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Investigation on Adhesive Wear Behaviour of Industrial Crystalline and Semi-Crystalline Polymers against Steel Counterface

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Abstract: In the present scenario, polymers are extensively used for manufacturing of sliding components (against metals or other materials) such as gears, bearings, cams, rollers in conveyors etc. which undergo wear and tear. Thus the study of wear behaviour of polymers becomes necessary in order to enhance the life of such components. In the present research work, the adhesive wear characteristics of crystalline polymer Polyacetal (Polyoxymethylene-POM) and semi-crystalline polymer such as Nylon 6, Nylon 66 (aliphatic polyamides) were investigated. Polymers considered for this study are potential candidate materials for rollers in hybrid chains in food processing industry, medical equipments etc. Sliding wear tests were carried out under dry conditions using a pin- on-disc (ASTM G99) arrangement. The wear tests were performed against a mild steel disc (HRB 67) at room temperature under various loads (60, 80, 100N) and sliding speeds (1.8, 2.3, 2.8m/s). Cylindrical shaped polymers of 25 mm diameter were used for the wear tests. Among the three polymers, Polyacetal was observed the least wear rate and coefficient of friction irrespective of load and speed because of its crystalline nature. Nylon 6 exhibits higher frictional coefficient at higher sliding velocity**.** Frictional heating and subsequent local melting of the polymer apparently play a role on the wear of the polymers.

Keywords: Polymers; Coefficient of friction; Wear rate; Wear Pattern; Sliding distance.

