DEGRADATION OF CARBON FIBER REINFORCED EPOXY COMPOSITES UNDER SLIDING IN AMBIENT AIR

H. Dhieb[1], J.G. Buijnsters[1], J.P. Celis[1]

[1] Katholieke Universiteit Leuven, Dept. MTM, Kasteelpark Arenberg 44, B3001 Leuven, Belgium

Abstract For many technical applications friction and wear are critical issues. Polymer composites reinforced by different components are currently widely used in various automotive and aerospace applications as well as structural engineering. However, the degradation of such composite materials in fretting contacts leads to change and loss of the material in use and the contact behaviour of these materials depend on the counter body, reinforcements, and operation time. In this paper, the wear and coefficient of friction of bulk epoxy and carbon fiber reinforced epoxy composite have been investigated under reciprocating sliding against alumina and stainless steel balls in ambient air. The effect of sliding direction with respect to the long and unidirectional carbon fibers has been studied. The coefficient of friction measured for the bulk epoxy against stainless steel and alumina is around 0.65, whereas the values measured for the epoxy reinforced with carbon fibers are significantly lower. It was found that sliding with stainless steel in a direction parallel to the fiber orientation results in a lower coefficient of friction than under sliding in anti parallel direction. The reduced wear volume of the composite is largely influenced by the carbon fiber reinforcement due the auto-protecting film formed on the contact area.

Keywords Carbon fiber reinforced epoxy composite, reciprocating sliding, friction and wear, material degradation

1 INTRODUCTION

Carbon fibre reinforced thermoset polymers are composite materials that are usually not applied for tribological purposes, although they have inherent great potential. When using such composites (e.g., in sports equipment, automotive, marine, and aerospace applications) one should bear in mind the sliding contact zone. Tribological properties of such materials in reciprocating contacts depend definitely on the properties of both matrix and reinforcement elements, and their interface. Research is thus needed to understand the degradation of the surface and subsurface of such materials. In that respect, tribochemical reactions and cracking occurring at the surface may be of large importance besides other mechanisms. Many researches have been done under sliding movement using the pin-on-disc system [1-5] as well as ring-on-block [6-8], ring-on-ring [9], disk-on-disk [10], wheel abrasion [11], face-contact-sliding [12], twin disc rings [13] and ball-on-prism [14] configurations to investigate the friction and wear behaviour and mechanisms like surface fatigue and abrasion of such kind of materials. As we mentioned before, the application fields of composite materials imply that contact vibrations can be the origin of material degradation. Up to now, research studies on the reciprocating movement of composites against different counter bodies have not been reported at all. In the multiple studies involving sliding movements, various reinforcements [15] and matrixes were investigated, such as short carbon fibres [4], glass fibres [2], graphite fillers [5], or a mix of different reinforcements [16]. The PEEK thermoplastic polymer is extensively used as a matrix, whereas the epoxy thermoset polymer is less well investigated. It is generally recognized that the most common types of wear of polymers are abrasion, adhesion and fatigue [17]. The carbon fibres increase the compressive strength and the creep resistance of the polymer matrix. It has been shown that the effect of fiber orientation is strongly dependent on the nominal contact pressure. It is evident that the abrasive wear behaviour of composites and specifically carbon fibre reinforced epoxy is complex and it is widely recognised that it needs more systematic investigation.

In this study, the friction and wear under reciprocating fretting contacts [18] were investigated. The wear tests were performed on a fretting/reciprocating sliding machine and the wear tracks on the samples and ball counter bodies were examined in detail. SEM and profilometry were employed to characterise the materials degradation. Our results provide valuable information of the evolution of the wear and the effect of fretting direction, and they help to understand the tribological behaviour of carbon fibre reinforced epoxy in contact with stainless steel and alumina counter bodies.

