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On the Abrasiveness and Reinforcement of Fillers in PTFE/Epoxy Composites

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This article addresses the question what the influence is of size and shape of glass both particles and fibers, as well as carbon fibers on the abrasiveness of polytetrafluoroethylene (PTFE)/epoxy composites sliding against steel balls. A size-dependence appears, i.e. large size glass particles (~80 μm , L) are more abrasive than medium-size (~50 μm , M) and small-size (~27 μm , S) glass particles. Longer glass fibers (sub-millimeter) are more abrasive. Nevertheless, longer glass fibers still enhance the intrinsic mechanical properties of the composites. Also, carbon fibers reinforced composites yield much better mechanical properties than the glass fibers reinforced composites, but much more abrasive wear on the steel ball due to less surface-adhered polymer layers on fibers. Mechanical properties are enhanced by an increasing amount of glass fillers and by adding a small concentration of nanofillers. POLYM. COMPOS., 39:698–707, 2018. © 2016 Society of Plastics Engineers

INTRODUCTION

Self-lubricating composites are a crucial component in dry sliding bearings, which are widely used in household, mining and construction equipment, as well as in some parts of high-speed trains. Hence, in the past a vast amount of research was focused on lowering the friction and improving the wear resistance and the mechanical performance of the self-lubricating composites, which mainly cover the influence of lubricants [1–3], polymer matrix [4–6], micro-fillers, and nanoparticles [7–11].

However, we have found that too much abrasive wear on the sliding counterpart (usually bearing steels) could also deteriorate the sliding condition and increase the fric-

tion force and abrasive wear [12, 13]. Reinforcements or fillers, such as glass fibers and carbon fibers, are the stiff and hard components of self-lubricating composites. Thus, an evaluation of the abrasiveness due to the fillers is necessary for improving the design of self-lubricating composites. In particle abrasion tests, the size and geometry of the abrasive particles both affect their abrasiveness [14–18]. However, when embedded in polymer matrix, effects of the size, and length of fillers on the abrasiveness of the composites is not yet reported to the best of our knowledge. Glass fibers are more abrasive than carbon fibers in some polymers [19–21], which is attributed to a higher hardness of glass fibers. However, their abrasiveness in the polytetrafluoroethylene (PTFE)/epoxy composites is not addressed yet. For a long-term stable sliding condition, it is relevant to examine the abrasiveness of glass particles filled composites and milled glass/carbon fibers filled composites.

Appropriate mechanical properties of self-lubricating composites are desirable to achieve a low wear rate of the composites and a long lifetime in service. Therefore, the mechanical properties should not be sacrificed too much in order to yield a low abrasiveness of the composites. It is of interests to optimize both the mechanical performance and the abrasiveness of the composites, especially when the sliding counterparts are not very wear resistant, such as steels or copper alloys.

This work aims at examining the abrasiveness and mechanical properties of PTFE/epoxy composites with the following fillers: glass spheres, milled glass fibers, and milled carbon fibers, as well as silicon oxide nanoparticles. The influence of the size of glass particles, the length of fibers, as well as the surface adhesion property was thoroughly investigated. The goal of this work is to contribute to an improved design of self-lubricating composites which could optimize the wear of both sides of sliding systems, when a sufficient lubrication is guaranteed.

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EXPERIMENTAL

Materials

Epoxy XB 6078 powder, supplied by Huntmans, is a fast-curing one-component solid epoxy system. The fast-curing solid epoxy powder is used to avoid a settling of large glass particles ($>70\text{ }\mu\text{m}$) to the bottom side of curing samples. A settling of large glass particles was observed in a liquid Specifix-20 epoxy system (initial viscosity $\approx 190\text{ mPa s}$) and in a liquid Epoxydharz C epoxy system (initial viscosity $\approx 3,200\text{ mPa s}$) by the authors. For readers who are interested in the settling speed of spherical particles in a liquid, reference is made to Stokes's law [22].

