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Effects of Environment and Fibre Architecture on Wear Properties of Nano-Filled Epoxy Polymer Composite

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ABSTRACT

In this paper, the wear properties of nano-filled Glass Fibre Reinforced Polymer (GFRP) composite are studied based on the effects of the architecture of the glass fibre and test environment. Wear tests were done under two different conditions; dry environment test and wet environment test. The dry and wet environment tests were conducted using the abrasion resistance tester (TR600) and slurry erosion tester, respectively; the slurry mixture of sand and water were used in the wet environment test. Two types of glass fibres architecture were understudied; unidirectional and woven. It was found that 3 wt.% filler content is the optimum amount to be used for the GFRP composite. Unidirectional nano-filled GFRP composites exhibited the lowest wear rates due to their closely aligned glass fibre arrangement. The unidirectional fibre alignment provided less empty spots for the interlocking process to take place, thus reducing the ploughing action of wearing. However, when tested in the wet environment, effects of other testing parameters such as the architecture of fibre and filler contents became less significant. The composites, which were tested in wet environment, showed the lowest wear rates compared to the ones tested in the dry environment. This is due to the presence of water that helps to wash away the pulverised glass fibre, thus reducing the friction and the three-body wear effect.

Keywords: Abrasive wear, dry sliding, glass fibre, polymer composite, slurry erosion test

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INTRODUCTION

Abrasive wear is described as when a material experiences loss in its mass due to continuous contact made with an abraded surface of a moving counter body. There are basically four main mechanisms associated with abrasive wear, namely micro-fatigue, micro-cutting, micro-cracking, and micro-ploughing (Morioka, Tsuchiya, & Shioya, 2015). Micro-fatigue is described when a rough worn surface could be observed on the material after abrasion. On the other hand, micro-cracking usually occurs to brittle materials due to high-stress concentration applied onto the material's surface by an abrasive surface. Micro-cutting is defined when there is detachment of particles from the material's surface. Lastly, micro-ploughing is when particles are being detached or swept sideways by an abrasive counter face, together with the presence of ridges and grooves (Morioka et al., 2015). There is another common wear behaviour that is always being associated with abrasive wear, i.e. the three-body abrasive wear. This behaviour occurs due to the debris, or removal or particles, are quite large in size, and consequently act as the third counter body which aids in abrading the material further, aside from the material and counter face (Hrabě & Müller, 2016).

Glass Fibre is a well-known fibre which is commonly used in composites in order to enhance the mechanical properties of polymer matrix composites. Albeit having a profound effect in improving the mechanical strength of the composite, it does not happen to have the same kind of effects in improving the wear properties of the composites due to the nature of the glass fibre which could be easily pulverised, as highlighted by Sumer, Unal, and Mimaroglu (2008). Therefore, in an extensive effort to improve the properties of Glass Fibre Reinforced Polymer composite (GFRP), nanofillers are incorporated into the polymer (Jumahat, Talib, & Abdullah, 2016; Jumahat, Kasolang, & Bahari, 2015; Basavarajappa & Ellangovan, 2012). Nano-fillers have been proven to improve the wear properties of the GFRP composite due to the ability of the fillers to form a tribo-protective layer where the layer protects the surface of the material from being further worn out by the counter body. On the other hand, the fillers are also said to have a cushioning effect on the asperities presence in the composite, thus helping in absorbing shock from the imposing and abrading counter body, as well as filling up the voids that may be present in the composite (Basavarajappa & Ellangovan, 2012). The optimum filler content being reported are between 1 wt.% and 4 wt.%. When the filler content is more than 5 wt.%, the fillers tend to agglomerate. This reduces the wear properties of the composites since the agglomerated nano-fillers will end up digging out in larger chunks affecting higher mass loss (Friedrich, Zhang, & Schlarb, 2015).

The load applied and speed used during the wear test are also said to affect the wear rate of the composite. Higher load and speed applied will contribute in higher friction built up. This induces softening of the matrix, as well as separation of the matrix from the reinforcement, thus higher mass loss will be experienced by the composite (Basavarajappa & Ellangovan, 2012; Sumer, Ugnal, & Mimaroglu, 2008; Agrawal, Singh, & Sarkar, 2016). However, there is another testing parameter which has a more significant effect on the wear rate compared to the speed and load which is environment test. Dhieb et al. (2016) highlighted that wear test conducted in water or lubricated environment diminished the speed and load effects on the wearing rate of the composite. This is because in a wet environment, the flowing fluid will wash away the debris produced from wearing motion. This will have either a positive or negative effect on the wear rate of the composite. If the debris produced by the materials is intended to be formed into a tribo-protective layer, then washing away the debris will not have a significant effect in improving wear as it has been expected to have. Meanwhile, if the debris produced was unwanted and could possibly cause the occurrence of three-body abrasive wearing, then washing it away would result in a better wear performance (Dhieb et al., 2016; Sumer, Unal, & Mimaroglu, 2008).