2 EXPERIMENTAL

The materials used in this study are bulk epoxy and carbon fiber reinforced epoxy. For the production of the bulk epoxy we have used standard DGEBA (Epikote 828) and Aradur 3486 (aliphatic polyamine) as a hardener (ratio epikote/hardener 100/30). For the carbon fiber reinforced samples, the resin was mixed, poured in a mould and cured at room temperature followed by an oven treatment. The cycle to cure those samples was 24 hrs at room temperature plus 8 hrs at 80°C. The reinforced epoxy sample contains 8 layers of unidirectional carbon fibre mixed with the epoxy to obtain 1 mm of thickness. The stack of pre-impregnated fibers is placed on a PTFE sheet on an aluminium base plate. It is covered with another PTFE layer and a 10-mm thick aluminium plate is put on top. The assembly is covered with bleeder fabric and a vacuum bag. Vacuum is applied through a tube that is incorporated in the sealing of the bag. A vacuum of 0.095 MPa is then applied for 15 min at room temperature to debulk. Following, the assembly is placed in an oven (while maintaining the vacuum) and heated to 90°C for 60 min and finally heated to 130°C for 90 min. After that, the assembly is taken out of the oven and the vacuum is released (Figure 1). The carbon fibre mixed with the epoxy is STS - 24K having the following specific properties: 24,000 filaments, 4,000 MPa tensile strength, 240 GPa tensile modulus, 1.7% elongation, 7-μm diameter, and 1.75 g /cm^3 density. All the specimens were cut into the same dimension (20 x 20 mm^2) for testing.

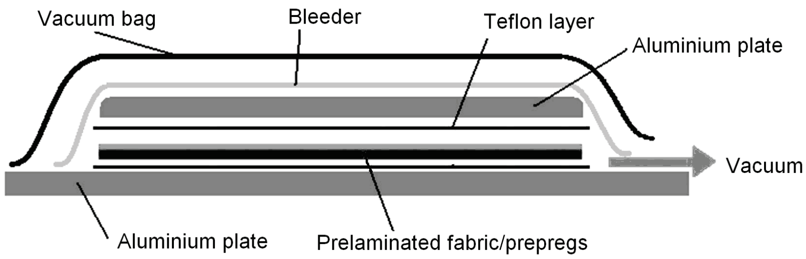

Figure 1. Carbon fibre reinforced epoxy's production set-up

Reciprocating tests were performed to investigate the coefficient of friction, the wear track and the wear volume lost. Stainless steel (AISI 316) and alumina balls, both with a diameter of 10 mm, were used as the counter body. All materials were degreased and cleaned prior to the fretting tests using acetone and ethanol. The reciprocating tests were carried out under ambient air conditions (temperature: 22 ºC, relative humidity: 50%) and the total number of cycles varied from 10,000 to 200,000. A normal load of 9 N, a frequency of 3 Hz, and a displacement distance of 600 μm were used for all tests. More details on the laboratory simulation of fretting and the applied test set-up can be found elsewhere [18]. Reciprocating sliding was analysed under dry condition through examining the wear tracks of the samples with scanning electron microscopy and a white light interferometer.

3 RESULTS AND DISCUSSION

SEM images of the worn bulk epoxy surfaces after 40,000 and 100,000 sliding cycles of sliding against the stainless steel ball are displayed in Figure 2. The relative directions of the sliding are indicated by the arrows in Figures 2a,b. The most damaged regions are situated near both edges of the wear tracks and they present many micro-cracks that appear perpendicular to the displacement (Figure 2d). These cracks are the result of the shear force during sliding. This fatigue wear causes micro-surface damage, which normally occurs at high temperatures. Another important aspect of the degradation process of the bulk epoxy material is the formation of debris in and around the wear tracks. Most of the debris is located outside the damaged area and, in particular, relatively large debris particles are observed at the very ends of the wear tracks. A specific form of debris or rollers is represented in Figure 2c. This form with different sizes is due to the rolling effect of the sample debris during sliding and probably consists of shear-deformed epoxy. It could reduce the shear stress, the coefficient of friction, and the contact temperature, which leads to a reduction of the damage. The formation of these rollers is considered an important process that plays a key role in enhancing the wear resistance. In general, the most recognized common types of wear of polymers are abrasion, adhesion, and fatigue [1].

SEM images of the wear tracks formed on the bulk epoxy after 40,000 and 100,000 sliding cycles against alumina balls are displayed in Figure 3. It is clear that the wear tracks differ from those produced with the stainless steel counter body (Figure 2). The material damage for the epoxy/alumina contact is significantly higher as can be concluded from the higher density of cracks and wear debris. In particular, the high number of rollers of accumulated epoxy in- and outside the wear track formed after 100,000 cycles (Figure 3b) is striking.

