On the Effect of Counterface Materials on Interface Temperature and Friction Coefficient of GFRE Composite Under Dry Sliding Contact

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Abstract: Nowadays, there is an increase interest in polymeric composite materials for high-performance in many industrial applications. In other words, the tribo-studies on polymeric materials are growing fast to enhance the polymeric products such as bearings, seals, ring and bushes. The current work presents an attempt to study the correlation between the type of counterface material and frictional heating at the interface surfaces for different, normal loads (23N, 49N and 72N), sliding velocities (0.18, 1.3 and 5.2 m s^{-1}) and interval time (0-720 sec). Sliding friction experiments are performed on a pin-on-ring (POR) tribometer under dry contact condition. Interface temperature and friction force were measured simultaneously during sliding of glass fiber reinforced epoxy (GFRE) composite against three different counter face materials, hardened steel (HS), cast iron (CI) and Aluminum alloy (Al). Experimental results showed that the type of counterface material greatly influences both interface temperature and friction coefficient. Higher temperature and friction coefficient were evident when sliding took place against HS surface, compared to sliding against CI and Al under same condition. When sliding took place against HS, the friction coefficient of GFRE composite was about an order of magnitude higher than sliding the GFRE composite against the other counter face materials. Based on the optical microscope graphs, the friction and induced temperature results of GFRE composite are analyzed and discussed.

Key words: GFRE, counterface materials, friction, temperature

INTRODUCTION

In recent years, there have been rapid growth in the developments and applications of glass fiber reinforced thermosetting polymer composites such as polyester and epoxy. This is due to the realization of their potential to combine high performance/cost ratios with rapid clean process ability and the attractions of their intrinsic recyclables. Fiber reinforced polymer matrix composites are finding ever-increasing usage for numerous industrial applications, such as bearings material, rollers, seals, gears, cams, wheels, clutches, etc. Therefore, the tribological behavior of these materials should be studied comprehensively. Other than, limited studies have been concentrated on the characteristics of friction and wear of these materials[1-6]. Although generated surface temperature is another equally important parameter in studying the tribological behavior of polymer composite[7,8], it is found that little attention has been paid to it.

Few methods of temperature measurements within a lubricated contact have been reviewed[9], but the present interest concerns the temperature within a dry contact. For dry sliding contact, some researchers have been attempted to measure the surface temperature and investigate its roles on the tribological behavior of polymer composite[7,9,10,11,2-16]. In measuring the surface temperature, they used an infrared fiber optic probe[10], an imbedded or natural thermocouple[11] and an infrared microscope focused directly on the contact region[7]. Their studies indicated that in most polymer composite, the high stiffness and low thermal conductivity result in high temperature at the sliding contact during friction[7]. The wear rates were found to increase very sharply beyond a certain critical temperature[15,17]. Furthermore, the low softening or melting and degradation temperatures of polymer matrix make surface temperatures more critical and affect the tribological properties of the polymer composite[1]. Thus, the surface heating in a sliding contact is a practical concern since the temperatures developed can influence the extent of surface damage and frictional behavior[12,15,16,18].

The author's particular interest is the friction properties of glass fiber reinforced epoxy (GFRE) composite as influenced by the induced sliding interface temperature at different counter face materials. Therefore, an attempt is made to measure the induced interface temperature simultaneously with the friction forces to better understand its effects on friction characteristics of GFRE composite. Results of friction coefficient and interface temperature are obtained under dry sliding condition of the GFRE composite when sliding took place against hardened steel (HS), cast iron (CI) and aluminum alloy (Al). The effect of varying sliding velocity, normal load and interval time on both interfacial temperature and friction coefficient are

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examined too with reference to the optical micrograph observations.

EXPERIMENTAL DETAILS

Test apparatus and procedure: The experimental tests were carried out using a pin-on-ring (POR) test apparatus[19], shown in Fig. 1. A cylindrical pin (1) of GFRE composite, of 15mm diameter and 23mm length, is loaded against a rotated cup (2). The main features of the test apparatus are a strain gauge (3) for measuring the friction force, a loading lever (4) for applying the normal load and a main thermocouple for measuring the interface temperature (5). With this apparatus, simultaneous measurements of friction force and sliding surface temperature can be obtained continuously during the test process.

