastics_10078_.pdf.
5. Kulkarni, M.V.; Elangovan, K.; and Hemachandra, R.K. (2013). Development of Electroplating process for plating polyamides. *Bangladesh Journal of Scientific and Industrial Research*, 48(3), 205-212.
6. Apichartpattanasiri, S.; Hay, J.N.; and Kukureka, S.N. (2001). A study of the tribological behaviour of polyamide 66 with varying injection-moulding parameters. *Wear*, 251(1-12), 1557-1566.
7. Lee, L.H. (Ed.). (1974). Advances in polymer friction and wear. *Polymer Science and Technology*, 5b, Plenum Press, New York.
8. Briscoe, B.J. (1998). Isolated contact stress deformations of polymers: the basis for interpreting polymer tribology. *Tribology International*, 31, 121-126.
9. Jia, B.-B.; Li, T.-S.; Liu, X.-J.; and Cong, P.-H. (2007). Tribological behaviours of several polymer–polymer sliding combinations under dry friction and oil-lubricated conditions. *Wear*, 262(11-12), 1353-1359.
10. Lancaster, J.K. (1972). *Friction and wear in polymer science*. North-Holland Publishing Company, New York.
11. Ludema, K.C.; and Tabor, D. (1966). The friction and visco-elastic properties of polymeric solids. *Wear*, 9(5), 329-348.
12. Bahadur, S.; and Ludema, K.C. (1972). The viscoelastic nature of the sliding friction of polyethylene, polypropylene and copolymers. *Wear*, 25(1), 109-128.
13. Kalácska, G. (2013). An engineering approach to dry friction behaviour of numerous engineering plastics with respect to the mechanical properties. *EXPRESS Polymer Letters*, 7(2), 199-221.
14. Bhushan, B. (2001). *Modern tribology handbook*, 1(2). CRC Press, Boca Raton, Florida.
15. Brostow, W.; Dutta, M.; De Souza, J. R.; Rusek, P.; De Medeiros, A.M.; and Ito, E. N. (2010). Nanocomposites of poly (methyl methacrylate) (PMMA) and montmorillonite (MMT) Brazilian clay: A tribological study. *Express Polymers Letters*, 4, 570-575.
16. Kalácska, G.; Zsidai, L.; Keresztes, R.; Tóth, A.; Mohai, M.; and Szépvölgyi, J.; (2012). Effect of nitrogen plasma immersion ion implantation of polyamide-6 on its sliding properties against steel surface. *Wear*, 290-291, 66-73.
17. Khan, M. S.; Lehmann, D.; Heinrich, G.; Gohs, U.; and Franke, R. (2009). Structure-property effects on mechanical, friction and wear properties of electron modified PTFE filled EPDM composite. *Express Polymers Letters*, 3, 39-48.

18. Kulkarni, M.V.; Elangovan, K.; and Hemachandra, R.K. (2013). Effects of electroplating on the mechanical properties of injection molded thermoplastics. *International Journal of Plastics Technology*, 17(2), 163-170.
19. Choi, J.M. (2010). An environment-friendly surface pretreatment of ABS plastic for electroless plating using chemical foaming agents. *Transactions on Electrical and Electronic Materials,* 11(4), 174-177.
20. Gui-Xiang, W.; Ning, L.; Hui-Li, H.; and Yuan-Chun, Y. (2006). Process of direct copper plating on ABS plastics, *Applied Surface Science*, 253, 480-484.
21. Chandrasekhar, U.; Venkatesh, K.; Elangovan, K.; and Rangaswamy, T. (2011). Integrated use of rapid prototyping and metal plating techniques for development of micro air vehicles. *International Journal of Engineering Science and Technology*, 3(1), 188-193.
22. Kannan, S.; and Senthilkumaran, D. (2014). Assessment of mechanical properties of Ni-coated ABS plastics using FDM process. *International Journal of Mechanical and Mechatronics Engineering*, 14(3), 30-35.
23. Raju, B.S.; Chandra Sekhar, U.; and Drakshayani, D.N. (2013). Studies on application of rapid prototyping for the generation of photoelastic models & experimental analysis. *International Journal of Application for Innovation in Engineering & Management*, 2(2), 209-215.
