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Experimental Response of Sliding Wear of Glass-Basalt Hybrid Thermoplastic Composites: Effect of Process Parameters

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Abstract: The influence of experimental load and velocity on sliding wear response of Glass-Basalt hybrid composites was studied. Three materials systems such as Polyamide66/Polytetrafluroethylene (PA66/PTFE) blend (80/20 wt. %), Blend (PA66/PTFE)/10 wt.% short glass fiber (SGF), Blend(PA66/PTFE)/10 wt.% short basalt fiber (SBF) and Blend (PA66/PTFE)/10 wt.% SGF/10 wt.% SBF (GB) were used for the study. These composites were produced by melt mix method in extrusion and followed by injection molding. The experimentation results revealed that the hybrid composites (GB) were more effective for sliding wear resistance. This is due to the hybridization effect of fibers and also formation of perfect transfer polymer substrate on counter disc by blend associates. On comparison among individual fibers, Blend/SGF composites were better than Blend/SBF composites for sliding wear behavior. The composites studied were sensitive to sliding load. The plastic deformation at thermal regime, frictional effect and fatigue loading were some of the reasons for tribological response. The combined matrix and fiber wear was credited to critical wear volume loss. Fiber misalignment, matrix deformation and fiber peeling were some of the failure mechanisms observed through SEM.

Keywords: sliding wear; basal fiber; Hybrid; thermoplastic; friction effects

I. INTRODUCTION

The role of polymers in modern industry is very important. The light weight and self lubrication of polymers are the credits to their usage in the industrial applications. Further, it is observed that wear of polymer is one of the critical issues in industrial applications. The applications like clutches, brake shoes, liners, sliding valves etc. were subjected to severe wear and fail to resist the application load[1]. Therefore, it is not possible by a homopolymer to support both tribological and mechanical load simultaneously. Due to this, failure of polymers is common. The aforesaid problems can be solved through polymer modification. Blending polymer is the most economical method among all the polymer modification methods [2]. Further, it was observed that blend is superior in performance than homopolymer [3]. The strong polymer composites can be designed through the base material using the concept of polymer blending. Many research studies suggested that the tribological response of composites can be improved through polymer modification by using fillers and or fibers. Further, reinforcing fibers in to polymers has promising results in wear resistance [4]. The hybridization of fibers is the best method for the modification of polymer composites. But the optimum volume fraction of fibers is the issue for the production. Therefore, the best formulations of composites should be designed and their tribological response relative to different process parameter has to be reported. Good specific modulus and strength per density of composites are good with fiber reinforced polymers. Short fibers made of glass (SGF), carbon (SCF), basalt (SBF) and kevlar (SKF) are some of the potential fibers used for the structural applications. Their mechanical and tribological behaviors are very much significant for the structural applications. Many research studies are focusing their attention towards the behavior of FRPs particularly on thermoplastics. The influence of

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SGF on mechanical and tribological behavior of Nylon 66/PPS blend was investigated by Chen et al. [5]. The composition of 70/30 vol. % PA66/PPS has been used for the matrix and is loaded with varying percentage of glass fiber. The volumetric loss of blend has been lowered with higher volume of SGF reinforcement. The frictional constant (0.35) of composites was lowered for 20 vol. % of short glass fibers in composites. Influence of SCFs on wear mechanisms of Polyamide 66/ Polyphenylene sulphide blend composites was revealed by Chen et al. [6]. The frictional coefficient of blend declined through rise in content of SCF. The wear rate of PA66/PPS blend has been lowered for a content of SCF less than 30 vol. %. The 30 vol. % SCF in blend exhibits the minimum frictional factor and volumetric loss with 70/30 vol. % PA66/PPS blend. The influence of reinforcement effect of fibers on wear mechanisms of PA66 in rolling – sliding has been reported by Kukureka and others [7]. The short fibers such as aramid fiber, glass fiber and carbon fiber were used for the investigation. It is shown that the aramid fiber is not a good fiber for the frictional factor. Both glass fiber and carbon fiber reduced the frictional constant substantially. The frictional effects and tribological behavior as an effect of applied pressure and speed of some of the engineering polymers such as PA66, POM, UHMWPE, 30% glass fiber filled PPS, 30% SGF filled PA46 and 30% SGF reinforced PPS were studied and results are analyzed [8, 9]. The experimental results revealed that the frictional constant of composite deteriorated with increase in applied pressure. The material removal rate showed very little sensitivity towards the applied pressure. The influence of short carbon fibers loading on mechanical and wear mechanisms of Polyoxymethylene has been reported by Yuquin and Junlong [10]. The frictional constant of pure POM and carbon fiber filled POM composites has been promoted with raise in load and lowered with increase with speed.

