TRIBOLOGIA - Finnish Journal of Tribology 1-2 vol 37/2020

https://doi.org/10.30678/fjt.88615

SUOMEN TRIBOLOGIAYHDISTYS RY
THE FINNISH SOCIETY FOR TRIBOLOGY
www.tribologysociety.fi

https://journal.fi/tribologia

Dry sliding friction and wear behavior of hybrid glass - carbon fiber reinforced PA66/PTFE composites

Rudresh B M[1*], Ravikumar B N[2], Madhu D[3]

[1]Government Engineering College, Department of Mechanical Engineering, K R Pet, India
[2]Bangalore Institute of Technology, Department of Mechanical Engineering, Bangalore, India
[3]Government Engineering College, Department of Mechanical Engineering, Ramanagaram, India

*Corresponding author: Rudresh B M (bmrudreshan@gmail.com)

ABSTRACT

The tribological response and the frictional effects in dry sliding wear behaviour of hybrid Glass –Carbon composites under the action of sliding load and sliding velocity was studied. The material systems considered for the investigation were PA66/PTFE blend (80/20 wt. %), Blend(PA66/PTFE)/10 wt.% short glass fiber (SGF), Blend (PA66/PTFE)/10 wt.% short carbon fiber (SCF) and Blend (PA66/PTFE)/10 wt.% SGF/10 wt.% SCF (GC).These composites were produced using melt mixing method through extrusion and followed by injection molding. The experimentation was conducted as per ASTM G99 method. The experimentation data revealed that the significant wear resistance was exhibited by Glass-Carbon hybrid composites under the action of all the test parameters. This is attributed to the hybrid effect of fibres which may restrict the early reaching of softening point of polymers thereby preventing melting wear. Further, the formation of uniform and defined transfer polymer substrate on the steel disc surface reduced the frictional effects. Further, Blend/SCF composites were better than Blend/SGF composites. The composites studied were sensitive to applied normal load compared to velocity. The combined matrix and fiber wear were credited to the critical wear volume loss. Fiber misalignment, matrix deformation, melting wear and fiber peeling were some of the failure mechanisms observed in the morphological study of hybrid composites through SEM images.

Keywords: PA66/PTFE, dry slide, hybrid, Glass – Carbon, frictional effects

Introduction

The tribological response of polymer materials must be viewed seriously under the action of different interactive agents such as surface forces, frictional effects, abrasions, etc. whenever the polymer is interacting with rough sliding surfaces. One of the reasons for the failure of polymer components in mechanical applications is due to sliding against hard counter parts. The frictional effects at the interface and wear due to melting are some of the problems which limit the usage of polymer composites. But light weight and self lubrication of polymers add credits to their usage in the industrial applications. The applications such as clutches, brake shoes, liners, sliding valves etc. were subjected to severe wear and fail to resist the applied load [1]. Therefore, it is not possible for a neat polymer to resist both tribological and mechanical loading simultaneously. This may lead to failure of polymers. The aforesaid problems can be solved through polymer modification. Polymer blending is the most economical method among all the polymer modification methods [2]. Further, it was observed that the blend is superior in performance than the neat polymer [3]. The polymer blending concept delivers good polymer composites to uphold both mechanical and tribological loads. Many research studies suggested that the tribological response of composites can be improved through polymer modification using fillers and or fibers. Further, the wear resistance of composites can be improved by reinforcing fibers in to polymers [4]. The effect of hybrid fibers is one among the factors which are influencing the properties of composites. But the optimum volume fraction of fibers is the issue for the formulation of composite system design. Therefore, the best formulations of composite system have to be designed and their tribological response under the action of different test parameters must be discussed. The fiber reinforced polymers are gaining their importance in the modern industrial applications because of their good specific strength and specific modulus. Short fibers made of glass (SGF), carbon (SCF), basalt (SBF) and kevlar (SKF) are some of the potential fibers used for structural applications. The role of fibers is very much significant in mechanical and tribological behaviors of fiber reinforced polymers (FRPs). Many research studies are focusing their attention towards the behavior of FRPs particularly on thermoplastics.

The study on tribological response and mechanical behavior of glass fiber filled Nylon 66/PPS blend composite was reported [5]. The composition of 70/30 vol. % PA66/ PPS was used as the matrix and loaded with varying percentage of glass fiber. They showed that the volumetric loss of the blend decreases with increase in volume fraction of SGF reinforcement. The coefficient of friction (COF) (0.35) was decreased for 20 vol. % of short glass fibers in composites. The effect of addition of SCFs on the wear mechanisms of Polyamide 66/ Polyphenylene sulphide blend composites was reported [6]. The COF of the blend decreases with increase in the percentage of SCF. The wear rate of the blend decreases when the percentage of SCF in composites was less than 30 vol. %. The 30 vol. % SCF in the blend exhibits the minimum COF and 70/30 vol. % PA66/PPS blend exhibits the least wear volume loss. The reinforcement effect of fibers on the wear mechanisms of Polyamide 66 in rolling – sliding was reported [7]. The short fibers such as aramid fiber, glass fiber and carbon fiber were used for the investigation. The COF of the composites studied decreases substantially under the influence of short fibers. The frictional mechanism and tribological behavior of some engineering polymers such as PA66, POM, UHMWPE, 30% glass fiber filled PPS, 30% SGF filled PA46 and 30% SGF reinforced PPS were studied under the action of varying applied pressure and speed [8, 9]. The experimental results revealed that the COF of composite deceases with increase in applied pressure. The material removal rate showed less sensitivity towards the applied pressure.

The influence of short carbon fibers loading on mechanical and wear mechanisms of Polyoxymethylene (POM) was reported by Yuquin and Junlong [10]. The COF of pure POM and carbon fiber filled POM composites increases with increase in load and decreases with increase in sliding speed. The study on the role of SCF in improving mechanical and tribological behavior of SCF filled PA6 composites was reported [11]. The carbon fiber reinforcement was varied from 0 to 30 vol. %. The 20 vol. % SCF in PA6 composites exhibits the minimal wear rate. The frictional effects and wear behavior of SCF reinforced Polyamide 6 and Polypropylene composites were reported [12]. The superior wear characteristics of CF/PP composites were due to the reinforcing effect of SCF. The composites studied exhibit the least COF and good wear resistance when the volume fraction of SCF was 20 wt. %. The composites showed an improvement in friction and wear behavior over the corresponding unfilled polymer. The individual effect of SCF and SGF reinforcement on mechanical and sliding wear behavior of Nylon 66 composites was reported [13]. They showed that the improvement in the strength of thin transfer film on the counter surface is responsible for the wear resistance of filled composites. Further, the glass fiber filled Polyamide 66 exhibits the minimum wear volume loss among the composites studied. The addition of these fibers decreased the volumetric loss and COF of PA6 based composites. The frictional effects and tribological characteristics of SCF reinforced PA6 composites were studied [14]. The addition of SCF has decreased or increased the COF of PA6 based composites. The best wear resistance was obtained for 20 vol. % SCF in composite. The influence of sliding speed and applied sliding pressure on the adhesive wear behavior of aramid fiber filled PA1010 composite was studied [15]. The fiber volume fraction of 5 to 15 % was loaded to PA1010 and their response to the tribological conditions was studied. The coefficient of friction (COF) of PA1010 composites was found to decrease as an effect of fiber loading. Further, the addition of aramid fiber deteriorated the volumetric loss of composites. The best tribo-performance of PA1010/ aramid fiber composites was obtained for 15 vol. % of aramid fiber in composite. The tribological response of SGF reinforced PP in dry sliding wear was reported [16]. It was found that the effect of fiber reinforcement is very much significant in influencing the adhesive wear behavior of composites. Further, they showed that the addition of glass fibers effectively improved the wear behavior of the composites studied. .