1. Introduction

Polymers are mainly used in many static and dynamic industrial applications such as bushes, gears, bearings, rollers, timing screws, washers etc. and replacing traditional materials like steel brass, bronze, copper & aluminum because of their excellent tribological properties, such as good wear resistance and low friction and also some polymers have proved to be appropriate choice for frictional applications. Sliding bearings made up of dry polymer material are widely found in home appliances, car engines, human artificial joints, pharmaceuticals, aeronautics and particularly in the food processing industry, due to their self-lubrication properties which lead to avoidance of any external chemical agent as lubricant. Moreover polymers used as industrial components are inert with respect to chemical contamination. Especially when in contact with food materials, the use of lubricants are forbidden to avoid food contamination. In such cases, polymers are often used since they are innocuous for humans and function well under dry sliding conditions. Lancaster[1] investigated the friction in semi-crystalline polymers such as Nylon 66 and Polypropylene, can be attributed to two prominent mechanisms viz. deformation and adhesion. The fragments adhere to the counterface and lead to irregular films, which are initially smooth and result in increased stresses and wear. The deformation mechanism involves dissipation of energy in the contact area and the adhesion component of friction of polymer results from the breakage of bonds between the polymer and mating surfaces**.** Friedrich et al. [2] studied the friction and wear properties of high temperature resistant polymers particularly polyetheretherketone (PEEK), under various testing conditions against smooth steel counterpart and reported that the coefficient of friction value increases with increase in load. Tanaka [3] investigated the wear properties of Polytetrafluoroethylene (PTFE), High density polyethylene (HDPE), Low density polyethylene (LDPE), and Nylon 6 at various sliding velocities and loads, and concluded that PTFE exhibits higher constant wear rate through out the wear process irrespective of the sliding velocities and loads compared to other polymers. Polymer wear could occur in polymers sliding on a transferred polymer layer. It is reported that all polymers except PTFE exhibited lower wear rates when sliding on the transferred layer. PTFE is observed to produce a very dense and coherent transferred layer compared with that of other polymers. Watanabe [4] investigated the friction and wear properties of polyamide (N6) and reported that the sliding velocity and load influence the frictional heating thereby increasing the wear rate due to increase in temperature. Kukureka et al. [5] studied the effect of fibre reinforcement (aramid, carbon and glass) on the friction and wear of PA66 in rolling-sliding contact. Aramid-fibre reinforcement did not significantly alter the friction of the matrix material. Particularly glass fibre reinforcement is found to reduce the coefficient of friction and hence allows the material to be used for higher loads and slips before the melting point of the matrix is reached. The wear process in glass fibre composite is reported, it differs from that of unreinforced nylon and involves the formation and removal of a thin surface layer of nylon or nylon and fibre fragments. Wang and Li [6] investigated the wear properties of UHMWPE polymer and found that the sliding velocity influences the sliding wear to a greater extent than the applied load. They distinguished the wear loss in three different periods during the operating time viz. the wear loss in running-in period, steady-state period and severe wear period. Liu et al. [7] made an attempt to model the wear behaviour of three polymers such as UHMWPE, PA-6/UHMWPE and PA-6 using regression analysis and reported that the contact pressure is the main controlling parameter for the wear process compared to other influencing parameters such as the sliding distance and speed. They also concluded that the results obtained from the regression analysis have good agreement with the experimental results. Franklin [8] investigated the friction and wear behaviour of POM and UHMWPE polymer under different conditions of sliding speed, mating surface roughness and roughness orientation and reported that the effect of sliding speed on the wear of polymers does not always follow the generally accepted engineering rule of ‘‘higher sliding speed, the higher wear rate’’. This effect is dependent on mating surface roughness. It is reported that the wear rates of POM and UHMWPE can decrease with increasing sliding speed when the roughness of the mating surface is low. Unal et al. [9] investigated the influence of speed and applied pressure on the friction and wear behaviour of Polyamide 66 (PA 66), Polyoxymethylene (POM), High Molecular Weight Polyethylene (UHMWPE) and aliphatic Polyketone (APK and reported that the temperature rise influenced by sliding speed results in considerable increase in friction coefficient and the sliding speed has stronger effect on the wear rate than the applied pressure**.** Luıs Seabra et al. [10] studied the tribological behaviour of food grade polymer namely PTFE, UHMWPE (green, black, white) Green and black grades are obtained by adding coloured pigments to the natural (white) material, High Molecular Weight Polyethylene (HMW-PE), Polyamide (PA 6), Polyacetal (POM C), Polyethylene terephthalate (PETP) under sugar interface dry sliding testing conditions**.** Among the food polymers tested UHMWPE-green is found to exhibit lowest frictional coefficient and good wear resistance. It is also concluded that, this polymer is one of the best option to match stainless steel because of the presence of green pigments. The composite of PETP with some percentage of PTFE could slightly reduce the frictional coefficient due to “tribo-sealing” action to block to some extent, the entry of the sugar in contact, thus reducing the wear rate. Unal et al. [11] studied the influence of speed and load on the friction and wear behaviour of pure Polytetrafluoroethylene (PTFE), Glass Fibre Reinforced (GFR) and Bronze and Carbon filled PTFE polymers. They found that Glass Reinforced PTFE exhibits lower wear rate and frictional coefficient compared with pure PTFE, and Bronze-Carbon Reinforcement. Bronze and Carbon fillers to PTFE polymers were found effective compared with the pure PTFE. Samyn et al. [12] investigated the tribological properties of some engineering polymers namely PET/Teflon, PTFE, UHMWPE/carbon, under various interface materials such as high alloy steel, stainless steel, and epoxy resin. They reported that PET/PTFE sliding against the stainless steel developing the transfer layer on to the steel surface, which leads to reduce in frictional coefficient. There is no wear debris found for UHMWPE/carbon against stainless steel, as it has higher toughness and allows the surface to tear without particle detachment, resulting in higher friction. Though many researchers had dealt with many polymers and reported that polyamide has a superior wear resistance during its sliding against a steel counterface compared to other polymers and the coefficient of friction of polyamide is found to be affected greatly by various factors such as normal load, sliding speed, and interface temperature, but still the wear behaviour of such polymers which are used in various industrial applications has to be studied in detail in order to understand the mechanism of wear. Particularly the present research work focused on the adhesive wear behavior of the polymers, which are mainly used as rollers in industrial applications.

2. Experimental Details

The as-received three different cylindrical shaped polymers of 25 mm diameter Nylon 6, Nylon 66, and Polyacetal has been selected for wear test as shown in Figure 1(a). The physical and mechanical properties of the polymers are mentioned in the Table 1. The aliphatic polyamides are generally known as Nylons, mainly used as bushes, washers, rollers and bearings. It can be either used as plastic as well as fibre, due its good tensile strength, abrasion resistant and toughness. It is less affected by moisture compared to other nylons because of its dense structure with small evenly spaced pores.