PTFE powder, purchased from Sigma-Aldrich, has an average particle size of about $12\text{ }\mu\text{m}$, according to manufacturer datasheet. Hollow (partially hollow) glass spheres (47Si, 37O, 8Na, 6Ca, 0.8Al, wt%, measured with energy dispersive X-ray spectroscopy), from Sigma-Aldrich, have an average diameter of around $8.4\text{ }\mu\text{m}$ as measured with light microscopy. Solid glass spheres (46Si, 33O, 10Na, 8Ca, 2.0Mg, 0.5Al) with diameter less than $106\text{ }\mu\text{m}$ diameter are purchased from Sigma-Aldrich.

The solid glass spheres are sieved through $100\text{ }\mu\text{m}$, $71\text{ }\mu\text{m}$, and $40\text{ }\mu\text{m}$ sieves. The size grades obtained are less than $40\text{ }\mu\text{m}$ (S), $40 - 71\text{ }\mu\text{m}$ (M), and $71 - 100\text{ }\mu\text{m}$ (L). The measured size distribution of the hollow glass spheres and the solid glass spheres of three grades are presented in Fig. 1 (in Appendix). The average diameters of the three-grade solid glass spheres are $27.1\text{ }\mu\text{m}$ (S), $49.9\text{ }\mu\text{m}$ (M), and $79.0\text{ }\mu\text{m}$ (L), respectively.

Milled glass fibers (GF) have an average diameter of about $12.3\text{ }\mu\text{m}$ (from: carbonwinkel.nl). As shown in Table 1 and Fig. 2 (in Appendix), milled glass fibers with three different average lengths are named as: Short-GF, GF (medium), and Long-GF. Milled carbon fibers (CF) have an average diameter of around $7.0\text{ }\mu\text{m}$ (from: easy-composite.co.uk). Silicon oxide (SiO_x) nano-particles have an average size of $15 - 20\text{ nm}$ (from: us-nano.com). Part of milled carbon fibers are ultrasonicated at 65°C in 65% nitric acid for 2 h to oxidize the surface of fibers, the process of which was reported in [23]. EDS results show about $6.3 \pm 1.3\text{ wt\%}$ oxygen content in the treated carbon fibers, about 2.2 wt% higher than the original carbon fibers.

Sample Preparation

After weighing, the epoxy and the PTFE powder was ball milled in a water medium at 450 rpm for 7 min using a planetary mill. Then, the hollow glass spheres were added in and milled for another 2 min. Afterwards other particles or fibers were added in and milled for only 30 s. The powder, after drying, was then cured in a curing mold at 8 bar pressure for 10 min at 112°C in a hot press. After cooling and de-molding, the composite disks (around $\phi 30\text{ mm} \times 7.5\text{ mm}$) were polished until 4,000

FIG. 1. Light micrographs showing the wear scar of the steel balls sliding against the composites: (a) M, (b) L, (c) CF, and (d) GF samples, at 20 N load, and 20 mm/s speed, after 1,500 m sliding distance. The arrow indicates the relative sliding direction of the sliding counterpart (same in the following figures).

grade polishing paper. The compositions and the names of the composites are listed in Table 1. The density of all the cured samples are around $1.47 \times 10^3\text{ kg/m}^3$.

TABLE 1. The composition and abbreviation of the composites.

Compositions				Sample abbreviation
Epoxy (wt%)	PTFE (wt%)	Hollow glass (wt%)	Others (wt%)	
47.5	15	37.5	—	HG
47.5	15	27.5	10% solid glass spheres, <40 μm	S
47.5	15	27.5	10% solid glass spheres, 40-71 μm	M
47.5	15	27.5	10% solid glass spheres, 71-100 μm	L
47.5	15	27.5	10% milled carbon fibers, 108.5 μm	CF
47.5	15	27.5	10% milled glass fibers, 120.2 μm	GF
47.5	15	27.5	10% milled glass fibers, 59.1 μm	Short-GF
47.5	15	27.5	10% milled glass fibers, 245.4 μm	Long-GF