The effect of SCF reinforcement on friction and mechanical behavior of PPS/PTFE blend composites was studied [17]. The percentage of SCF was varied from 0 to 15 vol. %. The material removal rate and the COF of 5.2 x 10-6 mm^3/ N-m and 0.085 were respectively exhibited by the composites for 15 vol. % SCF. This is 88% and 47% lower than the neat blend PPS/PTFE. The study on the wear behavior of fiber- filled polyimide (PI) composites was reported [18]. The individual effect of 15 vol. % SGF, SCF and short aramid fibers on the tribological behavior of PI composites were studied. It is reported from the study that the fiber reinforcement in to PI composites greatly affected the tribological properties. The best performance under the test condition was exhibited by inorganic fibers reinforced composites due to the significant sharing of load between the contact surfaces. The frictional behavior of PTFE and its composite under dry sliding condition was studied. [19]. The effect of sliding speed and sliding load on the sliding wear behavior of pure PTFE, SGF filled PTFE, bronze and carbon packed PTFE composites was reported. It was found that the inclusion of glass fibers, bronze along with carbon to Polytetrfluroethylene has exhibited the least wear volume loss. Further, the wear rate was highly sensitive to the experimental speed and the load. The composite PTFE + 17 vol. % SGF was considered as the best material for tribological applications. The effect of Molybdenum disulphide (MoS_2) on the sliding wear and frictional properties of SCF filled Nylon 1010 composites was studied [20]. It is proved from the study that MoS_2 filler is most powerful in lowering the frictional effects of nylon but it increases the wear rate. On the other hand, the effect of SCF addition has lowered the wear rate of composites. A synergism between MoS_2 and short carbon fibers has deteriorated the wear rate and frictional behavior of Nylon 1010 composites.

From the above literature survey, it is clear that the blend (PA66/PTFE) as a matrix was not extensively studied. Further, PA66 is a high strength engineering polymer and PTFE is known for its superior wear resistance in combination. Therefore, the blend (PA66/PTFE) was used as the base material for tribological and mechanical loading. Further, the individual effect of fibers on the thermoplastics behavior is available in plenty. But the effect of hybrid fibers is less often reported. On the other hand, the hybrid combination of Glass- Carbon is not reported. Glass fiber and carbon fibers are known for their superior strength, wear resistance and thermal resistance when used as reinforcements with the thermoplastics. Furthermore, the influence of sliding load, sliding velocity and sliding distance on the dry slide wear behavior of hybrid fiber filled thermoplastic composites has to be discussed systematically. Keeping this in view, the effects of aforesaid experimental parameters on sliding wear behavior of hybrid Glass-Carbon composites was studied and reported systematically.

Materials, processing and testing of composites

The materials and their details used for the production process are detailed in Table 1. Further, the weight fraction percentage formulations of composites are detailed in Table 2.

Processing of Composites

The polymers of known proportions such as PA66, PTFE and short fibers such as glass fibers and carbon fibers (Table 2) were dried at about 80 °C for 24 hours in the separate basins to prevent the effect of hydrolyzing and plasticization. Here two step processing is required. In the first step, the dried PA66 and PTFE were mixed in the mixer and rotated at about 20 RPM to ensure proper mixing and uniform distribution. This mixture is then subjected to melt mix method through twin screw extruder to from melt mix. The extruder chamber consists of five heating zones with a temperature of 220°C, 235°C, 240°C, 265°C and 270° C respectively and the temperature at the die was maintained at 220°C. The extruder screw was allowed to spin at a speed of 100 rpm for a fixed feed rate. The cylindrical extrudates of the blend were quenched with the cold water and then pelletized using pelletizing machine. In the second step, these blended pellets are once again subjected to extrusion process along with glass fibers and carbon fibers. The hybrid composite pellets were obtained by pelletization method. These hybrid composite pellets were once again subjected to heating process. These pellets were once again dried at 100 °C before injection molding. The zonal temperature in the injection molding barrel was maintained in two locations with 265 °C and 290 °C respectively and the mold was maintained with a temperature of 65 °C. Around 10-15 rpm speed was allowed for the screw. The injection pressure of around 700 bar was used for the process. The injection and cooling time of 10s and 35s with an ejection time of 2s have been maintained during injection molding. This method is for the production of GC hybrid composites.

Experimentation of Sliding wear behavior : ASTM G99

The dry sliding wear test was conducted on Pin on disc machine (Ducom Bangalore) as per ASTM G99 method (Figure.1). The samples used for the test were prepared using cutting machine and were cut into proper dimensions prescribed by ASTM G99 method. The generally used dimensions were 6 mm x 6 mm x 3.2 mm. The prepared specimens were rubbed against smooth abrasives of 600 Grit abrasive paper in order to prepare the perfect sliding surface against the counter steel disc. The samples to be tested were attached to the steel pins of 8 mm diameter with a length of 27 mm. The weight of the specimen was measured before subjecting them to sliding process along with the pin. The counter surface was cleaned with the help of soft material using acetone before sliding process to ensure no polymer substrate of previous experiment was present. The details of the experimentation and the test parameters used for the test as per ASTM G99 is depicted in the Table 3.

The test parameters such as normal load, sliding dis-

Table 1. Materials data used in the production.

Materials	Designation	Form	size	Density (g/cc)
Polyamide	PA66	Granules	---	1.14
Teflon	PTFE	Powder	12-14 (μm)	2.2
Short glass fiber	SGF	Cylindrical	Length = 5 -6 mm Diameter = 10-20 mm	2.45
Short carbon fibers	SCF	Cylindrical	Length = 5-6 mm Diameter = 10-20	1.57

Table 2. Materials system formulations in weight fraction percentage.

Composition	Mat. ID	Weight fraction percentage			
		PA66	PTFE	SGF	SCF
Blend (PA66/PTFE)	Blend	80	20	--	--
Blend /Glass fibers	Blend /SGF	80	20	10	--
Blend/ Carbon fibers	Blend/SCF	80	20	--	10
Blend/Glass fibers/Carbon fibers	Blend/SGF/SCF	80	20	10	10

Table 3. Experimental parameters used for sliding wear **test**

Process Parameters	
Sliding load (N)	75, 100, 125 and 150
Sliding velocity (m/s)	0.5, 1, 1.5 and 2
Sliding distance (m)	1000

