Self-lubricating polymer composites
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This chapter addresses the question what the influence will be of size and shape of glass particles and fiber fillers on the abrasive wear resistance of polytetrafluoroethylene (PTFE)/epoxy composites sliding against steel balls. It turns out that a size effect 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 (submicron) tend to be 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. Mechanical properties are enhanced with an increasing amount of glass fillers adding of a small concentration of nano-fillers.
5.1 Introduction

In the past a vast amount of research was focused on lowering the friction and improving the wear resistance and the mechanical property of the self-lubricating composites, which mainly cover the influence of lubricants [1, 2, 3], polymer matrix [4, 5, 6], fillers and nano-particles [7, 8, 9, 10, 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 friction force and abrasive wear [12, 13]. Reinforcers 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 of the fillers is necessary for improving the materials design of self-lubricating composites. Given that both the size and geometry of the abrasive particles could affect their abrasiveness [14, 15, 16, 17], different glass fillers embedded in composites could also lead to different abrasiveness of the composites. Glass fibers are more abrasive than carbon fibers [18, 19, 20], which is attributed to a higher hardness of glass fibers. As regards a long-term stable sliding condition, it is relevant to examine the abrasiveness of the glass particles filled composites and milled glass/carbon fibers filled composites.

Nano-particles filled composites had shown advantages over micro-particles filled composites in enhancing the mechanical and tribological properties. An evident increase of tensile (and flexural) modulus and strength and impact strength of epoxy composites by adding few percent nano-fillers have been reported [21, 22]. Regarding the tribological performance, McCook and Sawyer et al. have found that by adding 1 vol.% ZnO into PTFE/epoxy composites, the wear rate was reduced by about 50%, while more than 3.5 vol.% ZnO yielded a higher wear rate. Moreover, adding few percent of nano-Si$_3$N$_4$, nano-Al$_2$O$_3$ or nano-TiO$_2$ particles could also reduce the wear rate of epoxy composites [22, 23, 24].

This work aims at evaluating the abrasiveness and reinforcing effect of some common fillers: glass spheres, milled glass fibers and milled carbon fibers, as well as some nano particles. 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 counterparts, when a sufficient lubrication is guaranteed.
5.2 Experimental

Materials

Epoxy XB 6078 powder, supplied by Huntsmans, is a one-component solid epoxy system. It can be cured by heating up to around 110-130 °C in several minutes. A fast-curing solid epoxy powder is used as the matrix, which is designed to avoid the settling of large glass particles (> 70 µm) into the bottom side of the curing sample in conventional liquid epoxy system. The settling of large glass particles was observed in a Specifix-20 epoxy system (initial viscosity ≈ 190 mPa-s) and even in an Epoxydharz C epoxy system (initial viscosity ≈ 3200 mPa-s) by the authors. For readers who are interested in the settling speed of spherical particles in a liquid, it can be estimated by Stokes’ law [25], see also Appendix 4.

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

The solid glass spheres are sieved through 100 µm, 71 µm and 40 µm sieves. The size grades obtained are less than 40 µm (S), 40-71 µm (M) and 71-100 µm (L). The measured size distribution of hollow glass spheres and solid glass spheres of three grades are presented in Fig. A.5 (in appendix). The average diameters of the three-grade solid glass spheres are 27.1 µm (S), 49.9 µm (M) and 79.0 µm (L), respectively.

Milled glass fibers (GF) have an average diameter of about 12.3 µm (from: carbonwinkel.nl). As shown in Table 5.1 and Fig. A.6 (in appendix), milled glass fibers with three different average length are named as: Short-GF, GF (medium), and Long-GF. Milled carbon fibers (CF) have an average diameter around 7.0 µm (from: easycomposite.co.uk). Silicon oxide (SiOx) nano-particles have an average size of 15-20 nm (from: us-nano.com).

Sample preparation

After weighing, the epoxy and the PTFE powder together with 6.5 g water was ball milled (10 ø6 mm 100Cr6 steel balls) at 450 rpm for 7 min using a planetary mill (Fritsch Pulverisette). Then, the hollow glass spheres were added in and milled for another 2 min. Afterwards, the glass spheres, irregular glass particles or short carbon fibers were added in and milled...
for only 45 seconds. The mixture was dried in a furnace at 40°C overnight. The dried powder was then gently ground and transferred to a curing mold. According to SEM observations, the glass particles or short carbon or glass fibers in the ground powder were not evidently fractured. The powder was cured at 8 bar pressure for 10 minutes in a curing mold which was placed in a hot press (Schwabenthan Polystat 100T). The curing temperature of the bottom heating plate and the top heating plate are 112°C and 245°C, respectively, due to that the distance of curing composites is 56 mm to the top plate and 20 mm to the bottom plate to enable de-molding process. After cooling down with compressed air and de-molding, the composite disks (around ø30 mm × 7.5 mm) were polished until 4000 grade polishing paper. The compositions and the names of the composites are listed in Table 5.1.