Measuring interface temperature: It was difficult to measure the temperature directly at the sliding interface (with a thermocouple) during the rotation of ring (Fig. 1). Therefore, un-through hole of 2mm diameter was drilled in the composite pin in which a thermocouple is inserted to measure the temperature of the composite pin at the bottom of the hole, 0.75, 1.5 and 2mm above the sliding surface as shown schematically in Fig. 2. The direct temperature of the interface between the composite pin and the surface of the cup (reference temperature) was measured with another thermocouple when the ring was stationary. These measurements were done before staring the actual test., as shown in Fig. 2a.

The procedure was to heat up the cup while the composite pin is placed against the upper surface of the cup. Thus, two readings of temperatures have been recorded. One is the direct temperature at the interface between the GFRE composite pin and the surface of the cup. The other is the corresponding temperature measured inside the GFRE pin. A series of temperature measurements were recorded for three composite pins with different bottom heights (0.75mm, 1.5mm and 2mm). Then, a calibration chart, Fig. 3, is produced to correlate both the direct temperature at the surface of the cup with corresponding temperature of the composite pin measured at the bottom of the hole. During experiments (Fig. 2b), the temperature of the composite pin was measured and corrected using the calibration chart (Fig. 3). The calibration process was prepared to give a temperature rise within the contact up to 140°C. It is believed that this technique is around 90% accurate compared to the other techniques[10,11,15,17]. However, grate effort has been made to reduce the error as much as possible.

Composite specimens and counterfaces: The composite selected for this study is a unidirectional glass fiber reinforced epoxy (GFRE). Some of the available specifications of GFRE composite are given in Table 1[1].
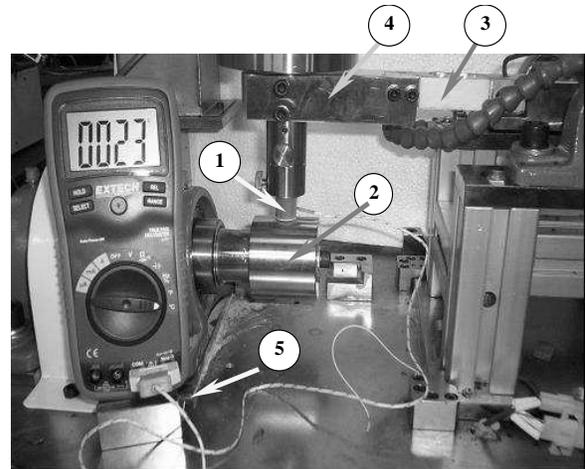

Fig. 1: Pin on disk tribo-tester
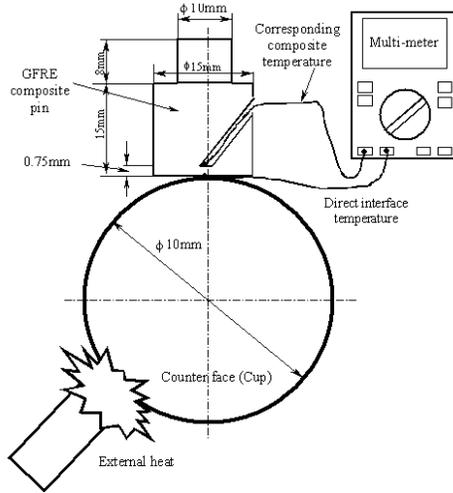1-GFRE pin, 2- ring (cup), 3-staingauge, 4-load lever, 5- thermocouple inserted inside GFRE pin

Table 1: Some mechanical properties of GFRE composite

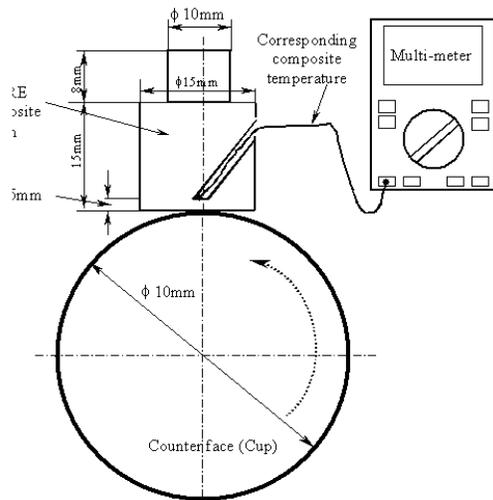| Material	Glass fiber	Epoxy matrix
Young's Modulus, GPa	72.4	4.1
Tensile Strength, GPa	3.4	0.11
Tensile Elongation, %	4.4	4.6
Poisson's Ratio	0.22	0.3