Table 1: **Physical and mechanical properties of polymers**

PROPERTIES	Nylon 6	Nylon 66	Polyacetal
Water Absorption	2 to 4%	3 to 4%	0.90%
Wear Resistance (Best value-20)	16 to 18	16 to 18	19
Electro Resistivity	1E15 ohm-cm	1E16 ohm-cm	1E12 ohm-cm
Continuous Service Temp.	-70 to 120 ˚C	-30 to 105 ˚C	85 to 148 ˚C
Melting Temperature	223˚C	260˚C	178˚C
Density (g/cc)	1.12 to 1.14	1.13 to 1.15	1.42
Impact Strength (N)	44 to 300	48 to 150	80
Bending strength (MPa)	110 to 120	115 to 125	79
Roughness, Microns (After wear)	1.264 (2.266)	1.326 (1.119)	0.816 (0.083)

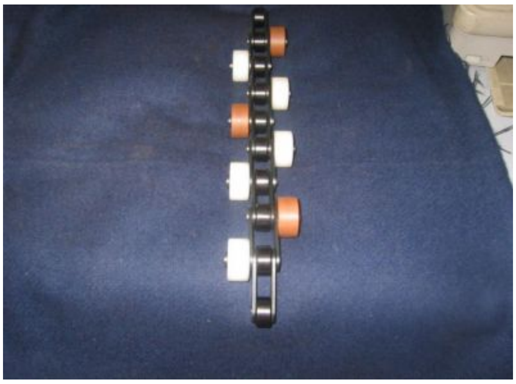


Fig. 1(a)

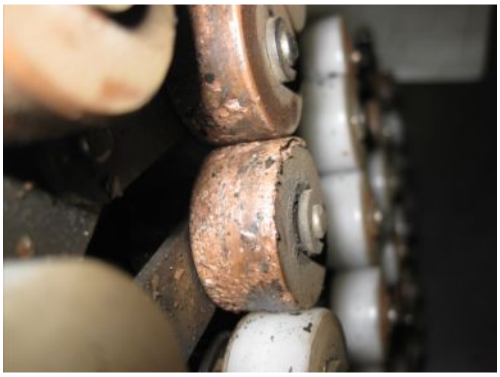


Fig. 1(b)

Figures 1(a): As-received polymers (used as rollers in hybrid chains)
Figures 1(b): Worn out used polymers as rollers in industry applications

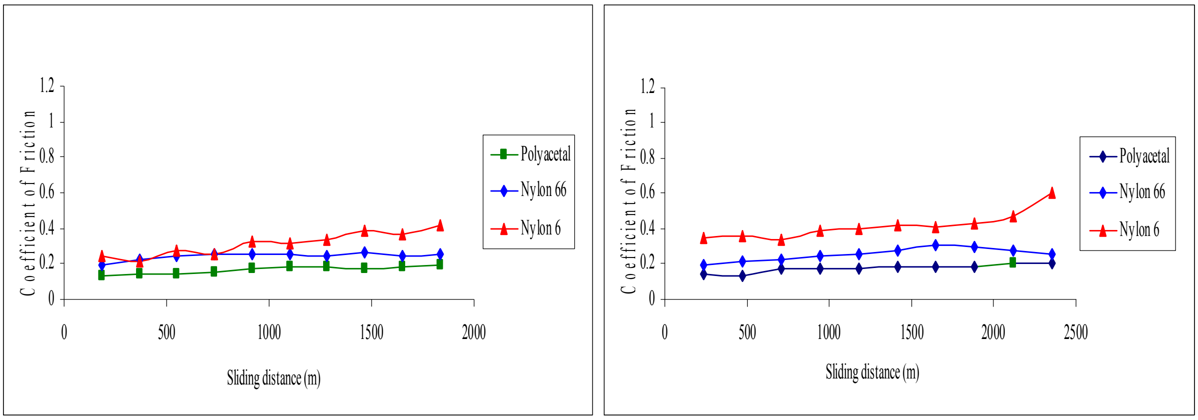
Polyoxymethylene commonly referred as Polyacetal is a highly crystalline and high performance engineering polymer used in precision parts because of its high stiffness, low friction and low moisture absorption, which results in excellent dimensional stability. Polyacetal is an excellent polymer for parts that must exhibit tight dimensional tolerances like timing screws, gears, bearings etc. even in moist environments. Computer assisted Pin-on-disk tribometer arrangement (ASTM G99) was used for performing dry sliding wear tests against a mild steel disc (HRB 67) at room temperature under various loads (60, 80,100N) and sliding speeds (1.8, 2.3, 2.8 m/s). The disc was cleaned with acetone and thoroughly dried, before and after the commencement of wear tests. For every test, the coefficient of friction at various loads and sliding speeds were correlated with the sliding distance, which was determined using a cantilever loading device with load cell. The wear rates of the polymers were measured from weight loss measurements using electronic weighing balance of 0.001 mg accuracy.

3. Results and Discussion

The wear rate and coefficient of friction of each polymer were correlated with load, sliding distances and sliding speed. Also optical micrographs of the worn out surfaces of these polymers were recorded in order to study the mechanism of wear.