Tribo-Tests

The friction behavior of the epoxy composites was studied using a CSM ball-on-disk rotational tribometer under dry sliding conditions. $\varnothing 13$ mm 100Cr6 bearing steel balls (7.8 g/cm³ density) were used as the stationary counterpart balls. The surface roughness (R_a) values of the steel balls were measured to be around 60 nm with confocal microscopy (60 μm cut-off, 705×728 μm image size). The sliding conditions were 20 N normal load and 20 mm/s sliding speed, otherwise will be specified. The sliding environment was $35\% \pm 2\%$ relative humidity and room temperature ($22 \pm 2^\circ\text{C}$). The relative humidity was adjusted with feedback controlled flux of dry air or water vapor into the testing chamber.

FIG. 2. The middle-line profiles (as indicated by the red line in Fig. 5) of the wear scars of the steel balls when sliding against the various epoxy composites at 20 N load and 20 mm/s speed for 1,500 m. The black lines indicate the profiles of the original surfaces. [Color figure can be viewed at wileyonlinelibrary.com]

Compression Tests

Each composite sample was cut and polished into three 7 mm x 7 mm x 14 mm cuboids. All the cuboids were tested with a Kammrath & Weiss compression tester, with the compressive forces being exerted on the two far ends. During testing, the displacement in compression linearly increased with time (21.7 $\mu\text{m/s}$) until the sample breaks. The stress and the strain were constantly recorded to obtain the compressive modulus, ultimate strength, and elongation at fracture of the samples.

Characterization

After the tribo-tests, the morphology and profile of the worn surfaces of the epoxy composites and of the balls were inspected using light microscopy and confocal microscopy (Nanofocus μSurf). The calculation of the composites wear volume was carried out with a home-made Matlab code with a margin of error of $\pm 5\%$. Energy dispersive X-ray spectroscopy (EDS, Philips XL-30 FEG ESEM) was used to analyze the elemental composition on the wear surfaces, with a 15 kV acceleration voltage. A thin Au layer was applied on the surface of the epoxy composites so as to avoid charging. To obtain the average elemental composition on the wear surfaces of the composites, at least three scans were executed with the size of the scanning areas of about 465×350 μm^2 .

RESULTS AND DISCUSSION

Abrasiveness of the Fillers in the Composites

Before discussing the effect of particle size and geometry, it should be mentioned that, as expected, the abrasiveness of the composites is found to increase with increasing concentration of glass spheres in the composites. A higher CoF and more scratched surfaces of steel ball (not shown here) were observed after tribo-tests when sliding against the composite with 50 wt% glass as compared to the composite with 37.5 wt% and 25 wt% glass.

Effect of the Particle Size

The size of the glass spheres could influence the abrasiveness of the composites. The CoF results of the epoxy

TABLE 2. EDS Fe content (EDS software calculated, automatic background) on wear track of composites, the average CoF values and the average wear rate of various composites, after sliding under 20 N for 1,500 m. (N.D.: no evidence Fe peak is detectable. weak peak: fairly weak Fe peaks, but visible).

Sample	Fe content (wt%)	CoF	Average wear rate ($\times 10^{-16}$ m ³ /Nm)
HG	N.D.	0.108 ± 0.002	6.1 ± 0.8
S	N.D.	0.114 ± 0.005	7.7 ± 1.3
M	N.D.	0.110 ± 0.003	8.1 ± 2.6
L	0.57 ± 0.17	0.112 ± 0.004	9.2 ± 2.7
CF	Weak peak	0.107 ± 0.003	8.3 ± 2.3
GF	Weak peak	0.109 ± 0.003	11.2 ± 1.9
Short-GF	N.D.	0.099 ± 0.002	10.5 ± 2.2
Long-GF	0.59 ± 0.15	0.105 ± 0.004	10.9 ± 2.4

composites with 10 wt% of various sizes of glass spheres are presented in Table 2, sliding under 20 N load and 20 mm/s speed. It is seen that in general, except for the S sample, the CoF increases with increasing diameter of the glass spheres. EDS results in Table 2 show the amount of back transferred Fe onto the worn composite surfaces after sliding for 1,500 m. A detectable amount of back transferred Fe is only found on the worn L sample surface.