Wearing of material also could be affected by the surface topography of the material. Higher surface roughness would incur a higher material loss as the increase in asperities' height and the number would provide a good interlocking spot between the material and counter body. Better interlocking will end up in higher mass loss of the material. Increment in surface topography, i.e. surface roughness, or difference in the homogeneity of the surface will also provide a good interlocking motion that will result in higher wear rate (Ruckdäschel, Sandler, & Altstädt, 2013; Chauhan, & Thakur, 2013). Therefore, this paper investigates the effects of different environments, dry sliding and slurry wear test, as well as the architecture of glass fibre, unidirectional and woven on the wear rate of the nano-filled epoxy polymer composite.

METHOD

Fabrication of Composite

Commercial epoxy (Miracast 1517 A/B), supplied by Miracon (M) Sdn. Bhd., Malaysia, was used for this study. Miracast 1517 epoxy was cured by Miracast 1517 hardener with the ratio of 100:30. The nano-clay I.30E, used as the filler, was supplied by Sigma-Aldrich (M) Sdn Bhd. 1 wt.%, 3 wt.% and 5 wt.% of nano-clay in the epoxy samples were fabricated using high shear mixing process. The mixtures were milled at 12 m/s speed and 60°C. Then, the nano-modified resin was applied onto the woven and unidirectional mat of glass fibres and the composite samples were produced using the vacuum bagging system.

Abrasive Wear and Slurry Erosion Test

The specimens were subjected to two types of tests, which are the abrasive wear and slurry erosion tests. The test parameters used are indicated in Table 1 and Table 2 for the abrasive wear and slurry erosion test, respectively.

Table 1
Test condition for abrasive wear test

Testing Parameters	Experimental Condition
Test Standard	ASTM D 3389
Contact Geometry	Cylinder on flat
Type of motion	Unidirectional sliding
Applied Load	20 N
Sliding Speed	267 rpm
Sliding distance	10,000 m (2000 m Interval)
Specimen Shape (Dimensions)	Disc (ø = 123 mm, t = 5-6 mm)

Table 2
Test condition for slurry erosion test

Testing Parameters	Experimental Condition
Slurry Material	Mixture of sand and water
Type of sand	Medium size (ø= 0.2- 0.63 mm)
Type of motion	Unidirectional sliding
Sliding Speed	267 rpm
Sliding distance	10,000 m (2000 m interval)
Specimen Shape (Dimensions)	Bar (L= 75 mm, W= 25 mm, t= 6 mm)

For every 2000 mm interval, the machine was stopped and the mass of the specimen was weighed. The specific wear rate of the composite was calculated using formula 1, by substituting the recorded mass loss into the formulae:

$$W_s = \frac{\Delta m\,(g)}{L\,(m) \times \rho\left(\frac{g}{mm^3}\right) \times F\,(N)} \qquad [1]$$

Where the specific wear rate (Ws) was described as the function of mass loss (Δm) over the multiplication of the sliding distance (L), density (ρ), and applied load (F). The specific wear rate is expressed in mm^3/Nm unit (Nordin et al., 2013).

RESULTS AND DISCUSSION

First of all, the optimum filler content that is the most suitable to be used in GFRP composite needs to be determined. From Figure 1, it could be observed that when unidirectional glass fibre was used to reinforce the epoxy matrix, the specific wear rate increased significantly compared to pure epoxy. This is due to the nature of the glass fibre being easily pulverised, as highlighted by Sumer et al. (2016). When nano-clay filler was incorporated into the GFRP composite, the wear shows a different effect depending on the amount of nano-clay used in the composite. When 1 wt. % of nano-clay was used in the UniGFRP composite, the wear rate seemed to be improving. However, after 6000 m of sliding distance, it was observed that the wear rate started to worsen. This might be due to the amount of filler incorporated which was too little; therefore, after 6000 m, the filler had all been dug out by the abrasive counter body. When there was no filler left in the epoxy, the surface topography of the composite started to increase, therefore, exposing the surface to easier ploughing and cutting of the surface by the abrasive counter body, as previously explained by Ruckdäschel et al. (2013), Morioka et al. (2015), and Friedrich et al. (2005).