The investigation on the role of SCF in improvement of mechanical and tribological mechanisms of SCF filled PA6 studied by Li and Xia [11]. The carbon fiber reinforcement was varied from 0 to 30 vol. %. The composites with 20 vol. % of SCF in PA6 exhibits the least wear rate. The frictional effects and volumetric loss of SCF and Polyamide 6 filled Polypropylene has been studied by Jian and Waiter [12]. The good wear behavior of CF/PP composites have been improved by the reinforcing effect of SCF. The tests were performed up to 20 vol. % SCF. The friction and wear behavior of composites showed an improvement over unfilled polymer. The individual effect of SCF and SGF reinforcement on strength and sliding wear behavior of Nylon 66 composites was reported by Srinath and Gnanamoorthy [13]. The design and improvement of thin transfer film on counter surface is responsible for the enhancement of wear resistance of filled composites. Further, the material removal rate of SGF/PA 66 composites was the least among the composites studied. Reinforcing Nylon 66 with carbon fiber or SGF decreased the volumetric loss and frictional constant of composites. The frictional and tribological characteristics of SCF loaded PA6 composites has been reported by Nie and Li [14]. The SCF addition into PA6 polymer may result in decreasing or increasing frictional coefficient. The best wear resistance was obtained for 20 vol. % SCF in composite. The influence of sliding speed and pressure on adhesive wear behavior of aramid fiber filled PA1010 composite was studied by Xu et al. [15]. They reinforced PA1010 polymer with 5 to 15% aramid fiber and their tribological behavior was studied. The frictional coefficient of PA1010 polymer found to be reduced as an effect of fiber loading. Further, the addition of aramid fiber decreased the volumetric loss of composites. The best tribo-performance of PA1010/ aramid fiber composites is obtained for 15% of aramid fiber in composite. The wear properties of SGF reinforced PP has been reported by Hufenbach et al. [16]. They revealed that the effect of fiber reinforcement was significantly influenced the adhesive wear behavior of composites. Also, they stated that the wear behavior of composites has been promoted by the loading of glass fibers. The effect of SCF reinforcement on frictional and strength behavior of PPS/PTFE blend was studied by Luo et al. [17]. The SCF from 0 to 15 vol. % was reinforced into the blend PPS/Teflon and their tribological behavior was studied. The material removal rate and the frictional constant of the blend reinforced with 15 vol. % CF exhibited 5.2 x 10^{-6} mm^3/ N-m and 0.085 respectively. This is 88% and 47% lower than the neat blend PPS/Teflon. The wear

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behavior of fiber- filled polyimide composites has been reported by Zhao and others [18]. Three different fibers are used for the composites. They areSGF, SCF and short aramid fibers. 15 vol.% of each fiber individually was reinforced into PI composites. It was demonstrated that the fiber reinforcement in to PI composites greatly affected the tribological properties. The best performance under 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 reported by Unal et al. [19]. The effect of speed and load on sliding wear behavior of pure PTFE, SGF filled PTFE, bronze and carbon packed PTFE composites was investigated. Inclusion of glass fibers, bronze along with carbon to Polytetrfluroethylene exhibited lower wear volume loss. Further, the wear rate was highly sensitive to experimental speed rather than the load. The composite PTFE + 17% SGF was considered as the best material for tribological applications. The effect of Molybdenum disulphide (MoS_2) on adhesive and frictional properties of SCF filled Nylon 1010 was reported by Wang et al. [20]. MoS_2 filler is most powerful in lowering the frictional effects of nylon but it increases the wear rate.

But the effect of SCF addition has lowered the wear rate of composites. A synergism between MoS_2 and SCF deteriorated the wear rate and frictional behavior of nylon 1010 composites.

From the above literature observations, it is clear that blend combination (PA66/PTFE) is not used. PA66 is a high strength polymer and PTFE is known for its superior wear resistance. Therefore, the blend (PA66/PTFE) has been used as the base material for tribological and mechanical loading. Further, the sole effect fiber on the wear behavior of polymer composites are available in plenty. But the effect of hybrid fibers is rarely reported. On the other hand, the hybrid combination of Glass- Basalt is not reported. Glass fiber is known for its strength and modulus whereas basalt fiber counters the thermal effects during sliding situations. Furthermore, the influence of load, velocity and distance in sliding needs to be discussed to evaluate the wear behavior. Keeping this in view, the effect of experimental parameters such as load, velocity and distance on the sliding wear behavior of Glass-Basalt hybrid composites have been reported effectively.

II. METHODOLOGY

2.1. Materials, Processing and Testing Composites

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

Table 1. Materials data used in the production
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Table 2. Materials system formulations in weight %.
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2.1.1 Processing of Composites

The defined proportions of PA66, PTFE, short fibers such as glass fibers and basalt fibers (Table 2) used for fabrication were dried at about 80 ^{0}C to prevent the effect of plasticization and hydrolyzing effects. Here, two step processing is required. In the first step, the blend composition of PA66/PTFE has been subjected to melt mix method and the corresponding pellets of blend were obtained with the help of extrusion technique followed by pelleting machine. These blended pellets are once again subjected to extrusion process along with glass fibers, basalt fibers, micro fillers and nano fillers and mixed thoroughly for uniform distribution. The mixture is then extruded using extruder. Five thermal zones in the barrel has been maintained with the temperature around 220 ^{0}C, 235 ^{0}C, 240 ^{0}C, 265 ^{0}C and 270 0C respectively and 220 ^{0}C has been maintained as the die temperature. The extruder screw has been allowed to spin at 100 rpm for a fixed feed rate. The cold water quenched extrudates were pelletized. The cylindrical extrudates were palletized using palletizing machine. These blended pellets were once again subjected to heating process. These pellets were once again dried at 100 ^{0}C before injection molding. The zonal

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temperature in the injection molding barrel has been maintained in two locations with 265 ^{0}C and 290 ^{0}C respectively and the mold has been maintained with a temperature of 65 ^{0}C. Around 10 -15 rpm of speed has been allowed for the screw. The injection pressure of around 700 bar was used for the process. The injection and cooling time of 10 s and 35 s with an ejection time of 2 s have been maintained during injection molding

2.1.2 Testing of Composites (Sliding wear behaviour : ASTM G99)

The Pin on disc machine supplied by Ducom Bangalore has been used to conduct the sliding wear experiment as per ASTM G99 method (Fig.1). The samples used for the test were prepared using cutting machine and were cut into proper dimensions prescribed by ASTM. The generally used dimensions as per the standards are 6 mm x 6 mm x 3.2 mm. The prepared specimens were rubbed against smooth abrasives of 600 Grit 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 is measured before subjecting them to sliding process along with the pin. The counter surface has been cleaned with the help of soft material using acetone before sliding process to ensure no polymer substrate of previous stroke was present. The details of the experimentation and the process parameters used for the test as per ASTM G99 have been depicted in the Table 3.