However, the GFRE composites were made from glass fiber and epoxy resin (CY-205, 1.27 gm cm^{-3}). The epoxy resin was mixed with a hardener (HY-951, 0.94 gm cm^{-3}) in a ratio of 10:1 by weight. Composite rods were moulded by a glass tube (12mm diameter and 100mm length). The casting cured at room temperature overnight and post-cured at 140°C for 3h in an oven. The composite has a composition of 40% fibers by weight. The specimens of the GFRE composite were shaped by turning small pins of 15mm diameter x 23mm length. The three different cups were made of hardened steel (1%C, 0.25%Si, 0.65%Mn, 0.2%Cr, 1%Mo, 0.14%S, 19%S), cast iron (3.6%C, 0.11%S, 0.86%Mn, 0.66%P, 1.65%Si, 56%Cr, 0.04%Ni) and aluminum alloy (84.6%Al, 9.4%Si, 2.4%Cu, 0.83%Fe, 0.2%Mn, 0.18%Mg, 2.2%Zn, 0.2%Ni, 0.036%Ti).

RESULTS AND DISCUSSION

Friction experiments were carried out for three different normal loads of (23N, 49N and 72N) and three different velocities (0.18, 1.3 and 5.2 m s^{-1}) at atmospheric condition. Each test was conducted for at least three repeated times at the same test conditions to ensure the repeatability. The ring surface was abraded before each test with a (P1500) grade emery paper; also, the pin was initially rubbed against the P1500 grade emery paper pasted on the ring to establish a conformal contact of the composite pin with the counterpart (cup).

(2a) Before rotating the ring (cup)

(2b) During rotating the ring (cup)

Fig. 2: Schematic illustration showing the arrangement of measuring the interface temperature

Interface temperature results: Figure 4 shows the variation of interface temperature versus interval time at different normal loads (23N, 49N, 72N) when the composite pin rubbed against three different cups (HS, CI, Al) at velocity of 5.3 m s^{-1}. The three different counter face materials gave similar trends of temperature with increasing the interval time. Above 300 sec of interval time, the interface temperature was consistently increased with increasing both normal load and interval time. In addition, sliding the GFRE composite against HS cup exhibited higher interface temperature (Fig. 4a) compared to the CI and Al (Fig. 4b and c) under same test conditions. This is about 95^{0}C at highest load level (72N, Fig. 4a).

The effects of sliding velocity on the interface temperature are presented in Fig. 5a-c when sliding took place against the three different cup materials, HS, CI and Al respectively at normal load of 34N.
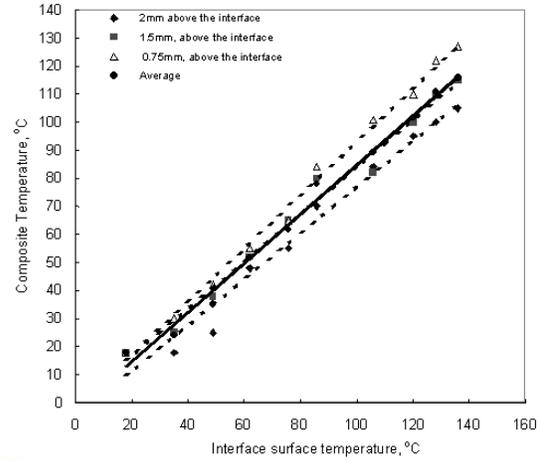

Fig. 3: Calibration chart for measuring interface temperature

Surface temperatures were increased from room temperature rather gradually and eventually reached a steady state value. Generally, the interface temperatures, for all types of counterface materials, were found to increase with an increase in sliding velocities. In addition, after 450 sec of interval time, the interface temperature reached steady values, for three different velocities tested. At low velocities (0.18 and 1.3 m s^{-1}), when the GFRE sliding against CI, there was no remarkable difference the interface temperature. In general, the highest temperature observed was about 83°C at highest velocity (5.2 m s^{-1}), Fig. 5b.