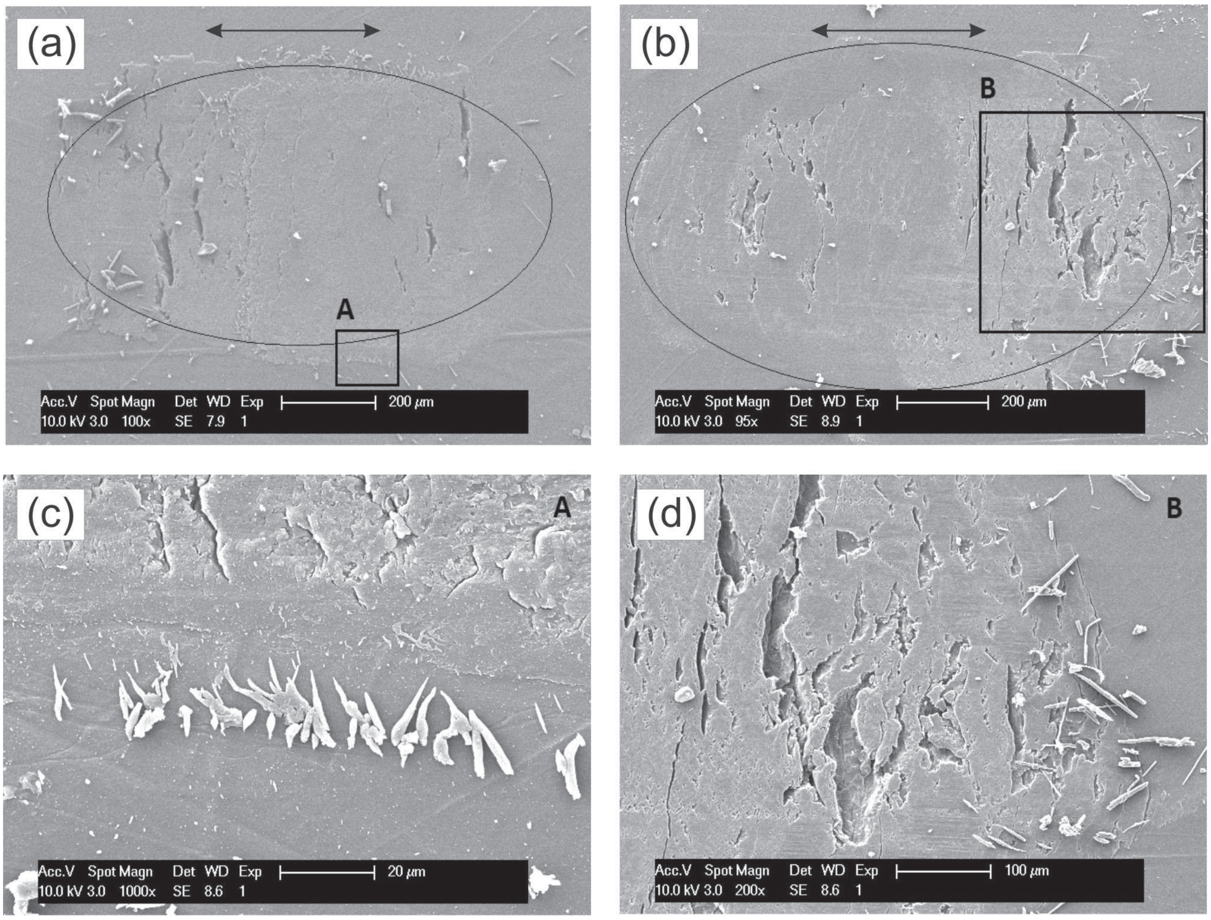

Figure 2. SEM images of the wear tracks of bulk epoxy sliding against stainless steel after (a) 40,000 cycles and (b) 100,000 cycles. (c) Zoom of debris outside the wear track (area A in Fig. 2a) and (d) zoom of cracks within the wear track (area B in Fig. 2b)