Table 3. Experimental Parameters used for sliding wear test (ASTM G99)
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The experimental parameter such as normal load, total travelling distance and velocity of sliding were inputted by setting the time and speed of the disc. When the predefined time is 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 has been measured. The experimentation has been conducted for different load, velocity and distance and loss in weight is recorded in every trial. The 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 has been obtained through the weight loss (W) using the density d (ρ) which is determined experimentally. The wear volume (ΔV) and specific wear rate (Ks) have been calculated using the wear volume loss from the experimentation. The wear volume loss 'ΔV' and specific wear rate 'Ks' polymer composites are calculated using the following formulas:

Wear volume = $\Delta V = W/\rho$ mm^3 (1)

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

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

Fig. 1. Sliding wear system for ASTM G99: a) Experimental set up and b) specimen details
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III. Results and Discussions

3.1 Tribological response in terms of Volume loss and specific wear rate of GB Hybrid Composites: Effect of load

The tribological response for varying experimental sliding load as a result of individual and hybrid fiber reinforcement effect on volumetric loss of blend PA66/PTFE is shown in fig. 2(a - c). The sliding velocity of 0.5 m/s has been maintained for a period of time (33.33 Mins.). The graph demonstrated that the volumetric loss has been promoted with increase in normal load. The tribological behavior of short fiber filled composites was studied against the sliding wear characteristics of PA66/PTFE blend (80/20 wt.%). The highest wear volume loss is experienced by PA66/PTFE blend among the composites studied. The experimental range of load is 75 N to 150 N. The wear volume loss of blend at lower load was 0.33 mm^3. As the sliding load is increased, the wear volume loss is found to increase linearly exhibiting the highest wear volume loss of 2.01 mm^3 which is 509% increase. The rise in frictional shear force at the surface interface promoted the higher wear volume loss [21]. The frictional and tribological behavior of blend PA66/PTFE is significantly influenced by the capability of a blend to form a transfer substrate on the steel counter face [22-24]. During low load conditions, PA66/PTFE forms a straight, parallel, unvarying and continuous polymer substrate on the counter surface of

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steel [21].

Fig. 2. Tribological response of GB hybrid composites under varying experimental load: a) volume loss, b) Wear rate and c) Frictional constant

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The low 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 result in friction between 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 during sliding against steel. Also, sliding of PTFE with hard surface results in scissioning of polymer chain causing active groups which chemically react with counter face [26]. Further, consecutive interaction of polymer surface 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].

Similar observations are made with SGF filled composites. SGF reinforcement effect has been found to decrease the wear volume loss of SGF filled composites even at higher and lower sliding load over blend. From the graph, around 9% and 31.8% wear volume loss has been exhibited as an effect of SGF reinforcement at lower and higher sliding load over the blend. Addition of 10 wt.% SGF enhanced the capability of SGF filled composites to form a strong polymer film on counter surface. During lower load, the SGF filled composites offered resistance against the shearing force. The resistance offered by SGF filled composite is more when compared to shearing force. During this process, fiber sliding wear is more prominent than matrix wear [5]. Therefore, less wear volume loss. But at higher load, sliding was accompanied by matrix melting. The combined action of frictional force and sliding load results in rupturing of glass fibers into very short fibers which were bounded by matrix. Hence, more 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 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 composites. The superior wear resistance of SBF Filled composites has been submitted to addition of short basalt fibers. The wear volume loss at lower load is small as other composites but the significant effect of wear resistance is observed at higher load. Even though, SBF is a normal load carrying member, but it can retain its originality even at its operating temperature than glass fibers [27]. As a hybrid effect of friction and normal load, the plastic deformation of blend was more due to matrix wear. During this process, SBF will not ruptured by these actions instead sliding of fibers occurs [27]. Therefore, the wear volume loss of composites at higher thermal conditions was controlled by basalt fibers in blend. Therefore, inclusion of SBF improved the wear resistance of PA66/PTFE/SBF composites.

But the effect of hybridization of fibers on volumetric loss of GB hybrid composites is very much significant. The combined effect of SGF and SBF improved the wear resistance of GB hybrid composites. At an average of 56% decrease in volumetric loss is experienced by GB hybrid composites irrespective of loading conditions. Reinforcement of hybrid fibers significantly enhanced the wear resistance of composites. Firstly, basalt fibers raised the thermal resistance of SBF filled composites and constrained the growth of melting wear [28]. Secondly, the hard SGF which were exposed at the sliding surface acts as a portion of normal load and reduced the penetration of steel asperity tips into soft matrix. This would avoid the chance of micro cutting and microploughing actions [29]. Thirdly, glass fibers and basalt fibers wear lesser than the matrix. Therefore, hybrid fibers effect has reduced the wear loss of composites by offering resistance against sliding. Among the composites

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studied, GB hybrid composites exhibited the better wear resistance. The resultant wear of GB hybrid composites is a result of matrix wear and fiber sliding wear [5]. The investigated results match with others works [5, 6, 27].