From literature[20], it is known that the slide-induced temperature rise would exhibit a transition phenomenon, which the temperature raises more rapidly than that before the transition. However, the present results for sliding against HS shows no such transition, but sliding GFRE against CI and Al shows a transition at 180 sec (23N, Fig. 4b) and at 60 sec (49N and 72N, Fig. 4b and c) for CI and well defined transition at 180 sec for sliding GFRE against Al at all loads tested.

Moreover, at sliding speed, 5.2 m s^{-1} Fig. 5b, sliding the GFRE against CI, showed two transitions, at 60 sec and 300 sec, which may be attributed to the formation of patchwork layer as will be discussed later.

Friction coefficient results: Typical curves of variations in friction coefficient with test duration (interval time) for different normal loads and different sliding speeds are shown in Fig. 6 and 7, respectively. In addition, the worn surfaces of the GFRE composite pins and the wear tracks on the three different cups were examined using optical microscope (Fig. 8-11). When GFRE composite pin rubbed against HS and CI (Fig. 6a and b) the friction coefficient increased gradually with increasing the sliding time until a steady value was reached.
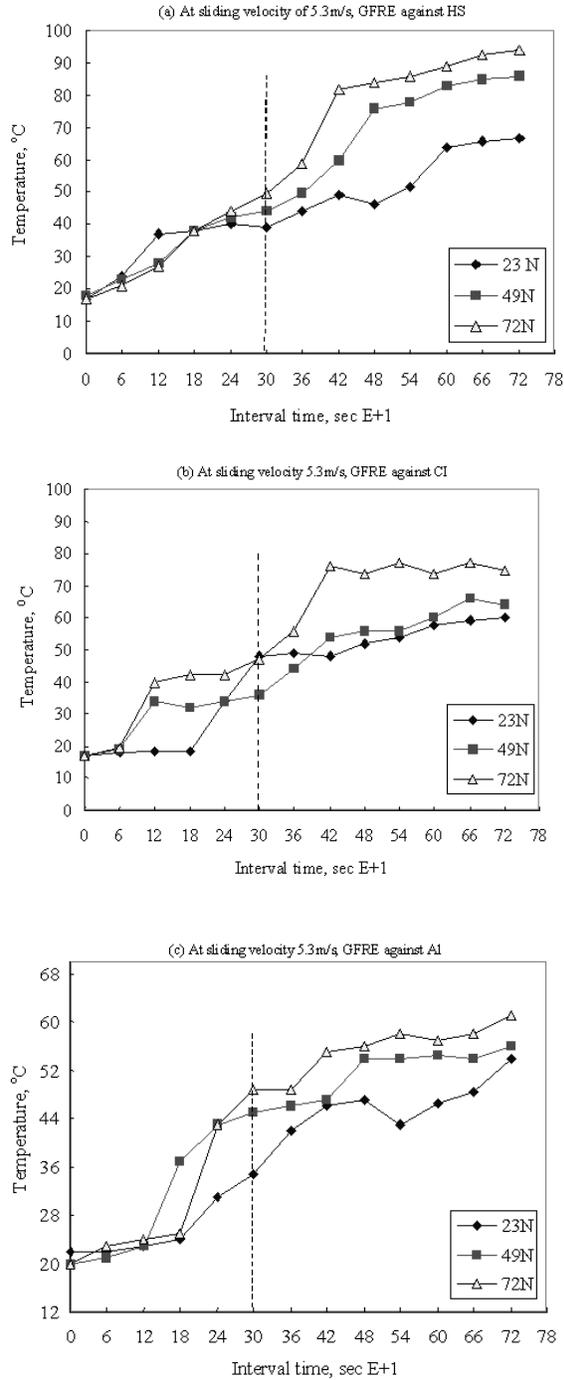
Fig. 4: The Interface temperature as a function of interval time for different counterface at different applied loads

Fig. 5: The interface temperature as a function of interval time for different counterfaces at different sliding velocities