**Table 5.1. The compositions of various composites and their abbreviations.**

<table>
<thead>
<tr>
<th>Compositions</th>
<th>Sample abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy (wt.%)</td>
<td>PTFE (wt.%)</td>
</tr>
<tr>
<td>47.5</td>
<td>15</td>
</tr>
<tr>
<td>47.5</td>
<td>15</td>
</tr>
<tr>
<td>47.5</td>
<td>15</td>
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<td>47.5</td>
<td>15</td>
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<tr>
<td>47.5</td>
<td>15</td>
</tr>
</tbody>
</table>

**Compression tests**

Each composite sample was cut and polished into three 7mm x 7mm x 14mm cuboids. All the cuboids were tested with a Kammrath & Weiss compression tester, with the compressive forces being exerted on the two far ends. During test, the compressive strain was linearly increased with time (21.7 µm/s) until the sample breaks. The stress and the strain was constantly recorded to obtain the compressive modulus, strength and elongation at break of the samples.

**Tribo-tests**

The friction behavior of the epoxy composites were studied using a CSM ball-on-disk rotational tribometer under dry sliding conditions. Ø13 mm 100Cr6 bearing steel balls (7.8 g/cm³ density) were used as the stationary counterparts balls. The surface roughness (Ra) values of the steel balls was
measured to be around 60 nm with confocal microscopy (60 µm cutoff, 705×728 µm image size). The sliding conditions were either 40 N normal load and 5 cm/s sliding speed, or 20 N normal load and 20 mm/s sliding speed due to the lower load bearing capacity of some samples. The sliding environment was 35 ± 2% relative humidity and room temperature (22 ± 2°C). The relative humidity was adjusted with feedback controlled flux of dry air or water vapor into the testing chamber.

**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 uses a Matlab code with a margin of error of ±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 about 465×350 µm².

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fe content (wt.%)</th>
<th>CoF</th>
<th>Average wear rate (×10⁻¹⁶ m³/Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG</td>
<td>N.D.</td>
<td>0.108</td>
<td>6.1</td>
</tr>
<tr>
<td>S</td>
<td>N.D.</td>
<td>0.114</td>
<td>7.7</td>
</tr>
<tr>
<td>M</td>
<td>N.D.</td>
<td>0.110</td>
<td>8.1</td>
</tr>
<tr>
<td>L</td>
<td>0.57±0.17</td>
<td>0.112</td>
<td>9.2</td>
</tr>
<tr>
<td>CF</td>
<td>weak peak</td>
<td>0.107</td>
<td>8.3</td>
</tr>
<tr>
<td>GF</td>
<td>weak peak</td>
<td>0.109</td>
<td>11.2</td>
</tr>
<tr>
<td>Short-GF</td>
<td>N.D.</td>
<td>0.099</td>
<td>10.5</td>
</tr>
<tr>
<td>Long-GF</td>
<td>0.59±0.15</td>
<td>0.105</td>
<td>10.9</td>
</tr>
</tbody>
</table>

**5.3 Results and discussion**

**5.3.1 Abrasiveness of the fillers**

It should be briefly mentioned that, as expected, the abrasiveness of the composites is found to increase with an increasing concentration of glass spheres in the composites. A higher CoF and a more scratched surface of
5.3.1.1 Effect of the particle size

The size of the glass spheres could influence the abrasiveness of the composites. The CoF results of the epoxy composites with 10 wt.% of various sizes of glass spheres are presented in Table 5.2, 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 5.2 show the amount of back transferred Fe onto the worn composite surfaces after sliding for 1500 m. A detectable amount of back transferred Fe is only found on the worn L sample surface.

![Fig. 5.1](image)

*Fig. 5.1* 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 1500 m sliding distance. The arrow indicates the relative sliding direction of the sliding counterpart (same in the following figures).
Fig. 5.1 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. 5.2, method see in Chapter 4, Fig. 4.8). 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 the in the 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 ≈ S.