Fig.4. SEM images of the worn surfaces of sliding wear for varying sliding load: a) Blend (PA66/PTFE) (75 N),b)Blend (PA66/PTFE) (150 N), c)Blend(PA66/PTFE)/SGF(75N),d)Blend(PA66/PTFE)/SGF(150N),e)Blend (PA66/PTFE)/SBF (150 N), f) Blend (PA66/PTFE)/ SBF (150 N), g) GB hybrid (75 N) and h) GB hybrid (150 N)
(Please see page 137)

The effect of hybrid fibers on specific wear rate (Ks) of PA66/PTFE blend under varying load is depicted in fig. 2 (b). The 'Ks' of composites studied has been increased with increase in sliding load. Among the composites studied, blend exhibited highest wear rate. This is due to pure matrix wear of composites. The 'Ks' of neat blend varied from 4.77 x 10^{-6} to 17 x 10^{-6} mm^3/ N-m. Similarly, the wear rate ranges from 4 x 10^{-6} to 10.17 x 10^{-6} mm^3/ N-m and 3.47 x 10^{-6} to 6.95 x 10^{-6} mm^3/ N - m for SGF filled and SBF filled composites respectively. At higher load, the 'Ks' of PA66/PTFE/SBF composites is 32% less than SGF filled composites. The GB hybrid composites exhibits the wear rate ranging from 2.14 x 10^{-6} to 6.2 x 10^{-6} mm^3/ N-m which is 39% and 7.5% less than the wear rate at higher load of SGF and SBF filled composites respectively.

Fig.2 (c) depicts the effect of fibers under varying load on frictional characteristics of the blend PA66/PTFE. It is concluded that the frictional coefficient (COF) is decreased with increase in sliding load. Also the hybrid effect of fiber found to decrease the frictional constant of blend. The COF depends on sliding load and also on the content of fibers in the blend. Basically, PTFE has very low frictional coefficient and its effect on the friction is most significant. At higher load, the frictional effects are most favorable. The blend has a COF of 0.23 against 0.22, 0.2 and 0.198 of SGF filled, SBF filled and GB hybrid composites respectively. This showed that the effect of hybrid fibers has reduced the COF by 14% than blend. The promotion of sliding load depromoted the COF of composites. The main reason for decreasing COF is that the exposed hybrid fibers supported the part of applied load there by arresting the steel asperity tips entering the polymer surface. Hence, the fiber wear was less when compared to matrix wear. The high frictional stresses made the blend PA66/PTFE to melt more and viscoelastic behavior under deformation made the material to decrease the COF with increase in load [30]. Among the composites studied, GB hybrid composites exhibited the least COF at higher load. These results match with the findings of the other researchers [30, 31].

The SEM micrograph of failure surfaces of PA66/PTFE blend under varying sliding load are shown in fig.4 (a - h). The SEM picture of worn surfaces of blend at a sliding load of 75 N is shown in fig. 4 (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 resulted in melting of matrix which is exhibited by the SEM picture 4 (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 fig.4 (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 were fractured into small fibers whose length is less than the un- rubbed fibers are seen in the fig.4 (c). These fibers were surmounted by the melted matrix blend witnessing the fracture of glass fiber through sliding under the influence of frictional shear and normal load. But at higher sliding load (Fig.4 (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

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this condition depends on the contribution of melting wear of blend and abrasive wear of ruptured fibers [6]

The SEM image of SBF filled composites under the action of varying load in sliding wear behavior is shown in fig.4 (e and f). At lower load, (fig.4(e)), matrix melting is severe along with fiber rupture. The ruptured SBFs embedded in melted matrix are seen in SEM pictures. The fracture through fibers and their pull out were few failure mechanisms noticed during this condition. But at higher sliding load, the fiber fracture along with melting wear is observed. From the fig. 4(f), it is observed that the wear mechanisms involved in wear process were matrix wear and fiber wear. All SBF are exposed at the wear surface. But the wear of these SBF filled composites results in fiber fracture and fiber cracking due to the application of heavy load. These mechanisms are shown clearly in the fig.4 (f). The failure surfaces of GB composites during sliding through SEM images are depicted in fig. 4 (g and h). The agglomeration of melt at the surface of specimen is seen in fig. 4 (g). But at higher load, the matrix furrows along with abrasives of short fibers are exhibited on the surface (Fig.4 (h)). These abrasive wear debris acts on the steel surface resulting higher wear volume loss. At higher load, the hybrid fiber sliding wear results in pulverization of fibers and these pulverized fibers filled the gap separated by debonding the matrix and fibers during sliding. This is clearly exhibited by the fig.4 (h). It is concluded from the SEM picture that the effect of sliding load results in fiber wear and matrix melting.

3.2 Tribological response in terms of wear volume and wear rate of GB Hybrid Composites: Influence of sliding velocity

The effect of individual and hybrid fiber reinforcement on the sliding wear response of the blend PA66/PTFE under the influence of sliding velocity is exhibited in fig.5 (a, b and c). The wear volume loss of blend composites as a function of sliding velocity is depicted in fig.5 (a). The experimental range of velocity considered for the test was 0.5 to 2 m/s for a particular period of time (33.33 Min.). The variation of wear volume loss with the sliding velocity is depicted in fig.5 (a). It has been observed that the volumetric loss has been promoted with raise sliding velocity. The volumetric loss of neat blend is more when compared to fibrous composites. At lesser sliding velocity, the volumetric loss of blend is 2 mm3. With the promotion of sliding velocity, the volumetric loss of composites increases. At higher velocity for a blend, it is 5.48 mm3 which is 174% increase. For increase of 300% sliding velocity, 174% increase in volumetric loss is exhibited by the blend. 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 respectively. Similar observations are made with SBF filled composites. It is 53% at lower velocity and 63% at peak velocity has been recorded over the blend. But the synergistic effects of both fibers reduced the wear volume loss of GB hybrid composites by 78% respectively between the range of sliding velocity relative to the blend. Therefore, it is believed that hybrid effect of fibers is most promising in enhancing the sliding wear resistance of thermoplastic composites. At lower speed, the frictional force generated on the interfacial surface is less. But as the velocity was increased, the frictional force is also increased. The frictional asperities at the interfacing surfaces promote high temperature [13]. The temperature at the rubbing surface is a function of sliding speed. When the temperature at the interface has attained the softening temperature of a polymer, adhesive component from the polymer surface transferred easily on to the metallic surface resulting in the formation of transfer film [13, 15]. But glass fibers supported the part of applied load against the frictional force. It avoids the early reaching of softening point of polymer. Therefore, less wear volume loss. Similarly, SBF is thermally strong and avoids the melting wear of matrix. But in hybrid mode, SGF supported the formation of polymer substrate and SBF avoids the melting wear of matrix. The sliding fiber wear and matrix melting were the results of hybrid fiber sliding mechanisms [6].