Figure 1 shows that when sliding against the M samples, the steel ball shows hardly any wear but only few scratches. On the other hand, when sliding against the L sample, the worn steel ball shows many scratches and evident abrasive wear. To obtain a clear assessment on the wear of the steel ball, confocal images were taken and the middle line profiles were used to compare the wear depth (in Fig. 2, method see in [12]). It is seen that there is only little wear of the steel ball when sliding against the M sample, while the wear depth of the steel ball is clearly larger when sliding against the L sample. It should also be noted that in case of sliding against the HG sample and the S sample, there is hardly any wear or scratch on the wear scar of the steel ball (not shown here). Thus, it is concluded that the amount of abrasiveness of the solid glass spheres in the epoxy composites follows the sequence of $L > M \approx S$.

Effect of Glass Fiber Length

The effect of the length of milled glass fibers on the abrasiveness of the glass fibers reinforced composites is a relevant issue. Among the glass fibers reinforced composites, it is found that the composite reinforced with the shortest glass fibers (Short-GF) yields the lowest CoF, as shown in Table 2. Light images of wear scars of the steel ball after sliding against the glass fibers reinforced composites are shown in Fig. 3. It is seen that the steel ball wears the most when sliding against the Long-GF sample, while the steel ball has the least wear and scratches when sliding against the Short-GF sample. Line profiles of confocal images in Fig. 4 and EDS results listed in Table 2 confirm that the Long-GF sample is the most abrasive one whereas the Short-GF sample is the least.

Milled Carbon Fibers

Sliding under 20 N load and 20 mm/s speed for 1,500 m, optical microscopy images in Fig. 1 show that there are much more abrasive scratches on the steel wear scar when sliding against the CF sample than that in the

FIG. 3. Light micrographs showing the wear scar of the steel balls sliding against the composites disc: (a) Short-GF (b) GF and (c) Long-GF samples, at 20 N load and 20 mm/s speed, after 1,500 m sliding distance.

FIG. 4. Middle-line profiles of wear scars of the steel balls when sliding against the epoxy composites with milled glass fibers of various average length, at 20 N load and 20 mm/s speed for 1,500 m. The black lines indicate the profiles of the original surfaces. [Color figure can be viewed at wileyonlinelibrary.com]

case of sliding against the GF, M, and MP sample. It should be noted that there is no pitting (or spalling) wear on the worn composite surface of the CF and the GF sample, the occurrence of which might lead to abrasive wear on the counterpart steel ball.

According to the EDS results in Table 2, the detected amount of back transferred Fe on the CF sample surface is similar to the GF sample after 1,500 m sliding. Confocal images of the steel wear scars confirm (shown in Fig. 2) that the CF sample is evidently more abrasive than the Short-GF and M sample. The abrasiveness wear types of the CF and the GF sample are different. Linking the light and confocal images of their steel counterparts, it is seen that the CF sample yields many shallow scratches while the GF sample gives rise to few fairly deep scratches. Upon extending the sliding distance to 4,000 m, it is found that the CoF of the CF sample has a significant increase after about 2,000 m, reaching about 0.16 at 4,000 m, while the CoF of the GF sample remains fairly stable and low in the 4,000 m sliding (in Fig. 6a). The wear-scar profiles of the steel ball after sliding against the CF sample and GF sample for 4,000 m is shown in Fig. 6b. It is seen that the steel ball wears much more in the case of the CF sample. This means that the CF sample is more abrasive than the GF sample. Although it has been reported that in polymer composites glass fibers are more abrasive than carbon fibers [19–21], it is not the case in the PTFE-epoxy system.

