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Influence of titanium carbide on the three- body abrasive wear behaviour of glass-fabric reinforced epoxy composites

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Abstract: The three-body abrasive wear of Titanium Carbide (TiC) filled and unfilled E-glass-epoxy (G-E) was experimentally investigated using rubber wheel abrasion tester (RWAT). The composites were fabricated by using vacuum assisted resin transfer molding (VARTM) with 0-6 wt % of TiC in steps of 2 wt %. The mechanical properties of the TiC filled and unfilled glass fabric reinforced epoxy (G-E) composites have been evaluated. From the experimental results, it is observed that the mechanical properties of the G-E composite are better with the inclusion of TiC filler. The effect of abrading distance, viz., 150, 300, 450 and 600 m and two different loads of 22 and 32N at 200 rpm have been studied. Angular grained silica sand particles of size 200–250 µm were used as dry and loose abrasives. The inclusion of TiC filler in the epoxy lead to a significant influence on abrasive wear resistance of G-E composites. The volume loss of the composite has been determined and it increases with the increasing abrading distance. The morphologies of the worn surface of the composites were analyzed to understand the wear mechanisms by means of scanning electron microscopy (SEM).

Keywords: Three-Body Abrasive Wear, Glass-Epoxy Composite, Titanium Carbide Filler, Rubber Wheel Abrasion Test, Scan-Ning Electron Microscopy

1. Introduction

The recent trend to manufacture advanced materials in industry is to combat wear situations, based on polymer composites. Polymer composites possess high specific strength, easy processing, and light weight, excellent strength to weight ratios, resistance to corrosion, self lubricating properties, better coefficient of friction and wear resistance. They are widely used in earth moving equipments, coal handling equipments in power plants and gear pumps handling industrial fluids where abrasive type of wear is predominant [1]. Abrasive wear is one type of wear where hard asperities on one surface move across a softer surface under load, which penetrate and removes material from the softer surface, leaving behind, and grooves. Abrasive wear can occur as two-body abrasion, three-body abrasion, or both [2]. Three-body abrasive wear is caused by interactions of hard asperities (hard debris or foreign particles trapped between the polymer and the mating surface) on one surface, which move across a softer surface and also leave grooves on the softer surfaces that may further increase or decrease the wear rate by several orders [3]. Most of the abrasive wear problems which arise in general engineering or machine components, involve three-body wear, while two-body abrasion occurs primarily in material removal operations. Tribiological properties of polymer matrix composites shall be improved with the incorporation of fibers/fillers [4–6]. Also the mechanical properties such as hardness, tensile strength can be improved by adding fillers to the matrix. The incorporation of silicon carbide (SiC) and tungsten carbide (WC) in epoxy, imparts good abrasion resistance and strength, over the unfilled one [7]. Suresha et. al [8] showed that inclusion of particulate SiC filled glass fabric–vinyl ester composite gives better abrasive wear performance when compared to graphite filled composite system. Suresha et. al [9] reported that inclusion of particulate SiC into epoxy matrix, improved its wear resistance. Mohan et.al [10] investigated the effect of addition of WC and tantalum niobium carbide on three-body abrasive wear behavior of glass fabric–epoxy composites. Three-body abrasion wear property has gained attention for researchers recently since the material is applied in agricultural and mining components. Moreover, the data regarding three-body abrasive wear of thermoset polymer composites is limited. Various researchers reported the effect of filler addition on three-body abrasive wear performance of polymer composites [11–13]. From the above literature review, it is clear that no reports are available on the increasing filler weight percent of TiC as filler in G–E composites. The thorough literature survey cited above reveals that there is scope to analyze the three-body abrasive wear of TiC filler filled glass fabric- reinforced epoxy composites. In this regard, the aim of the paper was to investigate the effect of TiC content on the abrasive wear of glass fabrics reinforced epoxy composites. The result reported in this paper has suggested the possibility of application of TiC as a filler material in abrasive wear situation.

2. Experimental Details

2.1. Materials

A bidirectional E–Glass woven fabric of 360 g/m2 having an average fiber diameter of 8–10µm was procured from M/s. Reva Composites, Bangalore, India. Bi-functional epoxy resin (LY 5052) and room temperature curing cycloaliphatic amine (HY 5052) (system) were obtained from M/s. HAM, India. The resin is a clear liquid with viscosity at 25˚C, 1000–1500 [mPa.s] and specific gravity of 1.17 g/cm3. The liquid hardener's viscosity is 40–60 [mPa.s] and specific gravity of 0.94 g/cm3. In this work the filler material was TiC powder of particle size in the range of 4-10 µm.(Density of TiC = 4.9 g/cm3). M/s Alfa Aesar, Bangalore, India, as shown in SEM image (Fig.1).