Therefore, less wear volume loss. Among the composites studied, GB hybrid composites exhibited the better wear response for sliding velocity. The effect of fiber reinforcement under varying sliding velocity

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on 'Ks' of GB hybrid composites are presented in fig.5 (b). It is found that 'Ks' of composites studied has been raised with the rise of sliding velocity. The specific wear rate of blend varied from 13.46 x 10^{-6} to 10.15 x 10^{-6} mm^3/ N-m. Similarly, the wear rate of SGF filled and SBF filled composites ranges from 10 x 10^{-6} to 6.53 x 10^{-6} mm^3/ N-m and 6.95 x 10^{-6} to 3.7 x10^{-6} mm^3/ N-m respectively. But the wear rate of hybrid fiber filled GB composites varied from 6.2 x 10^{-6} to 2 x 10^{-6} mm^3/ N-m which is 54% and 80% less than the wear rate of blend between varying velocities. This may be due to high shearing force which sheared the transfer film on the counter polymer surface than frictional force at higher velocity [15]. Among the composites studied, GB hybrid composites exhibited the better specific wear rate. The present findings are in line with the results of others work [13, 15].

The effect of fiber reinforcement on frictional coefficient (COF) of hybrid composites under the influence of varying velocities is shown in fig. 5 (c). The influence of fiber reinforcement declined the COF value of the composites. This is because of the influence of decrease in frictional force at the interface of fibers. At lesser sliding velocity, the neat blend PA66/PTFE exhibited the least COF (0.14). But at the same situation, SGF shoots COF to a higher value (0.36). During the glassy state of composites (normal temperature), at lower velocity, the impact of thermal effect promoted a glassy state to viscoelastic state leading to high frictional coefficient. But the SBF filled composite exhibited the better COF (0.3) value which is less than SGF filled one. But the hybrid composites showed the least COF (0.21). At lesser velocity, pure blend had the control over COF by using PTFE. But fiber filled composites exhibited the higher COF because of surface roughness of polymer.

Fig.5 Tribological response of GB hybrid composites under varying experimental velocity: a) Volume loss, b) Wear rate and c) Frictional constant
(Please see page 138)

But as the sliding velocity was increased, the corresponding increase in COF is observed. At higher velocity, the COF of 0.29, 0.36, 0.31 and 0.3 respectively exhibited by the blend, SGF filled, SBF filled and GB hybrid composites. But the least COF among the tested composites is obtained for 1 m/s sliding velocity. The SEM picture of failure surfaces of GB composites under the influence of sliding velocity is shown in fig.6 (a - h). The SEM picture of worn surface of neat blend with varying velocity is shown in fig.6 (a and b). At low sliding velocity, the plastic deformation of matrix occurs and PTFE has been dragged from the blend on to counter steel surface to form unvarying and consistent polymer surface. This is depicted in fig. 6(a). The thin regular wear paths were observed on the rubbed surface. The melting wear of blend is dominant during lower sliding velocity and hence the viscous nature of blend reflects the low wear rate of composites. But, at higher velocity, the frictional effects are high and the temperature at the surface has reached the softening point of composites. Due to these effects, the melting of matrix blend was severe resulting more volume loss. This is shown in fig.6 (b). The polymer layer of blend seemed to be over lapped due to accumulation of frictional heat during sliding [5]. This made the material to exhibit high wear rate. The SEM images of the worn surfaces of glass fiber filled composites subjected to varying sliding velocity is shown in fig. 6 (c and d). At lower velocity, the SGF filled composites were subjected to fiber rupture. This has reduced the length of fiber and is made to embed the fibers into the melted blend. The worn surfaces seemed to be uniform under the influence of transfer film. Due to this, SGF were not exposed to the surface. Hence, low wear rate. But at higher velocity (Fig.6 (d)), the melting wear along with fiber pull out is noticed. This caused more loss of material. But SGF surface 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 was extruded out of sliding surface indicating fibrillation of PTFE (Fig. 6(d)). These fibrils filled the grooves and lowered the wear rate of composites. Hence, the compatibility between SGF and matrix blend is superior.

The SEM image of SBF filled composites under the influence of varying velocity is shown in fig.6 (e and f). Fig.6 (e) showed that the fiber sliding wear is dominant. The fiber wear mechanisms involved in this

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case were fiber fracture, fiber cracking and also fiber – matrix bonding damage. Slight cracks are also seen due to debonding of matrix – fiber interface. These reduced the wear resistance of composites. Similar observations are made at higher velocity (Fig.6 (f)). But at higher velocity, the plastic deformations due to high frictional effects are more. This may transferred more volume of material on to counter surface. This has led to poor wear resistance. The SEM image of the worn surfaces of GB hybrid composites sliding against steel counter face under the influence of varying velocity is shown in fig.6 (g and h). The interfacial bond between the fiber and the matrix is seemed to be good which is clearly shown in the figure. But the embedded fibers are exposed to wear and the sliding wear of fiber occurs. This has transferred the fiber debris into matrix blend. The worn surface is full of wear debris. But at higher velocity, severe matrix melt along with the fiber rupture are noticed. But the worn surface was full of crushed SGF and at the same time fiber pulverization occurs. The excellent mechanical properties, superior hardness and also the high thermal stability of fibers improved the wear resistance of composites. There is a sign of matrix ploughing but its effect on wear rate was negligible. This is shown in fig. 6(h). The pull out of fibers and fracture through fibers is observed through SEM pictures are some of the failure mechanisms exhibited by the composites studied.