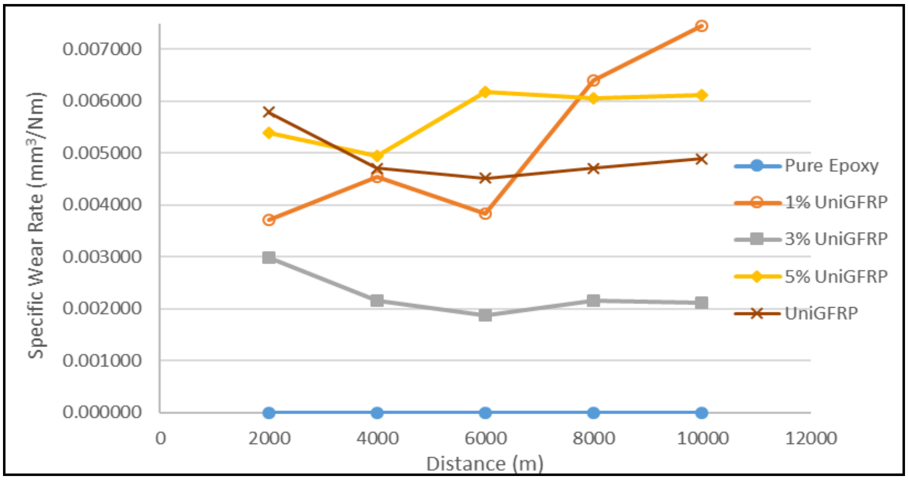

Figure 1. Specific wear rate of nano-modified unidirectional GFRP composite

When 3 wt.% of nano-clay was incorporated into the epoxy, the specific wear rate showed promising improvement. However, when 5 wt.% of nano-clay was used, the wear rate seemed to be increasing. As it was highlighted beforehand by Friedrich et al. (2005), the optimum filler content to be incorporated into the matrix is usually around 1% to 4%. When the filler amount exceeds 5%, the filler will have a high possibility to agglomerate. Agglomerated fillers will enable larger chunks of material to be dug out during abrasion. Hence, it could be stipulated that 3 wt.% of nano-clay is the optimum filler content that should be incorporated into the epoxy matrix in GFRP composite, and henceforth, this type of composite will be used for the wear rate study on the test environment and architecture of glass fibre.

When comparing the two architectures of the glass fibre tested in the dry environment from Figure 2, it could also be observed that the unidirectional GFRP (UniGFRP) significantly exhibited lesser and better specific wear rate compared to Woven GFRP (WGFRP). This is because the woven glass fibre provides more spots for the interlocking motion to take place. The empty space between each weave will provide an access for the interlocking between the surface and abraded counter body to take place, hence, better ploughing and cutting of the materials' surface took place, as described by Ruckdäschel et al. (2013), and Chauhan and Thakur (2013). As for the unidirectional GFRP, the fibres are aligned closely together and the spot for the interlocking process to take place is limited, and thus, avoiding the pulverisation and ploughing of the glass fibre which consequently result in lesser specific wear rate.

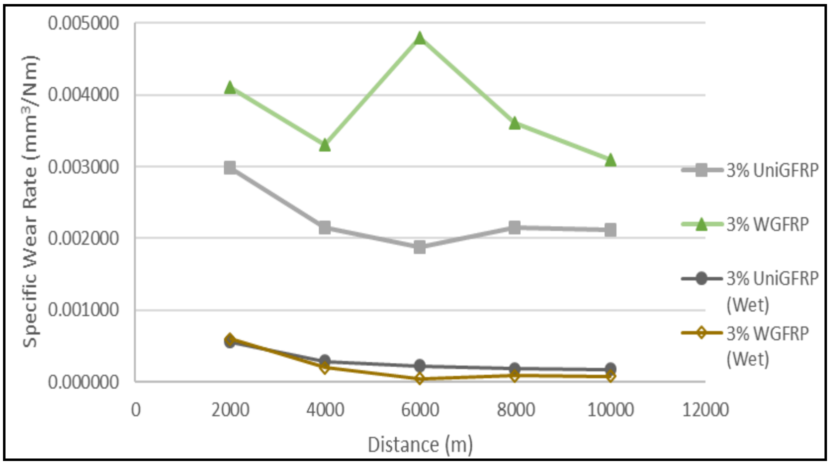

Figure 2. Specific Wear Rate of 3 wt. % Nano-modified Unidirectional and Woven GFRP Composite under dry and wet environment

Based on Figure 2, the specific wear rate of 3 wt.% nano-modified unidirectional and woven GFRP composite under dry and wet environment were observed. Compared to the dry environment, the wear rates exhibited by the composites tested in the wet environment are much lower. This result supports the claimed made by Sumer, Unal, and Mimaroglu (2008) and Dhieb et al. (2016), which stated that the wet condition would result in the best wear rate of the composite. When the composites were tested in wet condition, other testing parameters and the structure of the fibre did not have as much significant effect as the ones tested in the dry environment. This is because in wet condition, the water helps to wash away the debris made by the pulverised glass fibre. Washing away the debris will then reduce the three-body abrasive wear. Water also provides a lubricating layer which aids in a smoother sliding motion, hence reduces the friction and wear rate. Albeit insignificant, in the wet environment, the woven GFRP composite seems to have displayed better wear performance compared to unidirectional GFRP. This may be because in the wet environment, not only the pulverised glass fibres are being washed away by the water, but the sand helps in filling in the voids between each weave thus reducing exposed spots for interlocking activity. Reduction in interlocking spots will reduce the ploughing and cutting action of the WGFRP composite, thus resulting in reduced specific wear rates. The wear rates for the composites tested in the wet environment also seemed to exhibit wear rate almost similar to the pure epoxy in Figure 1.