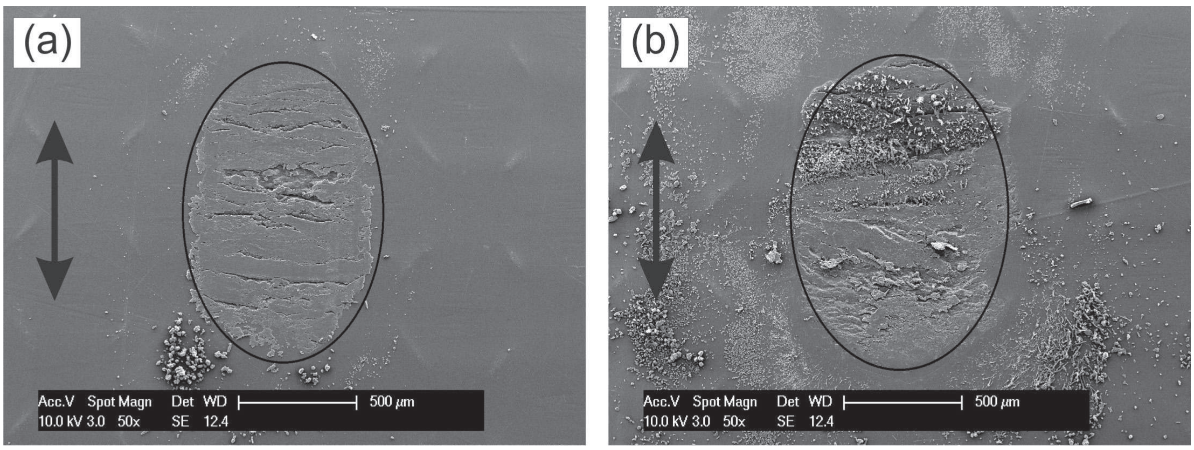

Figure 3. SEM images of the wear tracks of bulk epoxy against alumina after (a) 40,000 cycles and (b) 100,000 cycles

Figure 4 shows the wear tracks formed on the surfaces of the carbon fibre reinforced epoxy after 40,000 cycles against both the stainless steel and alumina counter faces. Tests have been worked out with a sliding direction parallel and anti-parallel to the orientation of the carbon fibre reinforcements (the latter orientation being indicated by the bundle of 4 parallel lines in Figure 4). Sliding against stainless steel (Figures 4a,b) results in a larger amount of wear debris (indicated by the black arrows) than for sliding against alumina (Figures 4c,d), irrespective of the sliding direction. Note that for the carbon fibre reinforced epoxy, the wear debris is mainly located at the circumference of the wear tracks, parallel to the direction of displacement. On the contrary, the wear debris is mostly located at the ends of the wear tracks for the bulk epoxy (Figures 2 and 3). The composite displays a higher wear resistance against stainless steel when the fibres are oriented parallel to the sliding direction. For all cases, the matrix has been affected within the wear track, since individual fibers are exposed and, therefore, the direct contact area is decreased. This could result in a higher contact pressure and increased surface stress, which might affect the microstructure of the composite surface at the sliding contact as well.