Meanwhile, the friction coefficient increased with increasing normal load. In contrast, sliding the GFRE composite against Al, Fig. 6c showed a different trend, i.e. a decrease in friction coefficient as the normal load increases within the first 500 sec. Then for the lower value of load (23N) the friction coefficient decreased with further increase in sliding time to a steady state value (transition phenomenon).
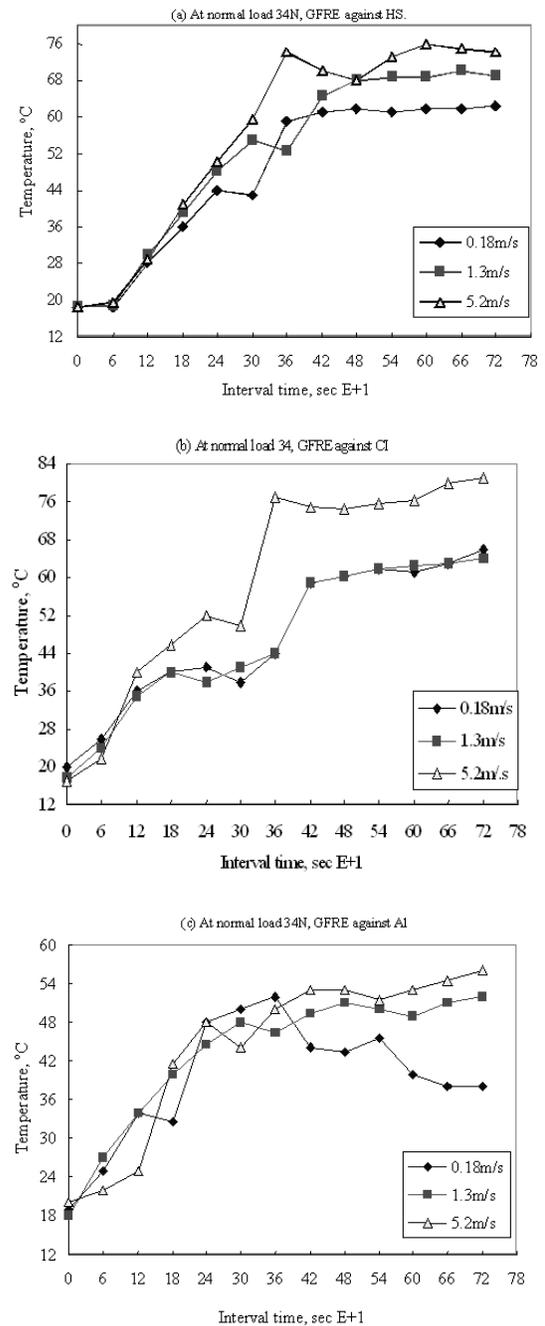
Eventually, the existence of glass fiber affects the contact area and the junction strength and so contributes directly to higher levels of friction coefficient and wear rate[1,2]. In the case of sliding GFRE against HS, the friction coefficient processes do not allow accumulation of wear debris at the tribosurface.