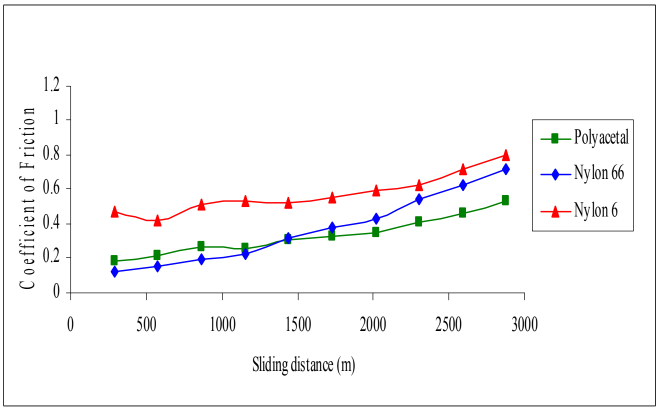
3.1 Effects of the Frictional Coefficient at Constant Applied Load Of 60n And At Different Sliding Speeds

Figures 2(a)-(c) show the plots of frictional coefficient of the three polymers at various sliding distances at constant applied load of 60N and three different sliding velocities such as 1.8, 2.3, and 2.8m/s respectively. From the figure 2(a) it can be observed that Polyacetal and Nylon 66 exhibit almost constant coefficient of friction value with respect to sliding distance. This may be attributed due to the strong bonding of electrons in H-C-H group in Polyacetal. Nylon 6 shows a constant increase in friction coefficient after the sliding distance of 1000 m. This may be due to the effect of adhesion due to the deformation of the asperities at contact points, which might have become plastic. Among the three polymers, Nylon 6 has higher frictional coefficient at this sliding velocity and applied load. The frictional coefficient of the polymers at 2.3 m/s sliding speed is depicted in the figure 2(b)**.** Similar trend on coefficient of friction is observed in case of Polyacetal and Nylon 66. This may be due to the constant interaction of the transfer film with the metal counterface. Also at this sliding velocity, the frictional coefficient of Nylon 6 is continuously increasing and reaches a maximum towards the end of the testing period. The increase in coefficient of friction at higher sliding distances is attributed due to high temperature softening of the polymer which leads to dominance of adhesive mechanism of friction**.** The variation of frictional coefficient at maximum sliding speed chosen for the test i.e. 2.8 m/s is depicted in the figure 2(c). In contrast to the earlier cases, the frictional coefficient is observed to increase with the sliding distances in all three cases of polymers.



2(a) 1.8 m/s

2(b) 2.3m/s



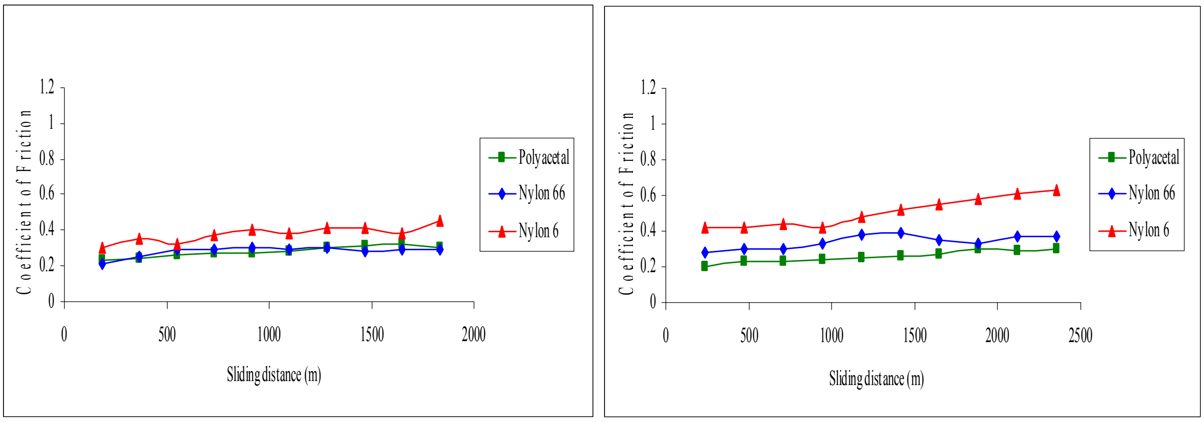
2(c) 2.8m/s

Figures 2(a)-(c): Coefficient of friction versus sliding distance for three different sliding velocities at constant load of 60N