Fig.6. SEM pictures of the failure surfaces of sliding wear for varying sliding velocity: a) Blend (PA66/PTFE) (0.5 m/s), b) Blend (PA66/PTFE) (2 m/s), c) Blend (PA66/PTFE)/SGF (0.5m/s) ,d)Blend (PA66/PTFE)/SGF(2m/s), e)Blend (PA66/PTFE)/SBF (0.5 m/s), f) Blend (PA66/PTFE)/SBF (2 m/s), g) GB hybrid composites (0.5 m/s) and h) GB hybrid composites (2 m/s) **(Please see page 139)**

IV. CONCLUSION

The sliding wear behaviour of GB hybrid composites has been studied under the influence of sliding load, velocity and distance. The blend PA66/PTFE seemed to be the best base material for the structural application. Fibre filled composites exhibited better wear resistance than the blend PA66/PTFE under all the experimental conditions. Further, SBF filled composites are better than SGF filled composites. But GB hybrid composites exhibited superior wear resistance during sliding because of hybridization effect of fibres. Matrix melting and its wear, fiber fracture and its wear and matrix deformation were observed through SEM micrographs analysis.

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Table 1. Materials data used in the production

Materials	Properties of composites			
	Form	Size(μm)	Trade Name	Density (g/cc)
PA66	Granules	---	Zytel 101L NC010	1.14
PTFE	Powder	12-14	MP1000	3.2
Short glass fibers	Cylindrical	Length = 3-4 mm Diameter = 10-20	----	2.45
Short basalt fibers	Cylindrical	Length = 5-6 mm Diameter = 10-20	-----	1.74

Table 2. Materials system formulations in weight %.

Materials	Weight percentage			
	PA66	PTFE	SGF	SBF
Blend (PA66/PTFE)	80	20	---	---
Blend /Short glass fiber	80	20	10	---
Blend /Short basalt fiber	80	20	--	10
Blend/SGF/SBF (GB)	80	20	10	10

Table 3. Experimental Parameters used for sliding wear test (ASTM G99)

Process Parameters	
Sliding load (N)	75, 100, 125 and 150
Sliding velocity (m/s)	0.5, 1, 1.5 and 2
Sliding distance (m)	4000

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

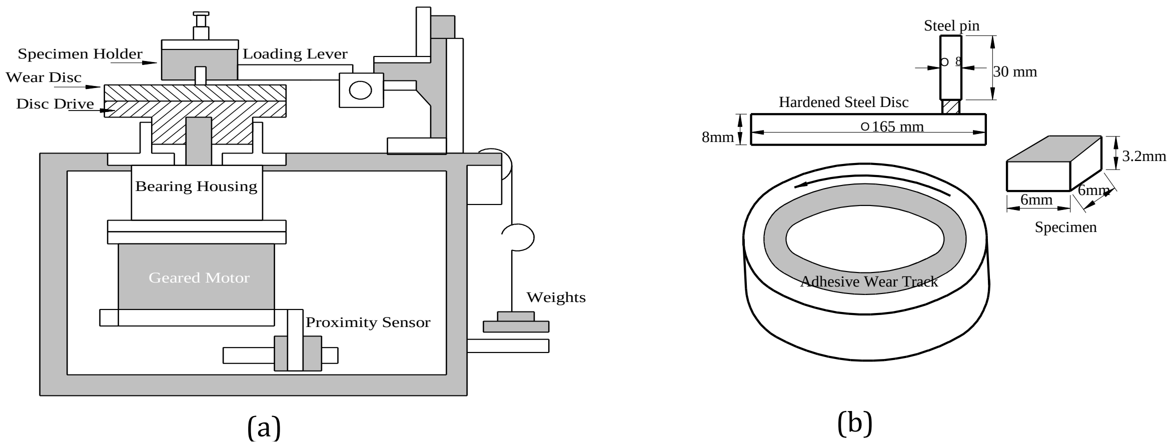

Fig. 2. Tribological response of GB hybrid composites under varying experimental load: a) volume loss, b) Wear rate and c) Frictional constant