24. Polyamide, http://en.wikipedia.org/wiki/Polyamide, Wikipedia-The Free Encyclopedia, Accessed December 12, 2013.
25. ABS-An Engineering Plastic, Technical Articles & Reports on Plastic Industry Accessed November 25, 2013, from http://www.plastemart.com/upload/Literature/84_abs_engineering_1.asp, Smartech Global Solutions Ltd.
26. Glaser, W.A. (1992). Materials for tribology. Tribology series 20, TJ1075.G53.
27. Devaux, E.; Bourbigot, S.; and Achari, A.E. (2002). Crystallization behavior of PA-6 Clay nanocomposite hybrid. *Journal of Applied Polymer Science,* 86, 2416–2423.
28. Anton. A.; and Baird. B.R. (2002). *Polyamides, fibers: In encyclopedia of polymer science and technology*. New York: John Wiley, 584-617
29. Nylon, http://www.sdplastics.com/nylon.html, San Diego Plastics, INC., Accessed September 3, 2013
30. Abacha, N.; Kubouchi, M.; and Sakai, T. (2009). Diffusion behavior of water in polyamide 6 organoclay nanocomposites. *Express Polymer Letters,* 3(4), 245-255.
31. Aneta Krzyżak.; Jacek Gąska.; and Branislav Duleba. (2013). Water absorption of thermoplastic matrix composites with polyamide 6. *Scientific Journals (Maritime University of Szczecin)*, 33(105), 62-68.
32. Chowdhury, M.A.; Nuruzzaman, D.M.; Kowser, A.; Rahman, M.; Roy; B.K; Chakraborty, S.; Hossen, S.; Uddin, I.; and Hossain, S. (2014). Frictional behaviour of polymers sliding against smooth and rough mild steel counter faces. *Middle-East Journal of Scientific Research*, 21(3), 477-486.
33. El-Tayeb, N.S.M.; and Mostafa, I.M. (1996). The effect of laminate orientations on friction and wear mechanisms of glass reinforced polyester composite. *Wear*, 195(1-2), 186-191.

34. El-Tayeb, N.S.M.; and Gadelrab, R.M. (1996). Friction and wear properties of E-glass fibre reinforced epoxy composites under different sliding contact conditions. *Wear*, 192(1-2), 112-117.
35. Bahadur, S.; and Zheng, Y. (1990). Mechanical and tribological behaviour of polyester reinforced with short glass fibers. *Wear*, 137(2), 251-266.
36. Bahadur, S.; and Polineni, V.K. (1996). Tribological studies of glass fabric-reinforced polyamide composites filled with CuO and PTFE. *Wear*, 200(1-2), 95-104.
37. Watanabe, M.; Karasawa, M.; and Matsubara, K. (1968). The frictional properties of nylon. *Wear*, 12, 185-191.
38. Tanaka, K. (1982). Transfer of semi crystalline polymers sliding against smooth steel surface. *Wear*, 75, 183-199.
39. Bahadur, S.; and Tabor, D. (1985). Role of fillers in the friction and wear behaviour of high-density polyethylene. In Lee, L.H. (Ed.), Polymer wear and its control, ACS Symposium Series, ACS Publications, Washington, DC, 287, 253-268.
40. Pihtili, H.; and Tosun, N. (2002a). Effect of load and speed on the wear behavior of woven glass fabrics and aramid fiber-reinforced composites. *Wear*, 252, 979-984.
41. Pihtili, H.; and Tosun, N. (2002b). Investigation of the wear behaviour of a glass fiber-reinforced composite and plain polyester resin. *Composites Science and Technology*, 62, 367-370.
42. Franklin, S.E. (2001). Wear experiments with selected engineering polymers and polymer composites under dry reciprocating sliding conditions. *Wear*, 251(1-12), 1591-1598.
43. Benabdallah, H. (2003). Friction and wear of blended polyoxymethylene sliding against coated steel plates. *Wear*, 254(12), 1239-1246.
44. Mahesh, K.S.; Lohith, V.B.; Sondur.; and Sondur, V.V. (2013). Influence of cryogenic treatment on the friction coefficient of nylon 6 and caprolactam-graphite composite. *International Journal of Mechanical Engineering*, 1(6), 10-15.
45. Chowdhury, M.A.; and Helali, M.M. (2008). The effect of amplitude of vibration on the coefficient of friction for different materials. *Tribology International*, 41(4), 307-314.