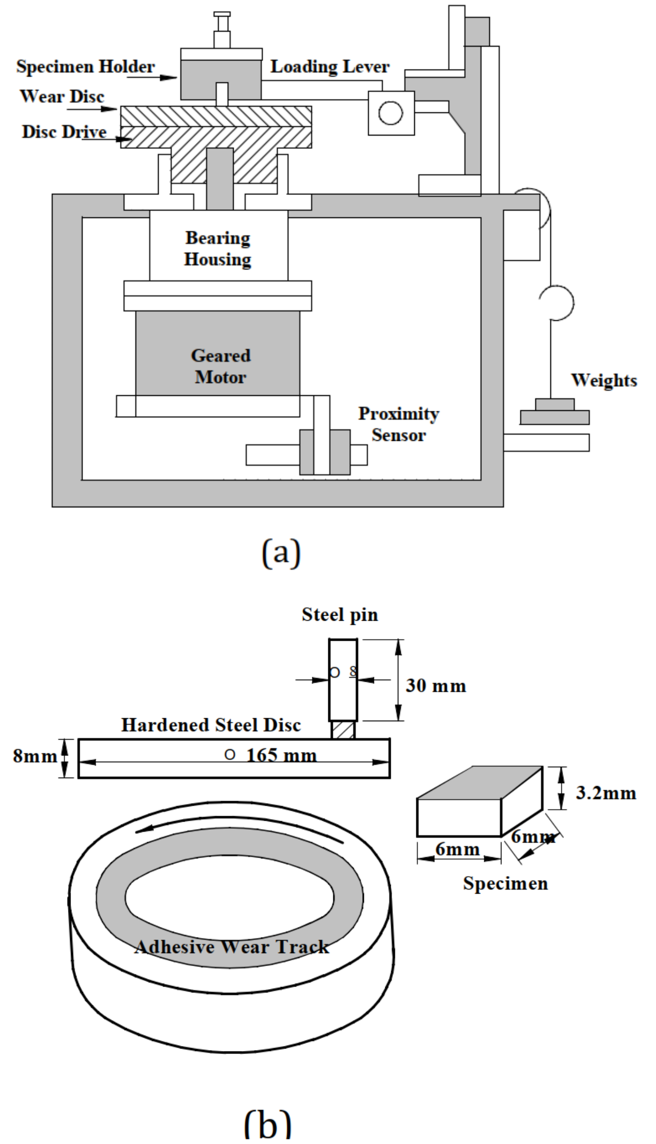

Figure 1. Sliding wear system for ASTM G99: a) Experimental set up and b) specimen details

tance and velocity of sliding were inputted by setting the time and speed of the disc. When the predefined time was reached, the timer mechanism equipped in the machine stops the machine automatically. The weight of the sample along with the pin after the sliding process is measured. The experimentation was conducted for different sliding load and sliding velocity for a known sliding distance and loss in weight was recorded in every trial. Three samples were tested for the same conditions and the average value of the same is considered to represent the data. The wear volume loss of composites is obtained through the weight loss (W) using the density (ρ) which is determined experimentally. The wear volume (ΔV) and the specific wear rate (Ks) are calculated using the wear volume loss from the experimentation. The wear volume loss 'ΔV' and specific wear rate 'Ks' of polymer composites are calculated using the following formulas:

$$\text{Wear volume} = \Delta V = W/\rho \ \text{mm}^3 \quad \text{----} \quad (1)$$

$$\text{Sp. wear rate} = Ks = (\Delta V/ (F^*D)) \ \text{mm}^3/\ \text{N-m---} \quad (2)$$

Where ρ = density in gr/cc, F the experimentally applied load in N and D, the sliding distance (m).

Results and discussion

Tribological response of GC hybrid composites under the action of sliding load: Volumetric loss and wear rate

The volumetric loss of fiber reinforced PA66/PTFE blend based hybrid composites under the influence of sliding load is studied and presented in fig. 1 (a–c). The experimentation was carried out for a period of time (33.33 mins.) through 0.5 m/s sliding velocity. The experimental range of load considered for the study was 75 N to 150 N. It is demonstrated from the graph that the volumetric loss increases with increase in sliding load. It is proved from the study that the sliding wear resistance of GC hybrid composites was improved significantly by the combined effect of hybrid fibers. The tribological behavior of short fiber filled composites was studied against the sliding wear characteristics of PA66/PTFE blend (80/20 wt. %). It is found that highest wear volume loss was experienced by PA66/PTFE blend among the composites studied. The blend has experienced the wear volume loss of 0.33 mm³ under lower sliding load. The wear volume loss is found to increase linearly exhibiting the highest wear volume loss of 2.01 mm³ which is 509% increase at higher sliding load. The increase in frictional shear force at the surface interface increased the wear volume loss [21]. The frictional and tribological behavior of the blend PA66/PTFE was controlled by the polymer substrate film formed on the steel surface [22 - 24]. During low load conditions, PA66/PTFE forms a straight, parallel, unvarying and continuous polymer substrate on the counter surface of steel [21]. The lower shear strength interfacial layer formed by melting PA66/PTFE on sliding surface acts as lubricant [25]. Furthermore, PTFE can be easily dragged out to form a third body polymer substrate, which results in an unvarying, ideal and reliable transfer layer on counter face. Further, this transfer layer disconnects the actual contact of polymer specimen with counter steel surface. This results in friction between the surfaces of polymer resulting low wear volume loss. With increase in load, the high frictional shear force breaks the transfer film. In this condition, plastic deformation of PA66/PTFE and its melting occurs due to the generation of heat by the resultant shear and applied force in sliding against steel. Also, sliding of PTFE with hard surface results in scissioning of polymer chain initiating active groups which chemically react with the counter face [26]. Further, consecutive interaction of polymer surface

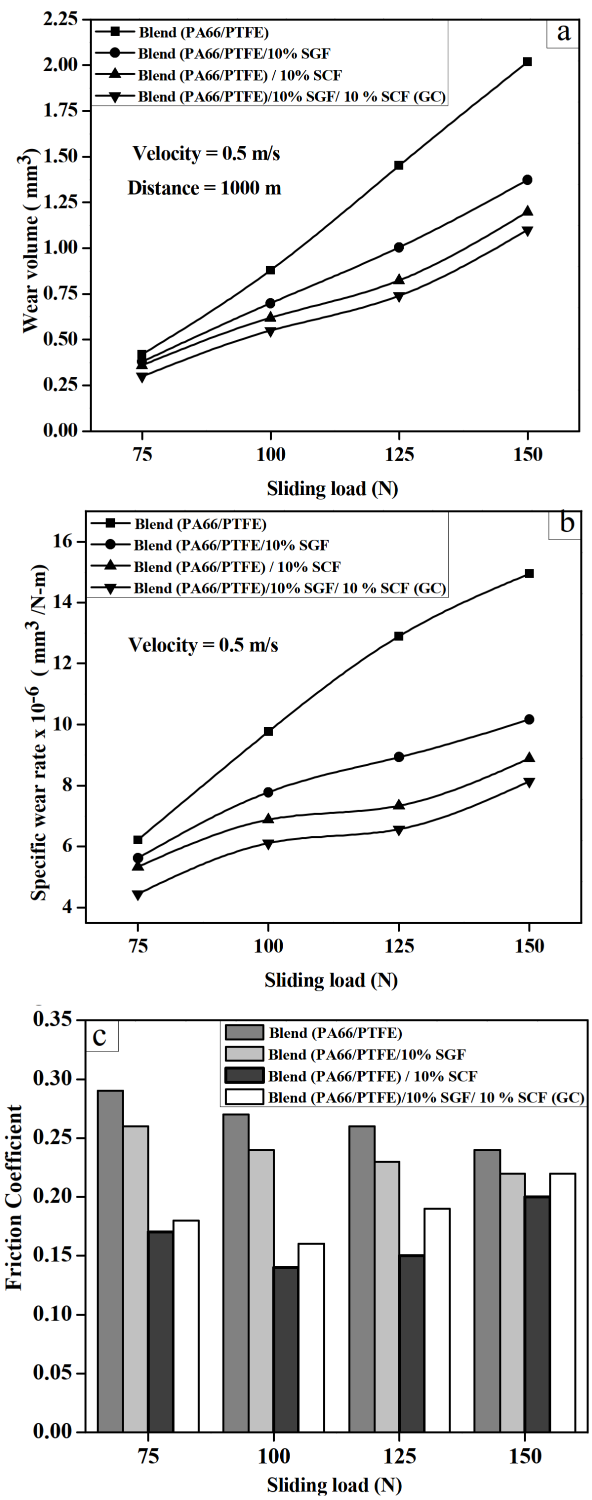

Figure 2. Tribological response of GC hybrid composites under varying experimental load: a) Volume loss, b) Wear rate and c) Frictional constant

with the transfer film results in anisotropic deformation of unit cell which results in easy shear of polymer chains and hence more wear volume loss at higher sliding load [21].