As to the sample filled with surface-oxidized carbon fibers, it is seen in Fig. 6a that it has a slightly lower CoF after 4,000 m than that with untreated carbon fibers. It causes less abrasive wear on the steel ball surface than that filled with untreated carbon fibers, but still much higher than that filled with glass fibers. After 4,000 m

sliding, the wear rate of the composite is about $5.7 \times 10^{-16} \text{ m}^3/\text{Nm}$, while that of the composite with untreated carbon fibers is around $9.6 \times 10^{-16} \text{ m}^3/\text{Nm}$. There is hardly any wear debris on the edge of the wear track of the composite, while in the case of the composite filled with untreated carbon fibers there is lots of wear debris. The wear debris contains quite a lot of debonded carbon fibers and glass particles.

DISCUSSION

Since it is generally believed that glass fibers are more abrasive than carbon fibers [19–21], the contradictory result observed in this work needs an explanation. Looking at the wear tracks of the composites (in Fig. 5), it is observed that the milled carbon fibers are bright and obvious on the worn surface, whilst the milled glass fibers are dull and much less obvious. On the polished surface and the wear track of the composite filled with surface-oxidized carbon fibers, we also see bright carbon fibers (not shown here), due to their intrinsic bulk property. A very bright area of a glass fiber which represents its original brightness is shown in the rectangle in Fig. 5b. It is observed with optical microscopy that the original glass fibers are brighter than the original carbon fibers. In the as-polished composite surface, the carbon fibers are brighter than the glass fibers, as well as in the composite surface after 50 m sliding and after 1,500 m sliding. Glass fibers lose their brightness in the composites because they are covered by a polymer layer, which is probably the reason for its lower abrasiveness than carbon fibers. To check the coverage of polymers on the fibers, EDS analysis is performed on the fibers. The results are listed in Table 3. It is seen that on the glass fibers in the composite, there is a trace of F content and a much higher C content than on the original glass fibers. Scanning on the carbon fibers in the composite, there is also a slight trace of F content but a lower O content than on the original carbon fibers. The O content is much higher on the epoxy matrix than that on carbon fibers, while the C content is much higher on the epoxy matrix than that on glass fibers. Hence, the higher C content on glass fibers in the composite is due to the existence of an epoxy layer, while the lower O content on the carbon fibers in the composite indicates the absence of an epoxy layer (or having very little). It is concluded that the glass fibers are covered with an epoxy/PTFE layer, while there is no evidence of epoxy covering on the carbon fibers in the wear track of the composite, but only a little PTFE. It is anticipated that a higher coverage of an epoxy/PTFE layer on glass fibers results in less steel-fiber contact and thus less scratches and abrasive wear on the steel surface than that of the carbon fibers.

Regarding the size dependence of glass spheres, larger glass spheres have larger flat surface on the as-polished composite surface. During sliding, the possibility of all the flat areas on the large glass spheres being covered

FIG. 5. Light micrographs of the wear tracks of (a) the CF sample and (b) the GF sample, after sliding against the steel ball for 1,500 m, under 20 N load and 20 mm/s speed. [Color figure can be viewed at wileyonlinelibrary.com]

with sufficient epoxy/PTFE layer is much smaller than in the case of small glass spheres. This may lead to a higher abrasiveness of the composite filled with larger glass spheres. On the other hand, a few large glass spheres on the composite surface make the contact with steel ball less conformal, due to the large flat area of a single large glass sphere. Assuming a close-to-point contact between the flat glass and the spherical steel, this gives rise to a reduction of whole contact area between glass and steel and an increase of the average contact stress between glass and steel as a result. The increase of the average contact stress will lead to a thinner epoxy/PTFE layer on the glass surface and thus to an increase of abrasiveness. Less epoxy/PTFE on large glass spheres is consistent with the observation in Fig. 7. A shining large glass sphere in Fig. 7a and a little shining spot on a medium-size glass sphere on the top-right corner of the Fig. 7b are observed, which are not seen on the worn surface of the S sample (Fig. 7c).