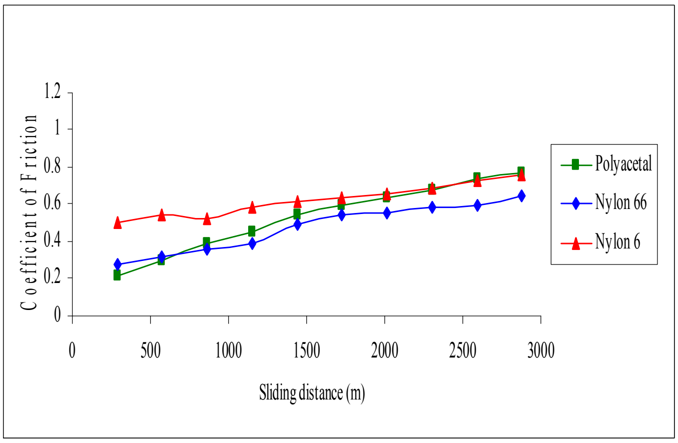
The reason may be due to the higher sliding velocity employed. However the coefficient of friction for Polyacetal and Nylon 66 is almost equal up to a particular threshold value of sliding distance and then it increases for both and attains the maximum value towards end.

3.2 Effects of the Frictional Coefficient at Constant Applied Load Of 80n and at Different Sliding Speeds

Figures 3(a)-(c) depict the influence of sliding speed on the frictional coefficient of polymers at a constant load of 80N and at the sliding speeds of 1.8, 2.3, and 2.8m/s respectively. The trend is very similar to that exhibited under the load of 60 N. In the case of Nylon 66, the frictional coefficient remains constant over a period due to the formation of transfer film and reaches maximum towards the end of testing period [12].



3(a) 1.8m/s **3(b) 2.3m/s**



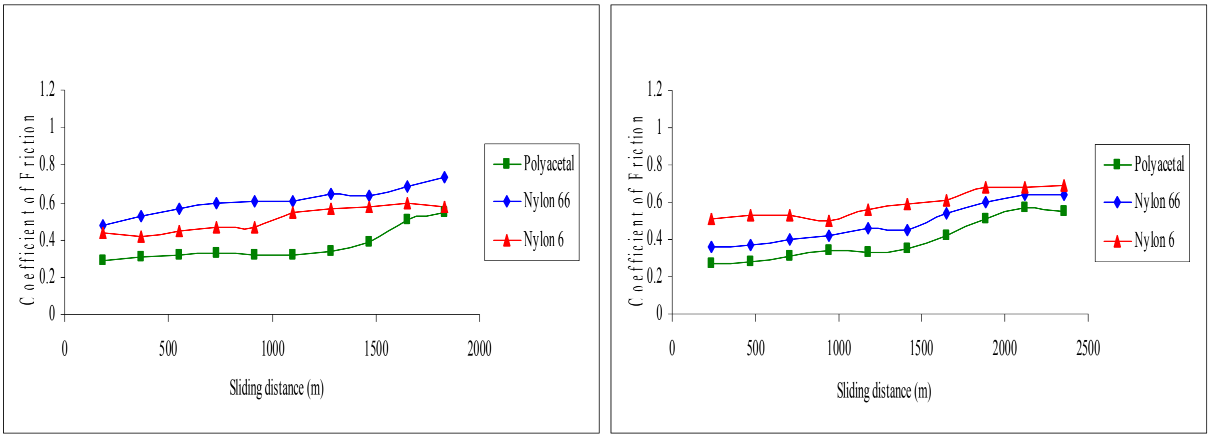
3(c) 2.8m/s

Figures 3(a)-(c): Coefficient of friction versus sliding distance for three different sliding velocities at constant load of 80N

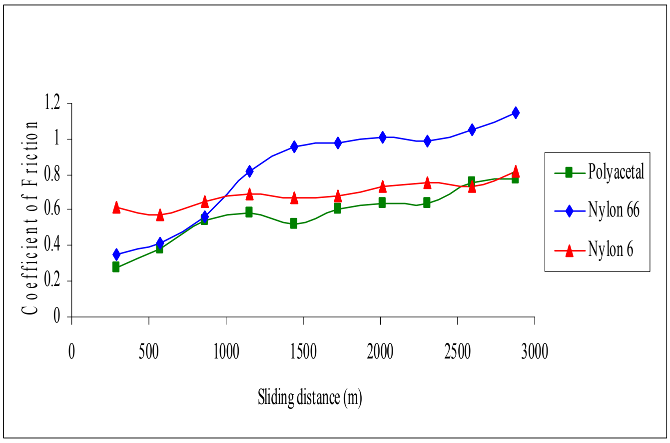
For Nylon 6 during the initial period at higher sliding speeds, the local melting causes sub surface deformation and eventually the transfer film breaks leading to increase in frictional coefficient.The coefficient of friction of this material increased continuously and attained steady state after a sliding distance of 1000 m. For Polyacetal, the increase in sliding velocity does not affect its wear rate in view of its hard and strong linkage of H-C-H.