The sliding wear characteristics of SGF filled composites exhibits the similar behavior. The volumetric loss of SGF filled composites is deteriorated due to SGF reinforcement effect at higher and lower sliding load over the blend. From the graph, around 9% and 31.8% wear volume loss was exhibited as an effect of SGF reinforcement at lower and higher sliding load over the blend respectively.

Addition of 10 wt. % SGF enhanced the capability of SGF filled composites to form a strong polymer film on the counter surface. Under lower load, the SGF filled composites offered resistance against the shearing force. During this process, fiber sliding wear is more dominant than the matrix wear [5]. Therefore, less wear volume loss. But at higher load, sliding was accompanied by the matrix melting. The combined action of the frictional force and the sliding load results in rupturing of glass fibers into very short fibers. Due to severe plastic deformation, these fibers were drained off from the surface resulting high wear volume loss. These SGF raised the thermal resistance of the blend PA66/PTFE and greatly controlled the promotion of melting wear. At this stage, the exposed glass fibers supported a part of applied load there by avoiding the entry of steel asperities into polymer surface and hence deteriorating the intensity of micro cutting and micro ploughing actions [5]. High modulus, good mechanical behavior, superior hardness and excellent thermal capacity of glass fibers defined the wear rate of SGF filled composites.

The effect of 10 wt. % SCF on the wear volume loss of blend is most significant. Least wear volume loss is exhibited by SCF filled composites compare to blend and SGF filled ones under the influence of sliding load. This is mainly due to the synergism developed between the carbon fibers and PTFE in the blend. The scissioning of PTFE fibers during sliding was protected by SCF due to effective bonding between them. The wear volume loss of SCF filled composites at a load of 75 N is 0.36 mm^3. The wear volume loss was increased with increase in sliding load. For increase of 100% sliding load, the wear volume loss was increased to 1.2 mm^3 which is 233% increase. At lower sliding load, the polymer matrix was exposed to low sliding load and the wear volume loss occurs purely due to the plastic deformation. But at higher load, the surface of SCF which were exposed to the frictional load is more and the ploughing action of the worn surface by the hard asperities was poor. Further, at higher sliding load, the matrix melting was prevented by SCF. Presence of 10 wt. % SCF in PA66/PTFE blend forms a uniform and consistent transfer film due to the presence of PTFE in composites. This layer avoids the actual contact of steel surface with the polymer. The crushed short fibers during sliding were transferred and embed in to the polymer surface as a result of frictional shear and applied load. It is observed that there was a good adhesion between SCF and polymer matrix which followed the Theberge's report [37]. The fibers pulled out during sliding forms the cavities on the polymer surface which were filled by the matrix through plastic deformation under the action of applied load [6]. During sliding process, the blended SCF with matrix forms a transfer film which improved the wear resistance of SCF filled composites. Therefore, high wear resistance of SCF filled composites. But higher percentage of SCF leads to poor wear resistance [6].

Similar observations are made with GC hybrid composites. But the wear volume loss of GC hybrid composites is very less relative to SCF filled one. The wear volume loss of all the composites exhibits the linear trend irrespective of sliding load. But for GC composites, the difference in wear volume loss among the successive sliding load is less in comparing the same with other composites. The matrix melting, fiber pull out, fiber pulverization and fiber fracture were some of the factors contributed to the critical wear volume loss of SCF filled composites. The hybrid effect of fibers has promoted the wear resistance of GC hybrid composites under the action of varying load. The wear volume loss of GC hybrid composites depends on the applied load, formation of transfer film and also on content of composites. At lower load, matrix melting was occurred due to the frictional shear and applied load. But fiber fracture, fiber crushing and matrix melting results in good transfer film which is much better than SCF filled one to resist the frictional shear of polymer film formed on steel surface. The least wear volume of 1.1 mm^3 is exhibited by GC hybrid composites against 2 mm^3 of PA66/PTFE blend which is 81% decrease at higher sliding load. Good mechanical properties, high thermal conductivity of SCF, high modulus of SGF and excellent friction behavior of SCF were some of the factors favored the wear resistance of GC hybrid composites [45]. At higher load, the crushed carbon and glass fibers which were in the form of abrasives reduce the stress concentration across the surface of fibers. This will avoid the sliding wear of short fibers. Among the composites studied, GC hybrid composites exhibits good wear resistance. The results are in good agreement with work of others [6, 35].

The effect of applied load on 'Ks' of GC hybrid composites is plotted in figure 2 (b). The 'Ks' of SCF filled composites was increased with increase in sliding load. It is indicated from the figure that 'Ks' of GC hybrid composites also followed the same trend. The wear rate of SCF filled composites varied from 5.34 x 10-6 to 8.9 x 10-6 mm^3/ N-m between the range of applied loads. Increase in load increased the frictional shear resulting more wear volume loss of composites. But GC hybrid composites exhibited the least wear rate. The wear rate of GC composites varied from 4.45 x 10-6 to 8.14 x 10-6 mm^3/ N-m which is 83 % increase. The frictional behavior of GC hybrid composites is shown in figure 2(c). The effect of SCF addition considerably decreased the coefficient of friction (COF) of SCF filled composites. The least COF (0.15) was obtained for SCF filled composites under 100 N. The COF of SCF filled composites increases with increase in sliding load. The increase in COF is due to high thermal conductivity of SCF. The COF of GC hybrid composites were increased slightly above the value of SCF filled ones. The COF of unfilled composites is high due to rough sliding surface. But the sliding of SCF has smoothened the frictional surface there by reducing the COF of composites. The addition of SCF into blend improved the interface between blend associates and improved the modulus of composites. Due to this, COF was reduced. The rigid phase of carbon fibers in soft polymer resin decreased the real area of interaction with the counter body under the applied load. This results in decrease in intensity of plough and adhesion between relative sliding parts. This will influence the frictional behavior of SCF filled composites [35].

The SEM (Vega3, Tescan) images of the failure surfaces of PA66/PTFE blend based composites under varying sliding load are shown in figure.3 (a - h). The SEM image of the worn surface of the blend at a sliding load of 75 N is shown in figure. 3 (a). At lesser sliding load, the plastic deformation of matrix is seen. A uniform belt like parallel wear tracks were seen in the direction parallel to friction. The sign of matrix melting is also seen in the picture as a result of accumulation of frictional heat during sliding. But the frictional behavior at a higher sliding load of 150 N is different. At higher load, severe plastic deformation results in matrix melting which is exhibited by the SEM picture 3 (b). A belt like transfer film with deep parallel wear tracks are seen as a result of higher load.