![Fig. 5.2](image)

**Fig. 5.2** The middle-line profiles (as indicated by the red line in Chapter 4 Fig. 4.8a) 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 1500 m. The black line (higher than the other line in each panel) indicate the profile of the original surface.
5.3.1.2 Effect of glass fiber length

The effect of the length of milled glass fibers on the abrasiveness of the glass fibers reinforced composites is also a relevant issue. In 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. 5.2. Light images of wear scars of the steel ball after sliding against glass fibers reinforced composites are shown in Fig. 5.3. 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. 5.4 and EDS results listed in Table. 5.2 confirm that the Long-GF sample is the most abrasive one whereas the Short-GF sample is the least.

![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 1500 m sliding distance.](image-url)
5.3.1.3 Milled carbon fibers

Sliding under 20 N load and 20 mm/s speed for 1500 m, light images in Fig. 5.1 shows that there are much more abrasive scratches on the steel wear scar when sliding against the CF sample than that in the case of sliding against the GF and M 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. 5.2, the detected amount of back transferred Fe on the CF sample surface is similar to the GF sample after 1500 m sliding. Confocal images of the steel wear scars confirm (shown in Fig. 5.2 & Fig. 5.4) 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 4000 m, it is found that the CoF of the CF sample has a significant increase after about 2000 m, reaching about 0.16 at 4000 m, while the CoF of the GF sample remains

Fig. 5.4 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 1500 m. The black lines indicate the profiles of the original surfaces.
fairly stable and low in the 4000 m sliding (in Fig. 5.5a). The wear-scar profiles of the steel ball after sliding against the CF sample and GF sample for 4000 m is shown in Fig. 5.5b. 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 [18, 19, 20], it is not the case in the PTFE-epoxy system.

**Fig. 5.5** (a) CoF results of the CF and the GF sample sliding against the steel ball for 4000 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 4000 m. The black lines in (b) indicate the profiles of the original surfaces.

**Fig. 5.6** Light micrographs of the wear tracks of (a) the CF sample and (b) the GF sample, after sliding against the steel ball for 1500 m, under 20 N load and 20 mm/s speed.
Discussion
Since it is generally believed that glass fibers are more abrasive than carbon fibers [18, 19, 20], the contradictory result observed in this work needs an explanation. Looking at the wear tracks of the composites (in Fig. 5.6), 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. A very bright area of a glass fiber which represents its original brightness is shown in the rectangle in Fig. 5.6b. It is observed with light 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 1500 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 5.3. 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-

Table 5.3. 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.)

<table>
<thead>
<tr>
<th>Sample</th>
<th>C (at.%)</th>
<th>O (at.%)</th>
<th>F (at.%)</th>
<th>Si (at.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>original glass fibers</td>
<td>10.4</td>
<td>39.5</td>
<td>-</td>
<td>37.6</td>
</tr>
<tr>
<td>glass fibers in composite</td>
<td>16.6</td>
<td>39.4</td>
<td>1.1</td>
<td>32.4</td>
</tr>
<tr>
<td>original carbon fibers</td>
<td>95.1</td>
<td>4.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>carbon fibers in composite</td>
<td>95.8</td>
<td>3.6</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>83.3</td>
<td>16.7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
fiber contact and thus less scratches and abrasive wear on the steel surface than that of the carbon fibers.

A similar reason could be responsible for the size effect 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 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 inconsistent with the observation in Fig. 5.7. A shinning large glass sphere in Fig. 5.7a and a little shinning spot on a medium-size glass sphere on the top-right corner of the Fig. 5.7b are observed, which are not seen on the worn surface of the S sample (Fig. 5.7c).

As to the glass fibers, it is found in Fig. 5.8 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. A.6 that almost all fibers are shorter than 200 µm in the Short-GF sample, while there are quite a few fibers longer than 400 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.

![Fig. 5.8](image)

**Fig. 5.8** (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 1500 m, at 20 N load, 20 mm/s speed.

### 5.3.2 Reinforcing effect

#### 5.3.2.1 Effect of the particle concentration

Fig. 5.9a 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 increases. 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 abrasiveness is too high but also the mechanical properties could be weakened if the vol.% of matrix is too low [26, 27].

![Graph](image1.png)

**Fig. 5.9** 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).

5.3.2.2 Effect of the particle size
As shown in Table 5.4, it seems that the particle size in the range of 8 to 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. [28]. The size effect 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. 5.9a that the 1 wt.% nano-SiO$_x$ filled composite yields clearly better mechanical properties than the HG sample without the nano-filler.

5.3.2.3 Effect of the glass fiber length
As presented in Fig. 5.9b, 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 [29]. 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 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.