As to the glass fibers, it is found in Fig. 8 that some glass fibers are broken into two parts in the GF and Long-GF sample after sliding tests, which is not easily seen in the Short-GF sample. We can see in Fig. 2 that almost all fibers are shorter than 200 μm in the Short-GF sample, while there are quite a few fibers longer than 400

FIG. 6. (a) CoF results of the CF and the GF sample sliding against the steel ball for 4,000 m, at 20 N load, 20 mm/s speed. (b) Middle-line profiles of wear scars of the steel balls when sliding against the CF and the GF epoxy composites, at 20 N load and 20 mm/s speed for 4,000 m. The black lines in (b) indicate the profiles of the original surfaces. [Color figure can be viewed at wileyonlinelibrary.com]

μm in the GF and especially in the Long-GF sample. It is anticipated that longer glass fibers are easier to be fractured during sliding, especially those with a part of fiber protruding onto the surface. The fracturing of glass fibers will introduce exposed sharp edges and broken glass pieces on the wear track of the composites and thus more abrasive wear on steel.

TABLE 3. The elemental composition from EDS analysis (5 kV) on the original fibers, fibers embedded in PTFE-epoxy composites, as well as the epoxy resin matrix. (Al at.% in glass fibers is not presented here).

Sample	C (at.%)	O (at.%)	F (at.%)	Si (at.%)
original glass fibers	10.4	39.5	—	37.6
glass fibers in composite	16.6	39.4	1.1	32.4
original carbon fibers	95.1	4.9	—	—
carbon fibers in composite	95.8	3.6	0.6	—
Epoxy resin	83.3	16.7	—	—

FIG. 7. Light micrographs of (a) the L sample, (b) the M sample and (c) the S sample, after sliding against the steel ball for 1,500 m, at 20 N load, 20 mm/s speed.

Reinforcing Effect of Fillers

Effect of the Particle Concentration. Figure 9a shows that the mechanical properties of the composites are closely related to the concentration of the glass spheres. As the concentration increases, both the compressive modulus and the compressive strength of the composites increase. It is due to the fact that more reinforcing fillers in the composite can transfer stress and stop/deviate cracks more efficiently. It should be noted that a concentration of reinforcing fillers higher than 50 wt% is not suitable for self-lubricating composites, because not only the abrasive-

ness is too high but also the mechanical properties could be weakened if the vol% of matrix is too low [24, 25].

Effect of the Particle Size. As shown in Table 4, it seems that the particle size in the range of 8–80 μm has little effect on the mechanical properties of the composites. A similar result in a glass particle/epoxy system was reported by Spanoudakis et al. [26]. The size dependence will be visible if the size of fillers goes to the nm scale, because their high surface area-to-volume ratio will have a high stress-transfer efficiency and consequently a high reinforcing effect. It is seen in Fig. 9a that the 1 wt% nano-SiO_x filled composite yields clearly better mechanical properties than the HG sample without the nanofiller.

Effect of the Glass Fiber Length. As presented in Fig. 9b, the samples reinforced with longer glass fibers show a higher compressive modulus. Cox already stated that the applied load is transferred from matrix to the fibers through interfacial shear stress, with maximum at the fiber ends and zero in the middle [27]. Therefore, the tensile stress is zero at the ends and maximum in the middle, meaning the maximum tensile stress the fiber could carry is related to the fiber length. As regarding the compressive strength, the

FIG. 8. (a,b) SEM micrographs showing two representative cases of fractured glass fibers in the GF sample and the Long-GF sample, after sliding against the steel ball for 1,500 m, at 20 N load, 20 mm/s speed.

FIG. 9. Measured compressive strength and compressive modulus of (a) 25 wt%, 37.5 wt% (HG), and 50 wt% partly hollow glass spheres reinforced epoxy composites, as well as the 1 wt% nano-SiO_x epoxy composites (two blue scattered dots); (b) glass fibers reinforced epoxy composites with different average fiber length, as well as the CF sample (two blue scattered dots). [Color figure can be viewed at wileyonlinelibrary.com]

compressive strength of the GF sample and Long-GF sample are similar, and higher than that of the Short-GF sample. The result indicates that longer glass fibers have a better reinforcement effect than the shorter ones.