The SEM image of glass fibers filled composites under the influence of varying sliding load is shown in figure.3 (c and d). The ability of a blend to form an unvarying polymer film on the steel surface was strictly related to fiber weight fraction of composites [5, 6]. At lower load, the glass fibers which were fractured into small fibers are seen in the figure.3 (c). These fibers were surmounted by the melted matrix witnessing the fracture of glass fiber through sliding under the influence of frictional shear and normal load. But at higher sliding load (Figure.3 (d)), the frictional shear of transfer film was severe. This will cause the breakage of polymer substrate formed on the steel surface. This may cause the loss of material due to heavy load. Even at this load also, the glass fibers were ruptured into small fibers due to frictional shear and normal load. At this condition, the melted matrix surmounts these fibers. The ultimate wear properties at this condition depends on the contribution of melting wear of matrix and abrasive wear of ruptured fibers [6, 34-35]

The SEM image of worn surfaces of SCF filled composites under the influence of varying load is shown in figure 3(e and f). It is seen from the figure that the non-uniform sliding surface is exhibited by SEM pictures (Figure 3 (e)). The furrows parallel to the sliding direction are seen on the surface. At lower load, the matrix melting has formed the rough polymer surface after sliding. A parallel belt like structures is seen on surface. The ruptured fibers embedded in the matrix are also seen in the picture. But at higher loading (figure 3 (f)), plastic deformation of matrix due to high frictional shear is noticed. A parallel belt like structure is formed with the matrix blend in the direction of sliding. It is clear from the figure that the adhesion between the matrix and fibers was good. Hence, good mechanical and tribological properties of composites. The deformed surface is smooth due to sliding of SCF along with PTFE.

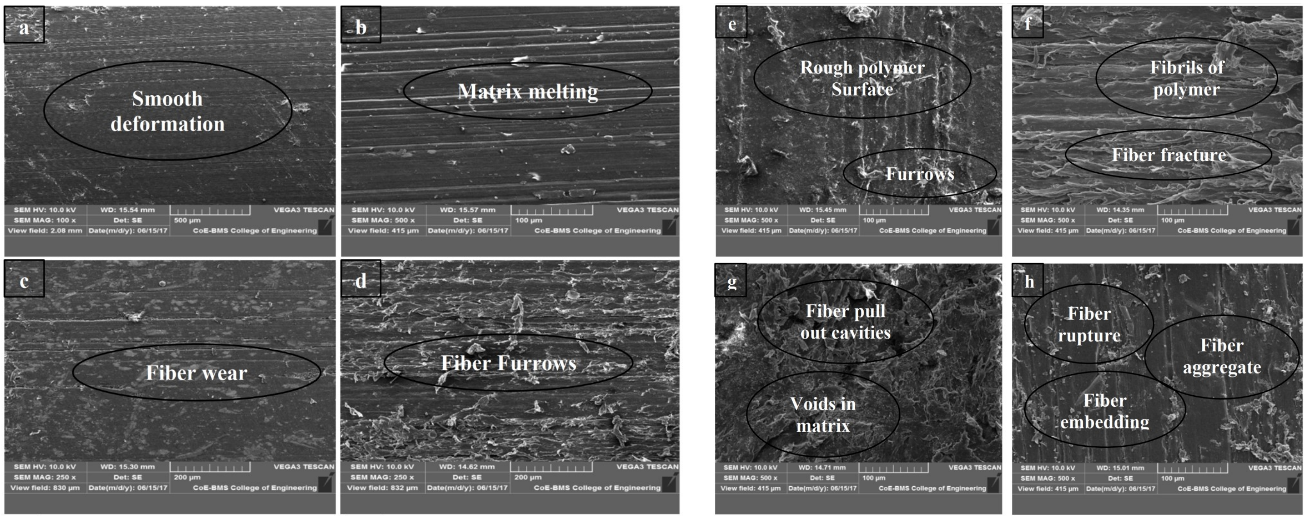

Figure 3. The SEM images of the worn surfaces of GC hybrid composites under the influence of sliding load: a) Blend (PA66/PTFE)(75 N), b) Blend (PA66/PTFE)(150 N), c) Blend(PA66/PTFE)/SGF (75 N), d) Blend(PA66/PTFE)/SGF (150 N), e) Blend(PA66/PTFE)/SCF (75 N), f) Blend(PA66/PTFE)/SCF (150 N), g) GC hybrid composites (75 N) and h) GC hybrid composites (150 N)

The SEM image of the worn surface of GC hybrid composites under the influence of varying load is seen in figure 3 (g and h). The sliding surface of GC composites under lower load is rough. It witnessed the presence of voids due to stress raisers. The interface between the fiber and matrix was good but the deformation was severe. The hard asperities of GC composites are seen on the surface. The furrows are extruded out of wear track. But the uniform surface is exhibited by the polymer due to the action of higher sliding load (Figure 3 (h)). The parallel wear tracks are seen as a result of sliding of pulverized fibers. The fractured fibers which are embedded in polymer blend supported the applied load along with transfer film.

Sliding wear response of fiber filled and GC hybrid composites under the action of sliding velocity: Wear volume loss and wear rate

The effect of sliding velocity and fiber reinforcement on the wear volume loss and specific wear rate of fiber filled composites is shown in figure.4 (a, b and c). The wear volume loss of composites studied as a function of sliding velocity is depicted in figure. 4(a). The experimental range of velocity considered for the test was 0.5 to 2 m/s for a constant duration (33.33 Min.). It is observed from the figure that the volumetric loss of composites increases with increase in sliding velocity. The volumetric loss of the blend is more when compared to the fibrous composites. At lesser sliding velocity, volumetric loss of the blend is 2 mm^3. With increase in sliding velocity, the volumetric loss increases. The wear volume loss of 5.48 mm^3 is exhibited by the neat blend at higher sliding velocity which is 174% increase. For increase of 300% sliding velocity, 174% increase in volumetric loss is exhibited by the blend against wear loss at lower sliding velocity. But the addition of 10 wt. % SGF decreased the wear volume loss of SGF filled composites. It is 32% and 36% decrease in volumetric loss of SGF filled composites over the blend was noticed between the range of experimental velocity studied.