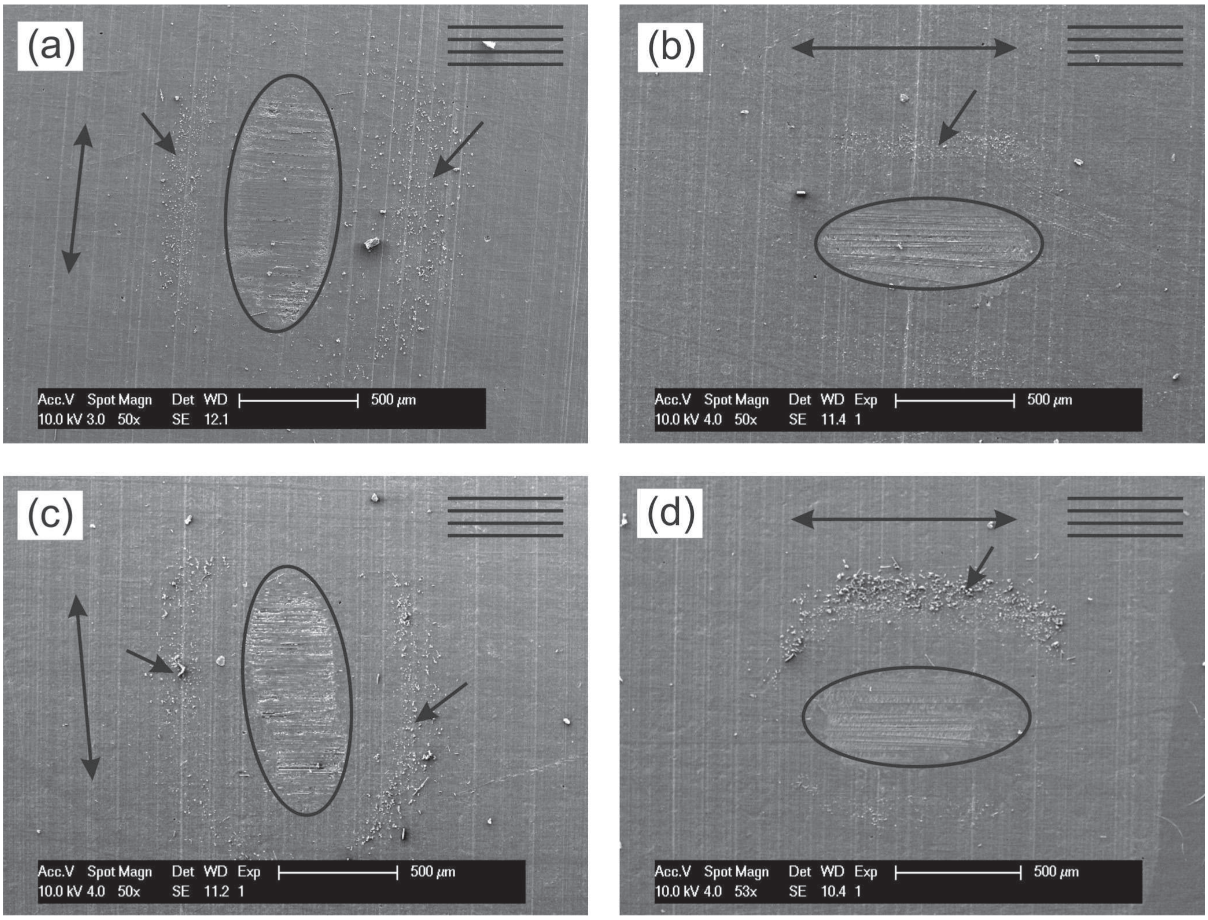

Figure 4. SEM images of the wear tracks of the carbon fibre reinforced epoxy after 40,000 cycles of reciprocated sliding against stainless steel with (a) anti-parallel and (b) parallel orientation, and alumina with (c) anti-parallel and (d) parallel orientation

The coefficient of friction for the different sliding contacts is presented in Figure 5. The coefficient of friction observed on the bulk epoxy is highest (0.65 $\pm$ 0.03) and is very similar and relatively constant throughout the whole reciprocating test of 10,000 cycles against either alumina or stainless steel. For the composite, the coefficient of friction strongly depends on the counter face material. It is high during the early stages of reciprocating sliding and reaches a value around 0.53 after about 500 to 1,000 cycles. On reciprocating sliding against alumina, the coefficient of friction is relatively high and it does not depend on the relative sliding direction. On the contrary, the relative sliding direction significantly affects the coefficient of friction recorded for sliding against the stainless steel counter face. It decreases to values as low as 0.25 after 10,000 sliding cycles with the sliding direction parallel to the orientation of the fibre reinforcements. In the case that the sliding is done anti-parallel to the fibre orientation, the coefficient of friction is somewhat higher. The coefficient of friction reaches lower steady-state values of 0.27 $\pm$ 0.05 and 0.11 $\pm$ 0.01 on sliding against stainless steel in the anti-parallel and parallel directions, respectively, after about 60,000 cycles (not shown). It is evident that the reciprocating sliding behaviour depends on the mechanical properties of, and possibly the tribochemical interaction with, the counter face material. Material originating from both the epoxy matrix and the fibre reinforcements might be transformed into a graphitic, low-friction tribolayer which will change the sliding contact behaviour. These kinds of lubricating surface layers are commonly observed for testing other soft and hard carbon-based materials, such as hydrogenated amorphous carbon [19]. In future work, micro-Raman spectroscopy and atomic force microscopy analysis will be employed to investigate the microstructural and topographical changes of the composite material at the sliding contacts as a function of test parameters and counter face material.