Table 5.4. Compressive modulus and strength of various epoxy composites.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Compressive modulus (GPa)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG</td>
<td>3.43±0.22</td>
<td>75.7±1.0</td>
</tr>
<tr>
<td>S</td>
<td>3.62±0.07</td>
<td>78.6±0.6</td>
</tr>
<tr>
<td>M</td>
<td>3.58±0.12</td>
<td>74.3±5.1</td>
</tr>
<tr>
<td>L</td>
<td>3.61±0.28</td>
<td>74.5±1.3</td>
</tr>
<tr>
<td>CF</td>
<td>4.24±0.05</td>
<td>89.4±0.7</td>
</tr>
<tr>
<td>GF</td>
<td>3.56±0.22</td>
<td>80.6±0.8</td>
</tr>
<tr>
<td>Short-GF</td>
<td>3.47±0.10</td>
<td>77.2±2.4</td>
</tr>
<tr>
<td>Long-GF</td>
<td>3.64±0.23</td>
<td>80.1±0.7</td>
</tr>
</tbody>
</table>

5.3.2.4 Milled carbon fibers
In this study, the highest compressive modulus and compressive strength are found in the CF sample, much higher than the GF sample, as shown in Fig. 5.9b. This is attributed to a higher modulus and strength of carbon fibers than glass fibers [30]. However, a drawback of the milled carbon fibers in the epoxy composites is the fairly high abrasiveness to the counterpart steel ball. Therefore, milled 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.

5.3.3 Nano-composites
As shown in Fig. 5.9a, the 1 wt.% nano-SiO$_x$ filled composite yields evidently better mechanical properties than the HG sample without the nano-filler. The abrasiveness of this sample is similar to the HG sample, because there is also hardly any scratch on the wear scar of the steel ball (light image is not shown here). This offers a way to further improve the mechanical properties of the epoxy composites without causing an evident wear on the counterpart steel ball.

The frictional and wear performance of 1 wt.% nano-fillers reinforced Epoxy 6078 composites is shown in Fig. 5.10. It is seen that the wear rates of all the nano-composites are evidently less than that of the HG composite without nano-fillers. The CoF values of all the samples are fairly close. Hence, it is concluded that the addition of 1 wt.% nano-fillers could
improve the mechanical and tribological performance of the epoxy composites. There is no clear increase of abrasiveness of the composites with the addition of 1 wt.% nano-fillers.

![Graph showing wear rate and CoF for different nano-composites and HG sample.](image)

**Fig. 5.10** The average CoFs and wear rates of the nano-composites as well as the HG sample, sliding against the steel ball under 40 N load, 5 cm/s speed for 1000 m.

The effect of concentrations of nano-fillers is also investigated on the Epoxy 25036 composites. It is found that as the concentration of nano-fillers increases, the hardness of the composites increases, as shown in Fig. 5.11. While the wear rate of the composites decreases with increasing nano-TiC content, the wear rate of the composites shows an increase as the nano-Al₂O₃ increases from 3 wt.% to 5 wt.% The difference may lie in a difference degree of agglomeration of nano-fillers. It was reported that the tensile strength and tensile modulus of polypropylene composites were enhanced by adding nano-Al₂O₃ up to 4 wt.%, while they were reduced as the content of nano-Al₂O₃ increased from 4 wt.% to 5 wt.% [31]. It is possible that the density of TiC is higher than Al₂O₃, meaning less volume of nano-TiC in the composite, which could lead to less tendency of agglomeration of the 5 wt.% nano-TiC sample. Regarding the frictional performance, the CoF only slightly increase as the concentration of nano-fillers rises (shown in Fig. A5 in Appendix 2). There is no sign of an evident increasing of abrasive wear on the steel ball surface with an increasing content of nano-fillers up to 5 wt.%. Considering the high cost of nano-fillers, it is therefore recommended not to add more than 5 wt.%
nano-fillers in the epoxy composites. After all, the reduction of wear rate from 1 wt.% to 5 wt.% nano-fillers is not significant.

![Graph](image.png)

**Fig. 5.11** (a) Average hardness (12 measurements) and (b) wear rates of the nano-composites as well as the HG sample, sliding against the steel ball under 60 N load, 5 cm/s speed for 1000 m.

### 5.4 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 a larger size of glass spheres give rise to a higher abrasive wear on the steel ball, while the difference is not significant when the average size 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.

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. Although the milled carbon fiber reinforced sample causes abrasive wear on the steel ball surface, its mechanical properties are much better than the glass fiber reinforced composites.
4. Adding 1 wt.% nano-fillers offer further improvement of the tribological and mechanical performance of the composites. Adding more than 3 wt.% nano-fillers does not necessarily yield a better performance.

5. 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 few wt.% nano-fillers.

References