The wear volume loss of fiber filled and GC hybrid composites as a function of sliding velocity is shown in figure 4 (a). The figure explains that the wear volume loss has followed the linear trend. The wear volume loss of composites was increased with increase in sliding velocity. This is purely attributed to the frictional shear at the interfacial surfaces. But the inclusion of 10 wt.% SCF into the blend enhanced the wear resistance of SCF filled composites than SGF filled ones. Initially at lower velocity, the deformation of matrix due to matrix melting is low and hence low wear volume loss. As the velocity was increased, the frictional shear at the interface increases the contact temperature nearer to the softening point of the polymer resulting more wear volume loss. The volumetric loss of composites is purely a function of sliding velocity. This is due to the surface interaction thermal effects [6, 35]. The energy dissipated during sliding is converted into heat and high thermal gradient was progressed in the normal direction to the surface. Due to low thermal conductivity of the blend, the frictional heat at the interface during sliding increases the contact temperature. The increase in sliding velocity proportionately increased the sliding temperature. Therefore, high sliding velocity results in higher wear volume loss due to severe deformation of matrix. The graphitized SCF was decomposed due to thermal effects into graphite fillers which could serve the purpose of lubrication. These graphite fragments formed the uniform film on the counter surface and reduced its abrasivity. This improves the wear behavior of composites. The volumetric loss of 1.2 mm^3 is exhibited by SCF filled composites at lower sliding velocity whereas 3 mm^3 at higher velocity which is 150% increase. But the wear volume loss of GC hybrid composites was decreased below the value of SCF filled ones by the hybrid effect of glass and carbon fibers

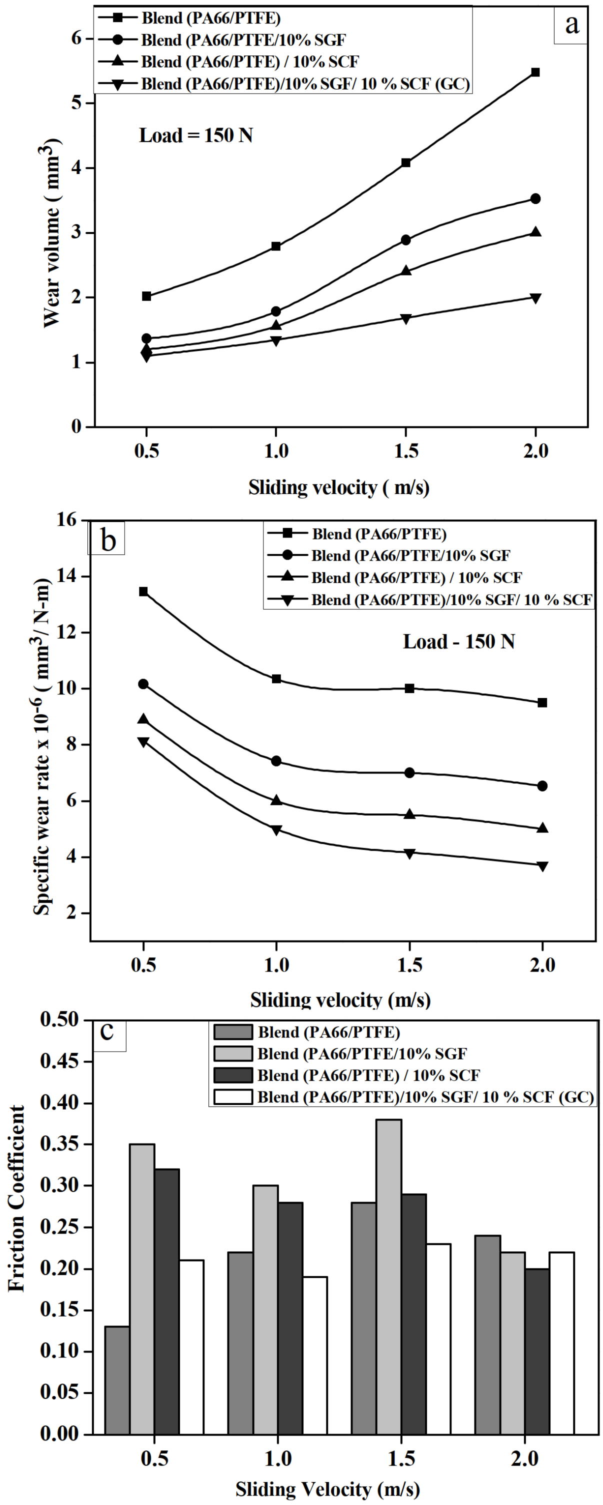

Figure. 4. Tribological response of fiber filled and GC hybrid composites under varying experimental velocity:
a) Volume loss, b) Wear rate and c) Frictional constant

This is purely attributed to the development of adhesion at the interface between hybrid fibers and matrix. The wear resistance of composites is due to high thermal resistance of composites. At higher sliding velocity, high modulus hybrid fibers were exposed to frictional surface and they reduced the frictional heat at the interface. This reduces the severe plastic deformation of the matrix and debonding of fibers from the matrix. But at higher velocity, fiber fracture and fiber crushing were noticed. The low wear volume loss of composites suggested that hybrid effect of fibers supported the applied load during sliding which indicate the better bonding between fibers and matrix. Among the composites studied, GC hybrid composites exhibited the better wear resistance. The present findings agree with the work of others [6, 36, 38].

The effect of sliding velocity on 'Ks' of GC hybrid composites is depicted in figure 4 (b). The figure demonstrates that 'Ks' of GC hybrid composites is a function of sliding velocity. The 'Ks' of GC composites decreases with increase in velocity. The wear rate of SCF filled composites varied from 8.9 x 10-6 to 5 x 10-6 mm^3 / N-m whereas the wear rate of GC hybrid composites varied from 8.14 x 10-6 to 3.72 x 10-6 mm^3 / N-m. The decrease in wear rate was due to decrease in friction effect at the interface by the hybrid effect of fibers. Among the composites studied, GC hybrid composites exhibited the least wear rate.

The COF of GC hybrid composites under the influence of varying velocity is shown in figure 4 (c). The effect of varying sliding velocity decreases the COF of SCF filled composites. This is due to the development of fracture at the fiber – matrix interface as a result of thermal energy dissipation during sliding [39]. The effect of graphitized carbon was the reason for low COF among all the composites studied. Increase in sliding velocity increases the chance of fiber damage and compaction of graphite minerals which results in low COF. But COF of GC hybrid composites decreases initially and then increases. The increase in COF of GC hybrid composites is due to fracture and crushing of SCF at higher velocity. This is due to increase in abrasivity of counter surface when rubbed against the steel surface. This requires more frictional force to detach the transfer film from the surface. Hence, high coefficient of friction (COF) of composites.

The SEM images of the failure surfaces of fiber filled composites under the influence of sliding velocity is shown in figure 5 (a - h). The SEM picture of neat blend with varying velocity is shown in figure.5 (a and b). At lower sliding velocity, the plastic deformation of matrix occurs and PTFE is slightly dragged from the blend on to counter steel surface to form unvarying and consistent polymer surface. This is depicted in figure 5(a). The thin regular wear paths were observed on the rubbed surface. The melting wear of the blend was seemed to be dominant during lower sliding velocity and hence the viscous nature of the blend reflects low wear rate of composites. The melting of matrix blend was severe resulting high wear volume loss. This is shown in figure 5(b). The polymer layer of the blend seemed to be over lapped due to accumulation of frictional heat during sliding [5]. This has made the material to exhibit high wear rate. The SEM image of the worn surfaces of glass fiber filled composites subjected to varying sliding velocity is shown in figure. 5(c and d). At lower velocity, the SGF filled composites were subjected to fiber rupture. This has