The combined effects of increasing both load and sliding time generates glass particles and drives them together with the soft matrix resin away from the interface.
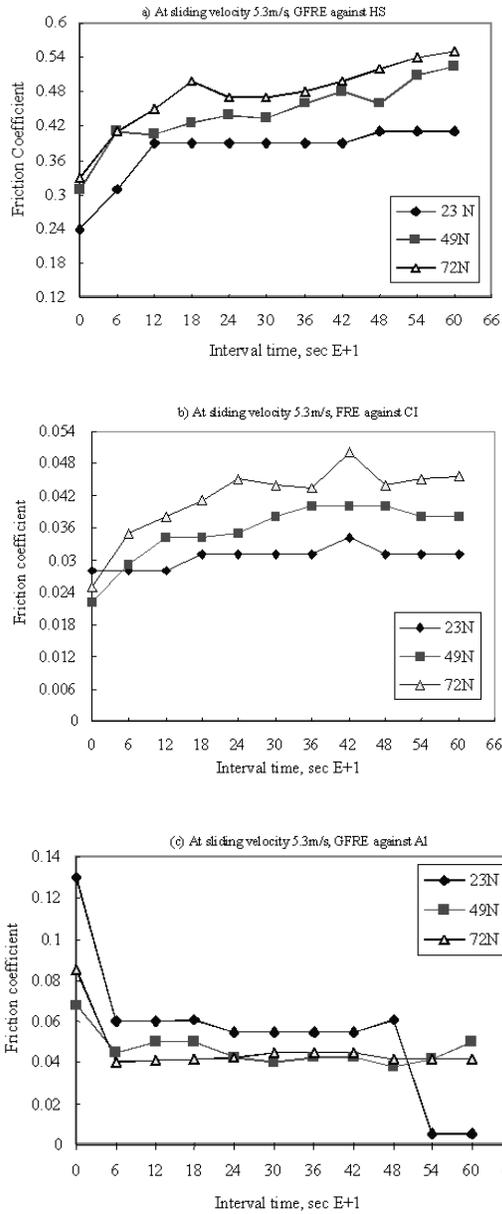
Fig. 6: The friction coefficient as a function of interval time for different counterfaces at different applied loads
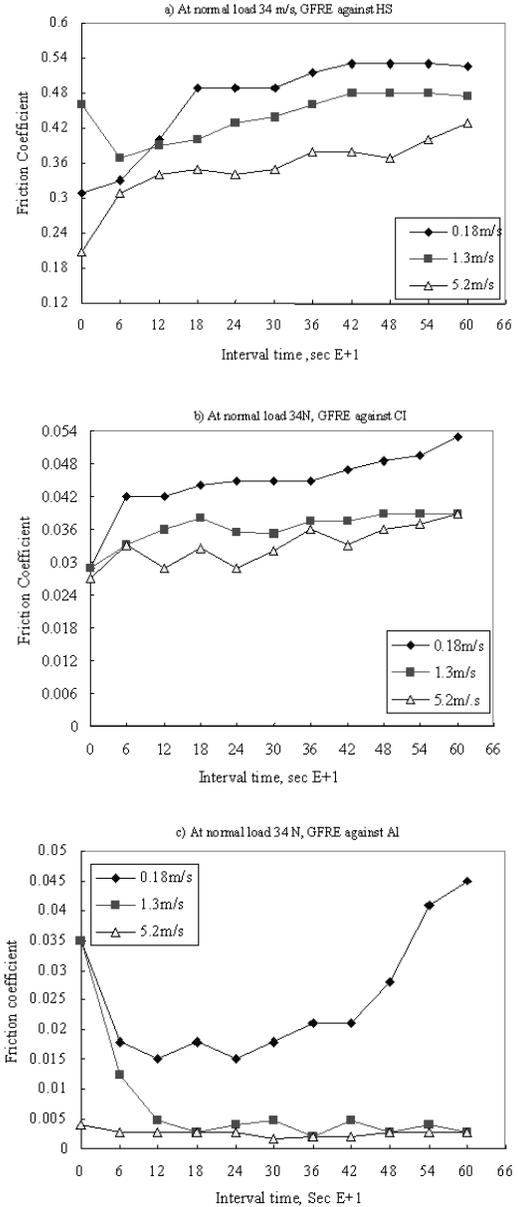

Fig. 7: The friction coefficient as function of interval time for different counterface materials at different sliding velocities