3.3 Effects of the Frictional Coefficient at Constant Applied Load of 100n and at Different Sliding Speeds

The variations of frictional coefficient with respect to various sliding distances at constant load of 100N and at three different sliding velocities have been depicted in the Figures 4(a)-(c). At 100 N and higher sliding distances values, Nylon 66 is observed to have higher coefficient of friction due to adhesion effect [13]. The examination of counterface for the Nylon 6 showed that most of the abrasion marks produced during cleaning was due to the presence of transfer film on the disc surface. Figure 4(a) shows the variation of frictional coefficient at a sliding speed of 1.8m/s for the various polymers. It may be concluded that the frictional coefficient of Polyacetal polymers has not been significantly affected by the variation of loads at lower sliding velocity. This is due to the inherent nature of strong molecular bonding in this polymer. Nylon 66 and Nylon 6 show a slightly greater and continuous increase in frictional coefficient at higher load. This may be attributed due to the visco-elastic transitions taking place at elevated temperature [4].



4 (a) 1.8m/s 4 (b) 2.3m/s



4 (c) 2.8m/s

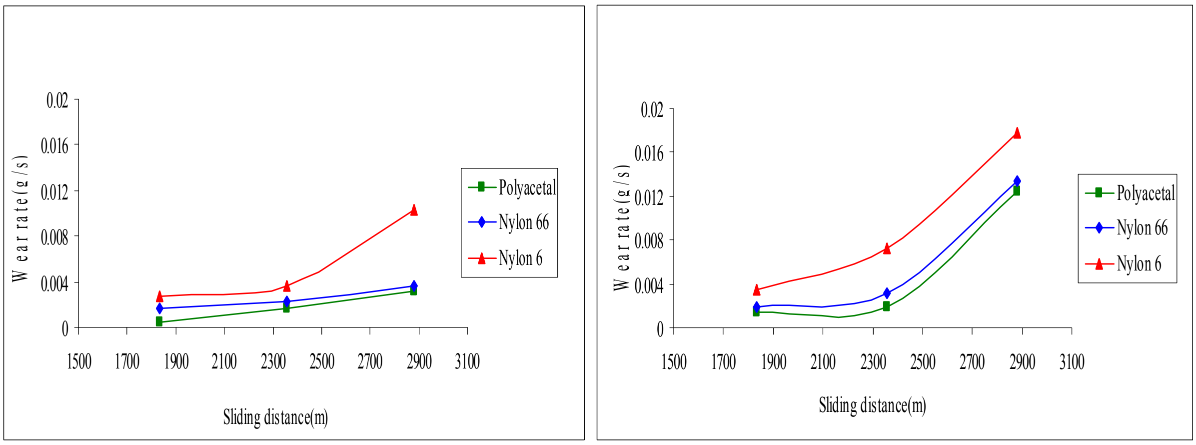
Figures 4(a)-(c): Coefficient of friction versus sliding distance for three different sliding velocities at constant load of 100N

The variation of frictional coefficient of various polymers with corresponding sliding distance at the sliding speed of 2.3m/s is pictured in the figure 4(b). In this case, the polymers exhibit constant increase in frictional coefficient values, which may be due to the spreading of transfer film between the contact asperities and the steel counter face at this higher load and sliding distance.The variation of frictional coefficient of the polymers at the sliding velocity of 2.8m/s is shown in the figure 4(c). Irrespective of the type of polymer, the friction coefficient is observed to increase with increasing load and sliding distance [7]. In case of Polyacetal, in particular, the increase in coefficient of friction may be due to the continuous formation of a patch-like transfer film and subsequent breaking at the higher load and speed.