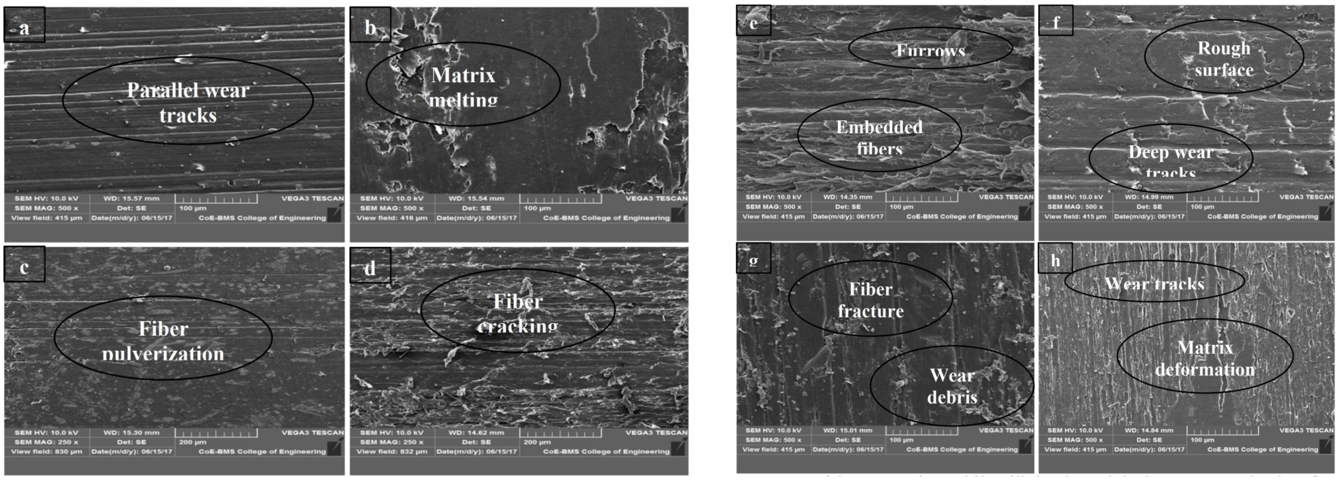

Fig 5. The SEM images of the worn surfaces of fiber filled and GC hybrid composites under the influence of sliding velocity: a) Blend (PA66/PTFE)(0.5 m/s), b) Blend (PA66/PTFE)(1 m/s), c) Blend (PA66/PTFE)/SGF (0.5 m/s), d)Bend (PA66/PTFE)/SGF (2m/s), e) Blend (PA66/PTFE)/SCF (0.5 m/s), f) Blend (PA66/PTFE)/SCF (2 m/s), g) GC hybrid composites (0.5 m/s) and h) GC hybrid composites (2 m/s)

reduced the length of fiber and made them to embed into the melted blend. The worn surfaces are seemed to be uniform under the influence of transfer film. Due to this, SGF were not exposed to the surface. But at higher velocity (Figure.5 (d)), the melting wear along with fiber pull out was noticed. This has caused more loss of material. But SGF surfaces which were exposed to higher velocity supported a part of applied load and hence high wear resistance of SGF filled composites. The wear debris as a result of higher velocity were extruded out of sliding surface indicating fibrillation of PTFE (Figure.5 (d)). These fibrils filled the grooves and lowered the wear rate of composites. Hence, the compatibility between SGF and the matrix blend is seemed to be superior.

The SEM images of the worn surface of GC hybrid composites under the influence sliding velocity is shown in figure 5 (g and h). At lower velocity, the SCF filled composites exhibits the smooth deformed surface with furrows (Figure 5 (g)). The fibers which were embedded in the matrix are also seen in picture. The matrix melting is more when compared to fiber wear. But at higher velocity, the worn surface exhibited the rough surface. This showed that, at higher sliding velocity, the detached fibers from the matrix embed in the transfer film and supported the applied load. The SEM images of the worn surface of GC hybrid composites at lower velocity is shown in figure 5 (g). Deep parallel wear tracks are seen on the surface. More fibers are also seen on the surface. The wear debris filled the fiber pulled out cavities during sliding. The interfacial bond seemed to be very good. The severe plastic deformation is seen on the surface of GC hybrid composites under the influence of higher velocity (Figure 5 (h)). The straight parallel tracks are observed during sliding. The severe plastic deformation as a result of frictional heat is observed.

Conclusion

The following are the conclusion drawn from the study on the sliding wear behavior of Glass-Carbon hybrid composites:

- The blend PA66/PTFE is found be the best blend combination for the composites studied
- The blend PA66/PTFE has experienced the high wear volume loss among the composites studied
- PA66/PTFE/SCF composites exhibits the better wear resistance compared to PA66/PTFE/SGF composites under all the conditions of test parameters
- The GC hybrid composites exhibits the better sliding wear resistance under all the conditions of test parameters
- All the composites studied were more sensitive to sliding velocity compared to sliding load
- The high thermal stability and thermal conductivity of SGF and SCF are likely contributing towards the better wear resistance of GC hybrid composites
- The fiber fracture, fiber wear, matrix melting and matrix wear were some of the dominating mechanisms observed in the study

Acknowledgements

I extend my heartfelt thanks to Dr. Sathisha N S, Principal, Government Engineering College, K R Pet, India and also to my guru Mr. Lepoxy Gowda, Senior lecturer, Government P U College, Kikkeri, India for their whole hearted support in completing this work.

References

[1] Y Yamaguchi, Tribology of plastic material, Tribology series16, Elsevier, New york, 1990

[2] C Z Liu, J Q Wu, J Q Li, L Q Ren, J Tong, A D Arnell, Tribological behaviors of PA/UHMWPE blend under dry and lubricating condition, Wear, 260,2006, 109-115. https://doi.org/10.1016/j.wear.2004.12.044

[3] L Q Ren , C Z Liu, M Jiang , J Tong , S. M .Green, R D Arnell, Effect of operating parameters on the lubricated wear behavior of PA6/UHMWPE blend: A statistical Analysis, Wear, 253,2002, 878-884. https://doi.org/10.1016/S0043-1648(02)00172-2

[4] N V Klaas , K Marcus, C Kellock, “The tribological behavior of glass filled polytetrafluroethylene” Trib. Intl., 38, 2005, 824-833. https://doi.org/10.1016/j.triboint.2005.02.010

[5] Zhaobin Chen, Xujun Liu, Renguo Lu and Tongsheng Li, Mechanical and tribological properties of PA66/PPS blend - III reinforced with glass fiber, J. Appl. Polym. Sci., 102, 2006, 523-529. https://doi.org/10.1002/app.24253

[6] Zhaobin Chen, Xujun Liu, Renguo Lu and Tongsheng Li, Mechanical and tribological properties of PA66/PPS blend reinforced with carbon fiber, J. Appl. Polym. Sci., 105, 2007, 602-608. https://doi.org/10.1002/app.25999

[7] S. N. Kukureka, C. J. Hooke, M. Rao, P. Liao, Y. K. Chen, The effect of fiber reinforcement on the friction and wear of polyamide 66 under dry rolling - sliding contact, Tribol. Intl., 32, 1999,107-116. https://doi.org/10.1016/S0301-679X(99)00017-1

[8] H. Unal, U. Sen and A. Mimaroglu, Dry sliding wear characteristics of some industrial polymers against steel counter face, Tribol. Intl., 37,2004, 727-732. https://doi.org/10.1016/j.triboint.2004.03.002

[9] A. Mimaroglu, H. Unal, A. Oztel, N. Filiz, K. Ozkan, C. Karadeniz and I. Kayo, Friction and wear behavior of engineering polymers against polymer, 2nd international conference on advanced tribology, iCAT, ,2008, 103-105, 2008