In the present work, this process leads to higher levels of friction coefficients (Fig. 6a) and consequently induced relatively higher temperature due to exposure of fresh fibers to the counterface (Fig. 4a and 6a). This evinced by the worn surfaces shown in Fig. 8a and b, in which a relatively smooth appearance with few patches of squeezed and compacted matrix masks the fiber cross section. A similar process is previously observed[2,9]. The effect of glass fiber debris on the cup surface is shown in Fig. 11a in which parallel scratches were left behind after the test. This is another factor that may contribute to the higher friction observed in the case of sliding GFRE against HS.
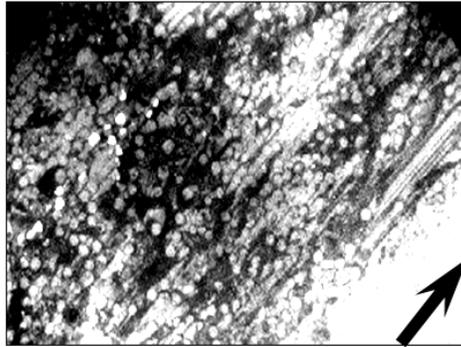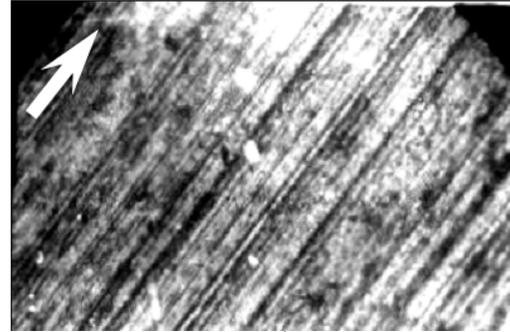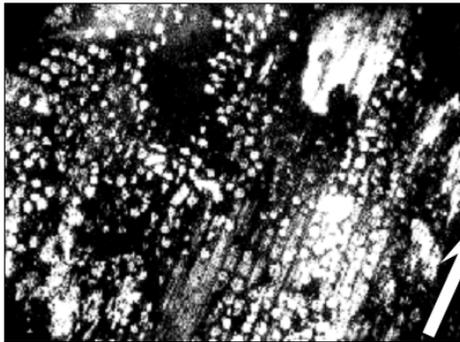
When the GFRE composite was tested against CI and Al, a reduction of about an order of magnitude in friction coefficient is evident (Fig. 6b and c). Figure 9a and b show micrographs worn surfaces of GFRE pin when rubbed against CI cup, in which formed patchwork layers can be seen. The rubbing against the CI shows more patchwork layers compared to rubbing against HS (compare Fig. 9a and b with Fig. 8a and b). These patchwork layers increases as the normal load and velocity increased. At a higher rang of normal loads and velocities, the sliding surface of the composite is almost covered by the smeared graphite particles (Fig. 9b) which acted as a lubricating layer.
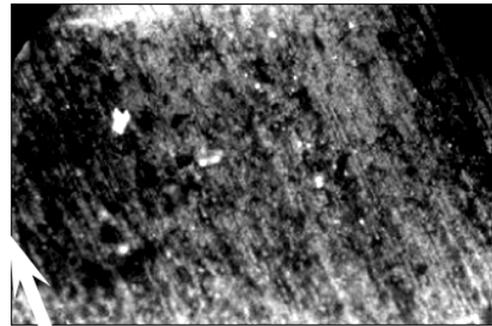
(a) At 1.3 m s^{-1} and 49 N
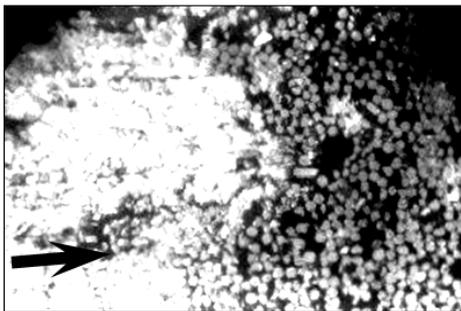

(b) At 5.2 m s^{-1} and 72 N

Fig. 8: Optical micrographs of the GFRE worn surface when rubbed against HS cup

(a) At 5.2 m s^{-1} and 49 N

(b) At 5.2 m s^{-1} and 72 N

Fig. 9: Optical micrographs of the GFRE worn surface when rubbed against CI cup

(a) At 5.3 m s^{-1} and 49 N

(b) At 5.2 m s^{-1} and 72 N

Fig 10: Optical micrographs of the GFRE worn surface when rubbed against AI cup

The corresponding wear track on the CI cup is shown in Fig.11b, in which some glass fragments and epoxy debris are embedded on the surface. Again, scratches parallel to the sliding direction can be seen clearly on the left and right sides of the micrograph implying that abrasive action took place during sliding.

The friction coefficients for GFRE against Al. under 23N normal load showed a transition from about (0.06-0.01) after 500 sec (Fig. 6c), while under 49N and 72N showed no significant change. This transition thought to be related to formation of a new layer at 500 sec. However, examining the micrographs of the worn surfaces and the wear track on the AL cups (Fig.10a and b and Fig. 11c) showed parallel scratches on the worn surfaces of the GFRE pin and grooves filled with matrix debris on the wear track of AL cup. Therefore, in this test, the GFRE composite suffered more serious damage than sliding against the other two materials. The well-defined scratches shown in Fig. 10 indicate that abrasive action was the predominant mechanism in material removal.