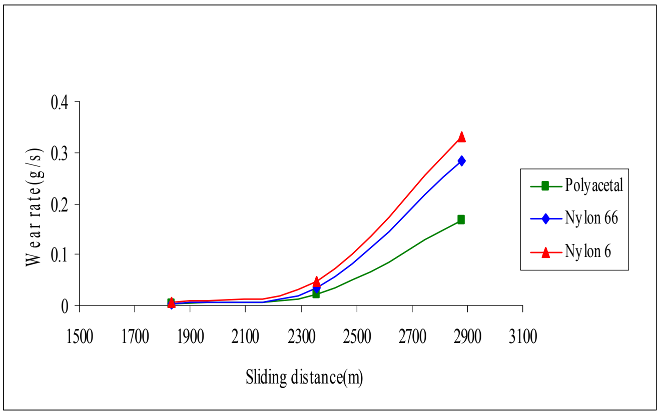
In general, the lower coefficient of friction observed in the case of Polyacetal may be attributed to the uniform transfer film. This also leads to reduced wear in this crystalline polymer. It is postulated [1] that the preferential orientation of molecular chains in the case of crystalline polymers (Polyacetal) could reduce the interfacial shear stress, thereby resulting in considerable reduction in coefficient of friction and wear.

3.4 Effects of Applied Load on the Wear Rate

The wear rate of polymers has been accurately determined from weight loss measurement using a three decimal accuracy digital balance. Loss of materials at maximum sliding distance for each sliding speed and applied load have been evaluated and correlated. Figures 5(a)-(c) show the wear rate versus sliding distance for the polymers corresponding to the loads of 60, 80 and 100N respectively. The polymers are exhibiting almost similar kind of wear behaviour irrespective of the load and sliding velocities. The rate of increase in wear rate is observed to be lower initially, up to a certain threshold value of sliding distance. Thereafter, a steep increase in wear rate was observed. Figure 5(a) illustrates the wear rate of polymers at constant applied load of 60N. At this lower load all polymers are subject to lower wear rate. However the polymers Nylon 6 and Nylon 66 exhibit higher rates of wear compared to Polyacetal. This might be attributed due to the fact that the strength of the adhesive bond formed between the contacting materials can exceed the cohesive strength, causing continuous formation of transfer film on the metal counter face. The wear rate of Polyacetal is lower compared to other two polymers irrespective of applied load and sliding speed due to its inherent property of high hardness and strong bonding between the molecules. Nylon 6 exhibit highest wear rate in all the cases of applied load and sliding velocities compared to Nylon 66 and Polyacetal. This may be because of local melting of material at higher temperatures. Nylon being a thermo-plastic might cause strong bonding of the transfer film on the metal counter-face at higher sliding distances and higher loads [4]. Figure 5(b) shows the wear rate of polymers with corresponding sliding distance for an applied load of 80N. At this moderate load once again the polymers Polyacetal and Nylon 66 show almost same kind of wear behaviour. Due to lower bonding strength of Nylon 6 maximum wear rate is undergone at this moderate load also.



5(a) 60N 5(b) 80N



5(c) 100N

Figures 5(a)-(c): Wear rate versus sliding distance for three different loads.

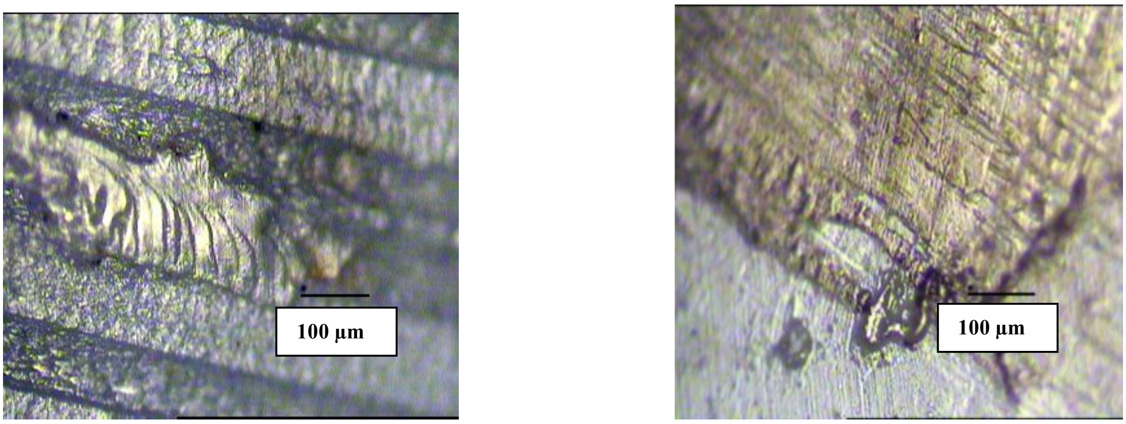
Figure 5(c) depicts the wear behaviour of the three polymers at the highest load (100N). The wear rate of Nylon 66 is intermediate to that of the polymers Polyacetal and Nylon 6. The wear rate of Polyacetal is significantly enhanced at this maximum applied load. Nylon being a visco-elastic polymer [4], is observed to undergo higher wear rates as a result of its increased shear strength on surface with increase in sliding velocity. Polyacetal is a better choice for wear-resistant, low friction applications, when compared to Nylon as shown in the Table 2.