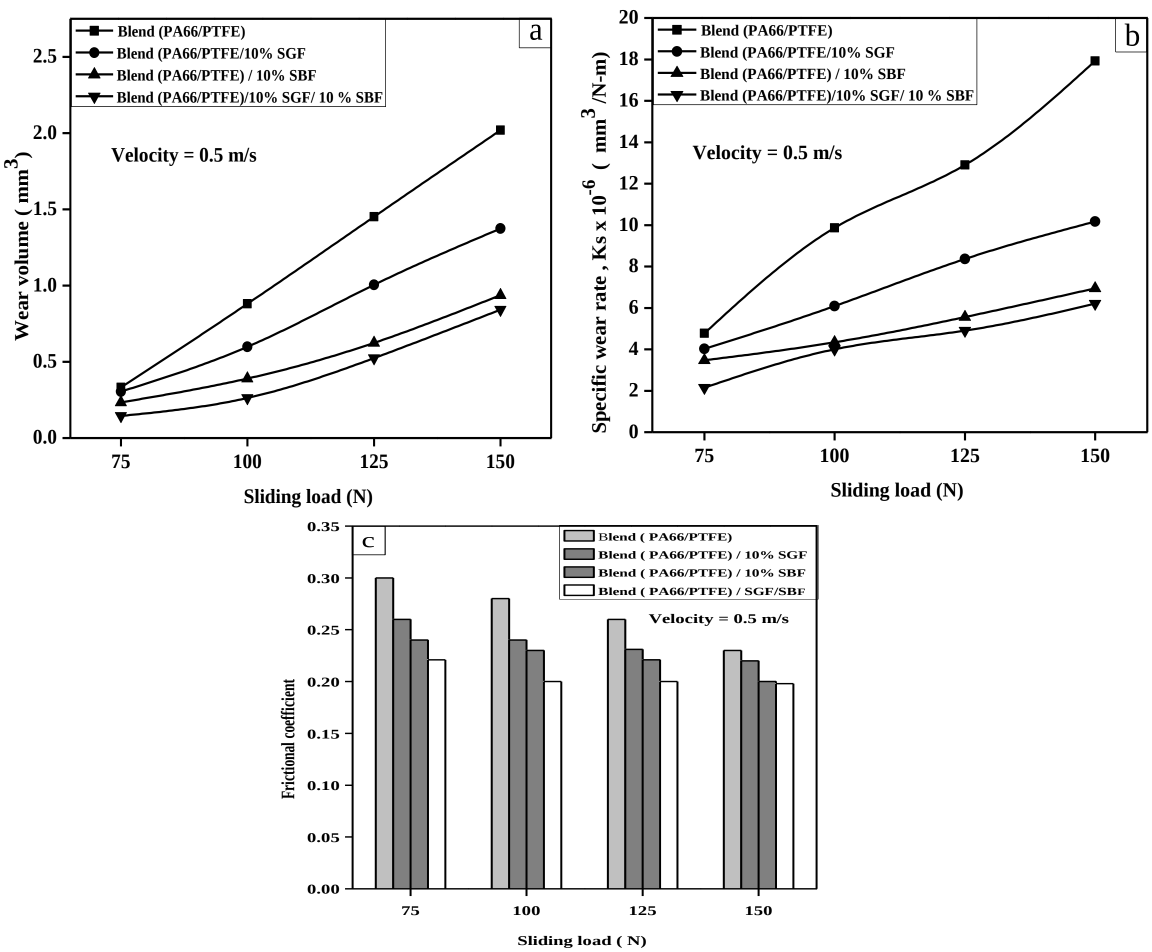

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Fig.4. SEM images of the worn surfaces of sliding wear for varying sliding load: a) Blend (PA66/PTFE) (75 N),b)Blend (PA66/PTFE) (150 N), c)Blend(PA66/PTFE)/SGF(75N),d)Blend(PA66/PTFE)/SGF(150N),e)Blend (PA66/PTFE)/SBF (150 N), f) Blend (PA66/PTFE)/ SBF (150 N), g) GB hybrid (75 N) and h) GB hybrid (150 N)