The results of friction coefficient against sliding time for the three different sliding velocities, Fig. 7, show that the friction coefficient decreases as the sliding velocity increases. It is shown elsewhere[7,21] that the surface temperature increases with an increase in sliding velocity and this is followed by decrease in the friction coefficient. In the case if GFRE sliding against

HS, smooth surfaces of composite pin and counterface result in an increase in the area of contact at the interface. Consequently, more asperities are in contact which gives rise to frictional heating (and interface temperature Fig.4a) and so increases the friction coefficient compared with the other two counterfaces used. Further increase in sliding time produces no change in the friction coefficient. The present results, shown in Fig. 7, are in agreement with similar findings[6,7,21]. In the case of GFRE sliding against CI the generated layers (patchwork) acted as a separator at the interface. This separator is characterized by low thermal conductivity which in turn reduces the effect of temperature and so the friction coefficient Fig. 6b and 7b.

a) Harden steel

(b) Cast iron

(c) Aluminum

Fig. 11: Optical micrographs of counterface materials after test of GFRE

At velocities of 1.3 and 5. 2m s^{-1}, the friction coefficient of GFRE against Al, showed no significant changes, rather it was maintained at a low level (0.03, Fig. 7b).

CONCLUSION

Based on the experimental observations, the following conclusions can be drawn:

Experimental results showed that the counter face materials greatly affected the friction coefficient and subsequently the interface temperature.
This was due to the wear debris layers generated during sliding process at the interface which were dependant on the material of the counter face, i.e. either abrasive (in the case of Al.) or non-abrasive (in the case of CI).
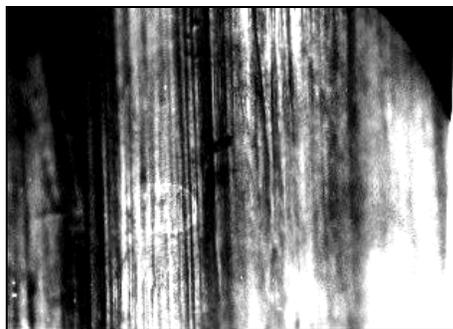
When sliding took place against HS, the continuous exposure of fresh glass fibers to the counter face greatly contributed to higher values of friction coefficients and followed by higher interface temperature compared to the other two counter face materials. The friction coefficient values observed during sliding against HS were found to be an order of magnitude higher than those were obtained in the sliding against the C.I. and Al. Higher temperature and friction coefficient were evident when sliding took place against hardened steel surface compared to other.

When sliding took place against CI, the non-abrasive layers formed at the interface, acted as a solid lubricant to minimize the friction coefficient of the composite. Thus, relatively lower temperature and values of friction coefficient were obtained.

When sliding took place against Al, the resulting abrasive debris acted as a third body abrader. These layers have affected the counter face, i.e. severe changes in the surface roughness. Such effect increases with the increase of normal loads and speeds. However, low values of friction coefficients were obtained at all values of normal load and sliding velocities studied. Mean while, transition of the temperature occurred at 180 sec afterward rapid increase in the interface temperature occurred.

For sliding GFRE composite pin against HS and CI, the friction coefficients increased with increasing normal load while decreasing with increasing sliding velocity. Whereas, sliding the GFRE pin against Al, the friction coefficient remained unchanged about (0.04) at (49 and 72N) normal loads and 0.06 at 23N normal load. After 500 sec, at 23N, transition of the friction coefficient took place (0.01).
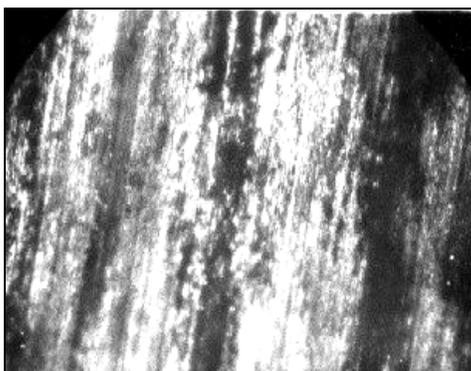
For all sliding cases, the interface temperature increased consistently with increasing normal load, sliding speed and sliding time. The maximum interface temperatures are found 96°C, 76°C and 62°C for sliding against HS, CI and Al respectively, which were less than the glass transition temperature of epoxy matrix (108°C).

A slight lag was observed between the friction peaks and the interface temperature and this is referred to small-localized debris passing through the contact and the thermocouple response.

The friction coefficient between HS surface and GFRE was about an order of magnitude higher than sliding against the other two materials.

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