Milled Carbon Fibers. In this study, the compressive modulus and compressive strength of the CF sample are higher than the GF sample, as shown in Fig. 9b. This is attributed to a higher modulus and strength of carbon fibers than glass fibers [28, 29]. The composite filled with surface-oxidized carbon fibers yields the highest compressive modulus and compressive strength in this study (shown in Table 4). The better adhesion between the surface-oxidized fibers and the epoxy could transfer the shear stress better and lead to a lower possibility of debonding of carbon fibers than in the case of untreated carbon fibers, which is responsible for its higher compressive properties than the CF sample. This result could at least partly explain the previous finding that much less wear debris is found in the sample filled with surface-oxidized carbon fibers than that with untreated carbon fibers. Hence, it gives rise to a more stable sliding condition, a lower CoF and less abrasive wear on the steel ball surface.

TABLE 4. Compressive modulus and strength of various epoxy composites.

Sample	Compressive modulus (GPa)	Compressive strength (MPa)
HG	3.43 ± 0.22	75.7 ± 1.0
S	3.62 ± 0.07	78.6 ± 0.6
M	3.58 ± 0.12	74.3 ± 5.1
L	3.61 ± 0.28	74.5 ± 1.3
CF	4.24 ± 0.05	89.4 ± 0.7
Oxidized-CF	4.31 ± 0.18	93.3 ± 0.8
GF	3.56 ± 0.22	80.6 ± 0.8
Short-GF	3.47 ± 0.10	77.2 ± 2.4
Long-GF	3.64 ± 0.23	80.1 ± 0.7

Although carbon fibers give rise to excellent compressive properties, a drawback of the carbon fibers in the epoxy composites is the fairly high abrasiveness to the counterpart steel ball. Therefore, carbon fibers could be a perfect filler for the mechanical purpose, but not necessarily a good filler for self-lubricating epoxy composites. A harder counterpart than the 100Cr6 steel may be required to achieve a stable sliding system in the case of milled carbon fibers being used in self-lubricating epoxy composites.

CONCLUSIONS

By studying the CoF, light images, confocal, and EDS results of worn surfaces of the glass particles and glass/carbon fibers filled epoxy composites and the 100Cr6 steel balls, it is revealed that the size and surface adhesion property of the fillers both affect the abrasiveness of the PTFE-epoxy composites. The following conclusions are drawn:

1. Epoxy composites with large glass spheres give rise to a higher abrasive wear on the steel ball, while the difference is not significant when the average diameter is below 50 μm. The abrasiveness of the glass spheres in the epoxy composites follows the order of L (79 μm) > M (50 μm) ≈ S (27 μm).
2. The abrasiveness of the milled glass fibers filled composites increases with the average length of the glass fibers. The milled carbon fiber reinforced sample is more abrasive than the milled glass fiber reinforced sample with a similar fiber length, due to less adhesion of polymer layers on carbon fibers.
3. The mechanical properties enhance with an increasing amount of glass fillers. Longer glass fibers are beneficial to yield better mechanical properties of the composites. The composite filled with milled carbon fibers, especially surface-oxidized ones, yields much better mechanical properties than the glass fiber reinforced composite.
4. To achieve a low wear rate of the steel ball counterpart as well as the composite, it is suggested to fill it with 25 wt%–37.5 wt% solid glass spheres of average size smaller than 40 μm, and with 1 wt% nano-SiO_x filler.

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APPENDIX A

FIG. A1. Measured size distribution of the diameter of (a) hollow glass spheres, (b) S, (c) M, and (d) L solid glass spheres. The average diameter is indicated in the legend. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. A2. Measured length distribution of (a) carbon fibers, (b) short glass fibers (c) glass fibers, and (d) long glass fibers. The average length is indicated in the legend. [Color figure can be viewed at wileyonlinelibrary.com]

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