[10] Tian Yuqin and Huo Junlong, The mechanical and tribological properties of carbon fiber reinforced POM composites, Appl. Mech. Mater., 182-183, 2012, 135-138. https://doi.org/10.4028/www.scientific.net/AMM.182-183.135

[11] J. Li and Y.C. Xia, The reinforcement effect of carbon fiber on the friction and wear properties of carbon fiber reinforced PA6 composites, Fibers and Polymers, 10 (4),2009, 519-525. https://doi.org/10.1007/s12221-009-0519-5

[12] Li Jian and Sharon Kao-Walter, The friction and wear properties of polypropylene composite filled with carbon fiber and polyamide 6, J. Therm. Comp., 10, 2010,1-8

[13] G. Srinath and Gnanamoorthy, Effect of short fiber reinforcement on the friction and wear behavior of Nylon 66, Appl. Comp. Mater., 12,2005, 369-383. https://doi.org/10.1007/s10443-005-5824-6

[14] W.Z. Nie and J. Li, Effect of carbon fiber content on friction and wear properties of carbon fiber reinforced PA6 composites, Plast. Rub. Comp., 39 (1),2010,10-15. https://doi.org/10.1179/174328910X12608851832056

[15] Lei Xu, Zhencai Zhu, Guoan Chen and Chao Qu, Effect of load and sliding velocity on tribological behaviors of aramid fiber reinforced PA1010 composites, Ind. Lub. Tribol., 62(1), 2010, 46-51. https://doi.org/10.1108/00368791011012461

[16] Werner A. Hufenbach, Alesksander Stelmakh, Klus Kunze, Robert Bohm and Robert Kupfer, Tribomechanical properties of glass fiber reinforced polypropylene composites, Tribol. Intl., 49, 2012, 8-16. https://doi.org/10.1016/j.triboint.2011.12.010

[17] Wei Luo, Qi Liu, Yi Li, Shengtai Zhou, Huawei Zou and Mei Liang, Enhanced mechanical and tribological properties in polyphenylenesulfide / polytetrafluroethyelene composites reinforced by short carbon fiber, Composites: Part B, 91, 2016, 579-588. https://doi.org/10.1016/j.compositesb.2016.01.036

[18] Gia Zhao, Irina Hussainova, Maksim Antonov, Qihua Wang and Tingmei Wang, Friction and wear of fiber reinforced polyimide composites, Wear, 301,2013, 122-129. https://doi.org/10.1016/j.wear.2012.12.019

[19] H. Unal, A. Mimaroglu, U. Kadioglu and H. Ekiz, Sliding friction and wear behavior of polytetrafluroethyelene and its composites under dry conditions, Mater. Des., 25, 2004, 239-245. https://doi.org/10.1016/j.matdes.2003.10.009

[20] Junxiang Wang, Mingyuan Gu, Bai Songhao and Shirong Ge, Investigation on the influence of MoS2 filler on the tribological properties of carbon fiber reinforced nylon 1010 composites, Wear, 255,2003, 774-779. https://doi.org/10.1016/S0043-1648(03)00268-0

[21] Sirirat Wacharawichanant and Tanakorn Siripattanasak, Mechanical and morphological properties of polypropylene /polyoxymethylene (PP/POM) blends, Adv. Chem. Engg. Sci., 3, 2013,202-205. https://doi.org/10.4236/aces.2013.33026

[22] S. Bahadur, The development of transfer layers and their role in polymer tribology, Wear, 245,2000, 92-99. https://doi.org/10.1016/S0043-1648(00)00469-5

[23] S. Bahadur, D. L. Gong and J. W. Anderegg, The role of copper composite as fillers in the transfer film formation and wear of nylon, Wear, 154 (2),1992, 207-223. https://doi.org/10.1016/0043-1648(92)90155-2

[24] N. P. Suh, N. Saka, Fundamentals of Tribology, MIT Press, Massachusetts, 1980, 733

[25] Zhaobin Chen, Tongsheng Li, Xujun Liu, Renguo Lu, Friction and wear mechanisms of PA66/HDPE blends, J. Polym. Sci.: Part B, 43, 2005,2514-2523. https://doi.org/10.1002/polb.20548

[26] S. Bahadur, The development of transfer layers and their role in polymer tribology, Wear, 245,2000, 92-99. https://doi.org/10.1016/S0043-1648(00)00469-5

[27] Basltex: The thread of stones, http://www.basaltex.com

[28] J. H. Yoo, M S Thesis, Mechanical Engineering, Virginia Polytechnic Institute and State university, Blacksburg, Virginia, 1991

[29] J. K. Lancaster, Polymer based bearing materials: The role of fillers and fiber reinforcement, Tribology, 5 (6), 1972, 249-255. https://doi.org/10.1016/0041-2678(72)90103-0

[30] H. Unal, A. Mimaroglu, U. Kadioglu and H. Ekiz, Sliding friction and wear behavior of polytetrafluroethyelene and its composites under dry conditions, Mater. Des., 25, 2004, 239-245. https://doi.org/10.1016/j.matdes.2003.10.009

[31] Junxiang Wang, Mingyuan Gu, Bai Songhao and Shirong Ge, Investigation on the influence of MoS2 filler on the tribological properties of carbon fiber reinforced nylon 1010 composites, Wear, 255,2003, 774-779. https://doi.org/10.1016/S0043-1648(03)00268-0

[32] S. A. R. Hashmi, Somit Neogi, Anuradha Pandey, Navin Chand, Sliding wear of PP/UHMWPE: Effect of blend composition, Wear, 247,2001, 9-14. https://doi.org/10.1016/S0043-1648(00)00513-5

[33] T. Deak, T. Czigany, P. Tamas and C S Nemeth, Enhancement of interfacial properties of basalt fiber reinforced nylon 6 matrix composites with silane coupling agents, Exp. Polym. Letters, 4(10), 2010, 590-598. https://doi.org/10.3144/expresspolymlett.2010.74

[34] Rudresh B M and Ravikumar B N, Effect of Short Glass Fiber Loading on the Mechanical Behaviour of PA66/PTFE Blend Composites, Trans. Ind. Inst. Met., 1, 2016, 1-10. https://doi.org/10.1007/s12666-016-0925-5

[35] Rudresh B M and Ravikumar B N, Influence of experimental parameters on friction and wear mechanisms of PA66/PTFE blend reinforced with glass fiber, Trans. Ind. Inst. Met., doi : 10.1007/s12666-017-1164-0, 2017. https://doi.org/10.1007/s12666-017-1164-0

[36] Li and Y.C. Xia, The reinforcement effect of carbon fiber on the friction and wear properties of carbon fiber reinforced PA6 composites, Fibers and Polymers ,10 (4), 2009, 519-525. https://doi.org/10.1007/s12221-009-0519-5

[37] J. Theberge and B. Arkles, Wear characteristics of carbon fiber reinforced composites, Lub. Engg. 30 , 1974, 585

[38] A. Mimaroglu, H. Unal, A. Oztel, N. Filiz, K. Ozkan, C. Karadeniz and I. Kayo, Friction and wear behavior of engineering polymers against polymer, 2nd international conference on advanced tribology, iCAT (2008) 103-105

[39] J. Li, Tribological properties of polyimide composites filled with glass fiber and graphite, Plast. Rub. Comp. 38(6), 2009, 248-252. https://doi.org/10.1179/174328909X435366