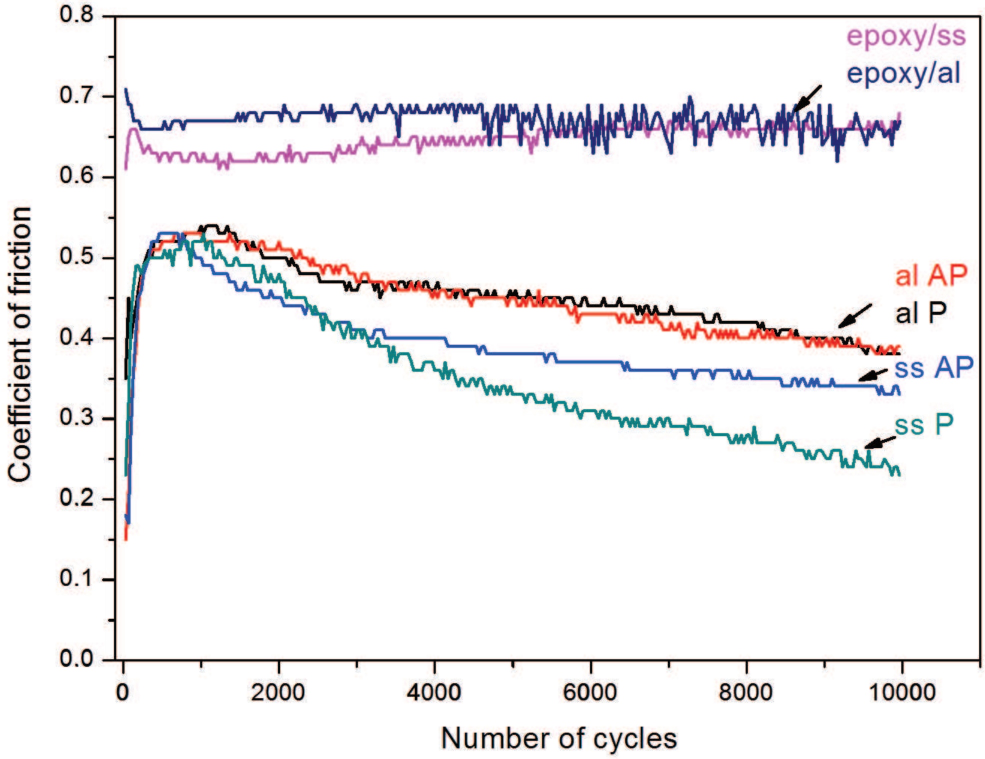

Figure 5. Representative evolution of the coefficients of friction recorded on bulk epoxy and carbon fibre reinforced epoxy sliding in parallel and anti parallel orientation against stainless steel and alumina counter bodies (al: alumina, ss: stainless steel, AP: anti parallel, P: parallel)

4 CONCLUSIONS

The results of this study on bulk epoxy and carbon fiber reinforced epoxy composite against alumina and stainless steel balls in a reciprocating mode revealed some interesting phenomena related to friction and wear.

1. The carbon fiber reinforcements improve the tribological properties of the thermoset epoxy by reducing the coefficient of friction, the wear volume lost, and the wear track damage and debris formation.
2. The wear track of the carbon fiber reinforcement epoxy is smoother than the wear track of the bulk epoxy due to the formation of an auto-protecting surface layer which changes the surface contact behaviour.
3. The choice of counter face material has no significant effect on the coefficient of friction (i.e., 0.65 ± 0.03) for bulk epoxy material.
4. The choice of counter face material has an important effect on the coefficient of friction for the carbon fiber reinforced epoxy composite. It is always lower on sliding against stainless steel.
5. When alumina is used as the counter face, the sliding direction with respect to the orientation of the carbon fibers has no effect on the coefficient of friction. For stainless steel, the steady-state value of the coefficient of friction in parallel sliding direction (0.11 ± 0.01) is lower than in the anti-parallel direction (0.27 ± 0.05).

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