Based on Figure 3, it could be observed that the results for specific wear rates obtained for 1, 3, and 5 wt.% nano-clay filled UniGFRP composites tested under the wet environment were different from the results which had been observed earlier in Figure 1. When being tested under the dry condition, it was found that 3 wt % of nano-clay was the most optimum amount of fillers to be added to the GFRP composites since it exhibited the least wear rates amongst other nano-filled unidirectional GFRP composites. However, for the tests which had been done under the wet environment, the amount of nano-fillers incorporated into the GFRP composite seemed to be less significant. The specific wear rates of these composites appeared to be almost similar, especially after 6000 m of sliding distance. Not only the wear rates are lesser than the ones tested under dry condition, but the specific wear rates for these composites exhibited wear rates almost comparable to pure epoxy, which is notable. This is because, when the repeating abrasive motion happens with the presence of water or fluid, the water serves as a lubricating layer which will aid in lessening the friction by reducing the effect of load and speed between the material surface and abrasive counterpart. As highlighted by Sumer, Unal, and Mimaroglu (2008) and Dhieb et al. (2016), the effects of filler content and testing parameters on the wear rates would be diminished when tested under a wet condition. Therefore, it could be concluded that nano-modified GFRP composites are highly potential to be used in a wet environment which also requires excellent mechanical strength and wear properties.

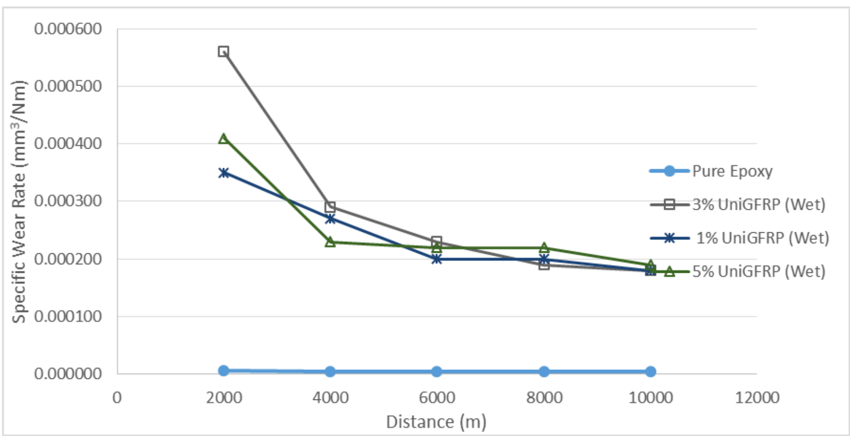

Figure 3. Specific wear rate of nano-modified unidirectional GFRP Composite tested in wet environment

CONCLUSION

Effects of the environments, as well as architecture of nano-clay modified composites, have been thoroughly studied. The optimum filler content for this composite in the dry condition was determined to be 3 wt. % since it showed the lowest wear rates compared to 1 wt.% and 5 wt.%. The wear rate for 3 wt.% nano-filled GFRP composites was also lower compared to the unmodified GFRP composite. Similarly, the architecture of the glass fibres also appeared to have some effects on the wear rates of the composites. The unidirectional GFRP displayed improved wear rate compared to the woven GFRP composite. This is because the unidirectional glass fibres are aligned closely together, which provide fewer voids or empty spots for the interlocking process to take place, therefore inhibiting the ploughing and cutting of the material. On the other hand, the wet environment demonstrates to have the most significant effect on the wear rate of composite and the best wear rates compared to the ones tested in the dry environment. In the wet environment, the effects of the architecture of the glass fibre and the amount of nano-fillers incorporated into the GFRP composites seemed to have been diminished. This is because in the slurry erosion test, water in the slurry mixture helped to wash away the debris produced during abrasion, thus reducing the three-body abrasive wear effect. The water also served as the lubricant, which helped to reduce the friction by reducing the effects of load and speed on the surface material when abraded. The sand in the mixture was also stipulated to help in filling in the voids between each fibre weave, thus reducing the spots for interlocking action to take place. The nano-modified GFRP composites were also postulated to be best applied in applications which operate under the wet environment that also requires excellent mechanical strength on top of good wear properties.

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