Table 2: **Average value of Coefficient of Friction and Wear rate of the polymers at 2.8 m/s and 100 N**

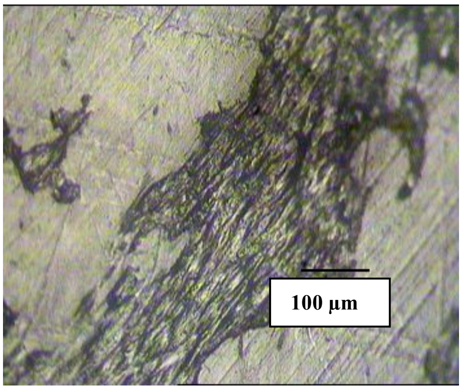
Polymer	Friction Coefficient (μ)	Wear Rate (g/s)
Nylon 6	0.691	0.179
Nylon 66	0.826	0.106
Polyacetal	0.572	0.062

3.5 Wear Pattern

Figure 6(a)-(c) illustrates the morphological observations of wear pattern of maximum worn out specimens of Nylon 6, Nylon 66, and Polyacetal polymers subjected to highest applied load and sliding velocity. Sliding wear in polymers was characterized by abrasion and polishing in addition to transfer. It is clearly evident from the figure 6(a) that some local melting due to heat generation at the contact interface has occurred in the case of Nylon 6 corresponding to the highest load and sliding velocity. As a result of this, Nylon 6 has invariably exhibited significantly higher frictional coefficient irrespective of loads and sliding velocities. Fragments of material have been detached from the interface as a result of heating. The adherence of such detached fragments on to the counterface leads to irregular film, which results in enhancement of friction and wear in semi-crystalline polymers such as Nylon6 and Nylon66. Wear track were observed as deep trenches. The wear pattern of Nylon 66 is pictured in the figure 6(b). There is no severe wear track formation observed from the figure and very less number of localized melting observed compared to the Nylon 6, which leads to moderate rise in frictional coefficient in all the cases of applied load and sliding speed.



6(a) Nylon 6 **6(b) Nylon 66**



6(c) Polyacetal

Figures 6(a)-(c): Photomicrographs of wear pattern for the three polymers

Micro cutting and plastic deformation morphology surfaces were also observed in the wear pattern. The melted layer is solidified into an amorphous brittle layer with a softer sub-layer. Catastrophic wear was identified at high loads and long sliding distance with the disruption of this brittle solidified layer. A few fragments of detached material are also observed in the micrograph. Localized flow of material has been taken place probably caused by thermal softening of the polymeric sliding surfaces. Micro cutting edges and patchy film transfer were also observed in the wear pattern of Polyacetal polymer.

4. Conclusions

The following conclusions can be drawn from the present research work.

1. Nylon6, Nylon66 and Polyacetal exhibits almost same values of coefficients of friction under sliding contact with smooth steel surface. However, the friction coefficient increases continuously with sliding distance and with load [7] for all the three polymers.

2. The transition to higher coefficients of friction values is attributed due to local melting and deformation effects of the polymers on the counterface surface at higher loads.

3. At higher loads, the increase in friction coefficient values of Nylon66 is possibly attributed to visco-elastic transitions taking place due to rise in interface temperature.

4. Polyacetal shows moderate frictional coefficient and low wear rate and no stick- slip, irrespective of the applied load and sliding velocities. This may be due to greater crystallinity of the polymer. At higher loads, due to elevated temperature at the interface, local melting results in formation of film which possibly reduces the friction in the case of Polyacetal.

5. The wear rates of both Nylon 6 and Nylon 66 are high compared to that of Polyacetal. Nylon 6 gets severely worn due to the contribution of tearing force that resulted from the combined action of tribo interface adhesion and shearing effect during friction.

6. Nylon 6 is known to have resistance to surface flow i.e. the shear strength of Nylon 6 becomes higher as the sliding velocity increases which in turn leads to rise in temperature. This causes the strong bonding of transfer film at metal counterface because Nylon 6 is a thermo plastic material [4].

7. Polyacetal is a found to be a preferred material for sliding applications with high wear resistance and lower friction coefficient compared to Nylon 66 and Nylon 6.

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