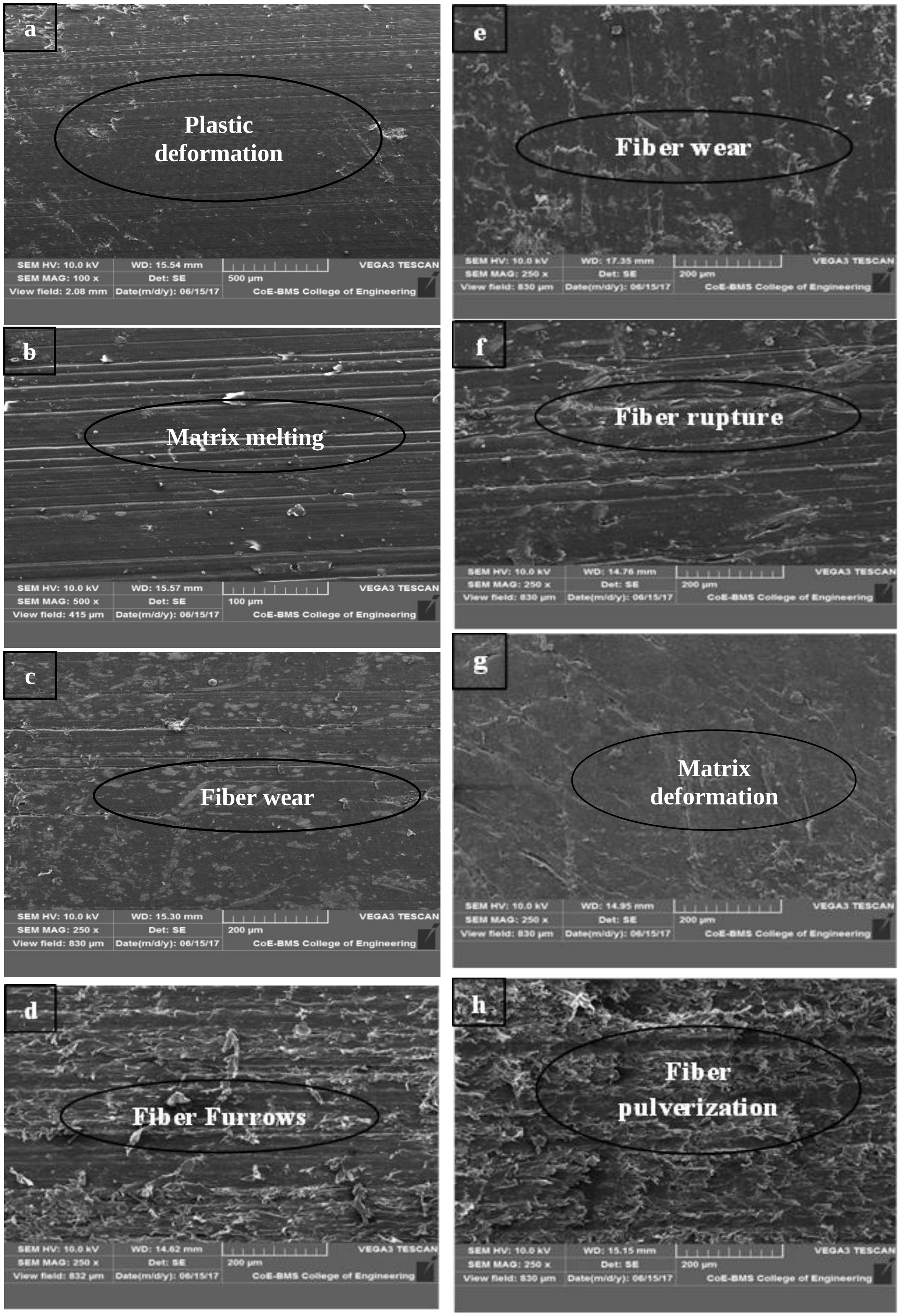

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Fig.5 Tribological response of GB hybrid composites under varying experimental velocity: a) Volume loss, b) Wear rate and c) Frictional constant

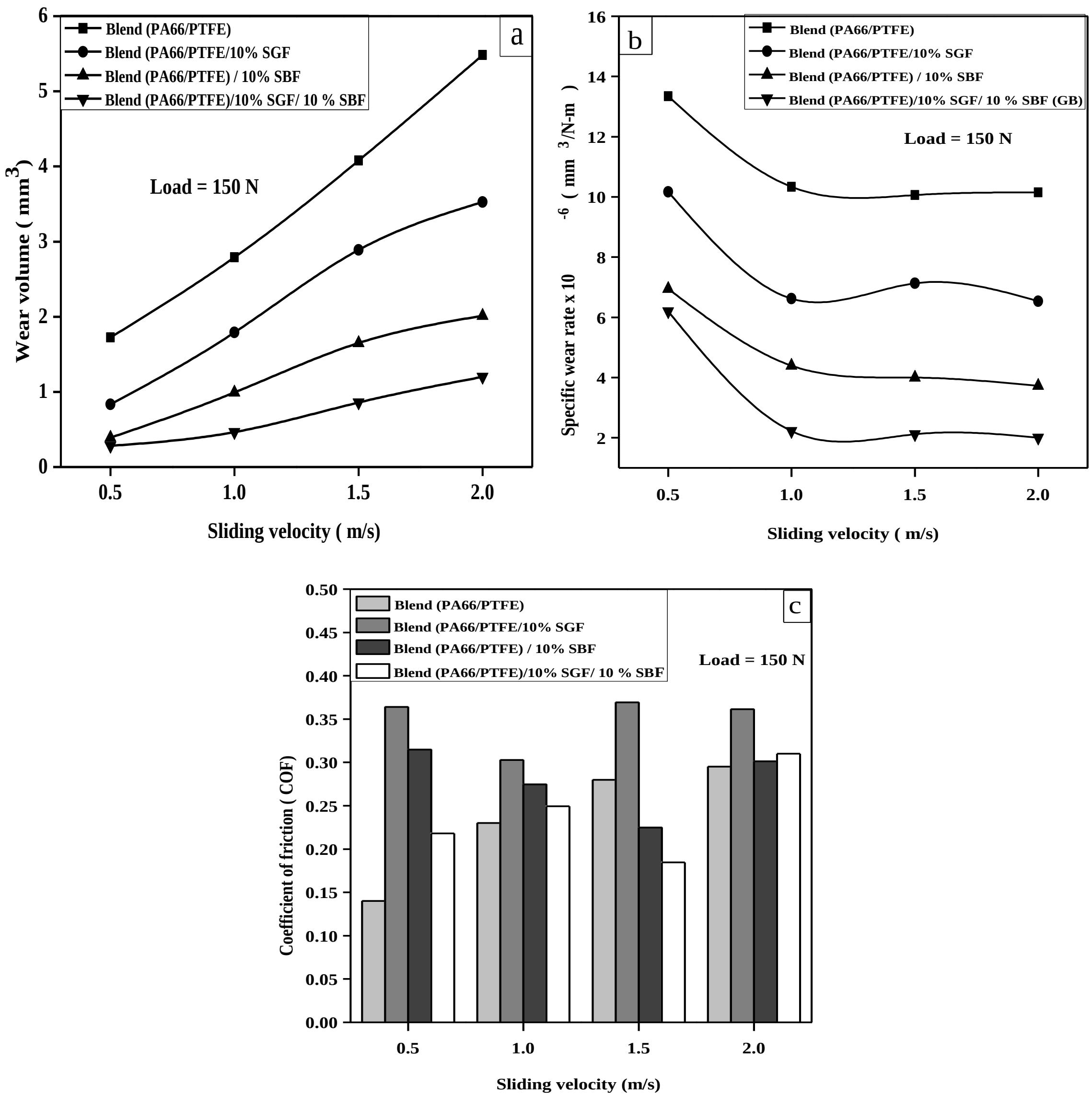

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Fig 6. SEM pictures of the failure surfaces of sliding wear for varying sliding velocity: a) Blend (PA66/PTFE) (0.5 m/s), b) Blend (PA66/PTFE) (2 m/s), c) Blend (PA66/PTFE)/SGF (0.5m/s) ,d)Blend (PA66/PTFE)/SGF(2m/s), e)Blend (PA66/PTFE)/SBF (0.5 m/s), f) Blend (PA66/PTFE)/SBF (2 m/s), g) GB hybrid composites (0.5 m/s) and h) GB hybrid composites (2 m/s)