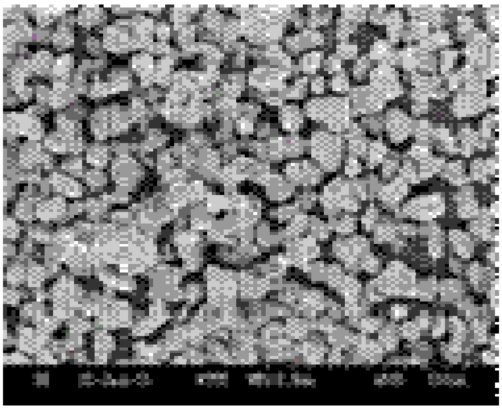


Figure 1. *SEM image of TiC powder used as filler for G-E composites.*

2.2. Fabrication of Composite Specimen

The composite fabrication consist of three steps: (a) mixing of the epoxy resin and filler using a mechanical stirrer, (b) mixing of the curing agent with the filled epoxy resin, and (c) fabrication of composites. Initially, a known quantity of filler was mixed with epoxy resin using a high speed mechanical stirrer to ensure the proper dispersion of filler in the epoxy resin. In the second step, the hardener was mixed into the filled epoxy resin using a mechanical stirrer. The ratio of epoxy resin to hardener was 100:38 on a weight basis. Finally, the epoxy resin was manually smeared onto the glass fabric and the resultant composites were fabricated using the VARTM process. Eight layers of the glass fiber fabric were stacked together and a distribution media was placed on the top. A vacuum was applied to the stack to provide the pressure gradient needed to infiltrate the suspension into the preform. Another consequence of the applied vacuum is that the stacked fiber mats are com-pressed due to the external atmospheric pressure on the sealed bag, increasing the fiber weight fraction. The TiC filled epoxy suspension was drawn through a tube into the mould. As soon as the suspension arrives at the vent located at the bottom, the injection is discontinued but the vacuum is maintained. After the suspension cures, the vacuum is released and the unfilled, TiC filled G-E composite part is de-molded. The composites were cured at room temperature under a pressure of 0.97 bar for 24 hrs and it is post cured up to 3 hr at 100˚C. The glass fiber: matrix (epoxy): filler ratio were 60:38:2, 60:36:4, 60:34:6. The unfilled glass epoxy composites were designated as G-E, 2 wt % TiC filled G-E composites as G-E+2,4 wt% TiC as G-E+4,6wt % TiC as G-E+6. The details of the composites and their mechanical properties are given in Table 1. The rectangular test specimens of size 75 x 25x 5 mm were cut from laminates, using a diamond tipped cutter.

Table 1.

Mechanical properties	**G-E**	**G-E+2**	**G-E+4**	**G-E+6**
Tensile strength(MPa)	148 ± 5	226.08 ± 9	172 ± 11	165 ± 10
Elongation(mm)-e	1.8 ± 0.11	1.5 ± 0.17	1.7 ± 0.12	1.1 ± 0.14
Hardness(H) (Rockwell)	98 ± 5	109 ± 4	106 ± 3	102 ± 5
1/(σ e) factor	6.23×10^{-4}	4.65×10^{-4}	5.99×10^{-4}	6.006×10^{-4}

The mechanical properties, such as tensile strength, hard-ness and elongation at fracture, were evaluated using a Fuel Instruments and Engineers Universal Testing Machine (UTN 40.SR No.:11/98-2450) as per ASTM D-638). Five samples were tested for each combination of the composites and the average values are reported. Hardness of unfilled and TiC filled G–E samples were measured using the Rockwell hardness tester (Rockwell C; New age testing instruments, Southampton).

2.3. Techniques

The wear experiments was conducted by dry sand/rubber wheel abrasion test set up (Fig. 2) as per ASTM-G65 and this test produced the closest simulation of the real tribo system.

Before starting the wear tests, the surfaces of the TiC filled and unfilled composites were cleaned with a soft paper soaked in acetone. The specimen weight was recorded using a digital electronic balance (0.1 mg accuracy). The abrasives were introduced between the test specimen and rotating abrasive wheel composed of chlorobutyl rubber tyre (hardness: 58–62 Durometer- A). The specimen was pressed against the rotating wheel at a specified force by means of a lever arm. The rotation of the abrasive wheel was such that its contacting face moves in the direction of sand flow. The pivot axis of the lever arm lies within a plane, which is ap-proximately tangent to the rubber wheel surface and is normal to the horizontal diameter along which the load is applied. At the end of a test duration, the specimen was removed, thoroughly cleaned and again weighed (final weight). The difference between initial and final weight of the specimen gives the measure of volume loss. The abrasive particles of AFS 60 grade silica sand were angular in shape with sharp edges and the abrasive was fed at the contacting face between the rotating rubber wheel and the test sample. The rate of feeding of the abrasive was 250 ± 10 g/min. The experiments were carried out for loads of 22 N and 32 N with a constant rubbing velocity of 2.33 m/s. Further, the abrading distances were varied from 150 to 600 m at equal intervals. The wear behavior was measured by the loss in weight, which was then converted into wear volume using the measured density data. The specific wear rate (KS) was calculated from the equation;

$$\mathbf{K}_s = \frac{\Delta V}{L \times d} \tag{1}$$

where ΔV is the volume loss in m3, L is the load in Newton, and d is the abrading distance in meters. The wear resistance of a material is calculated by the inverse of the wear rate.

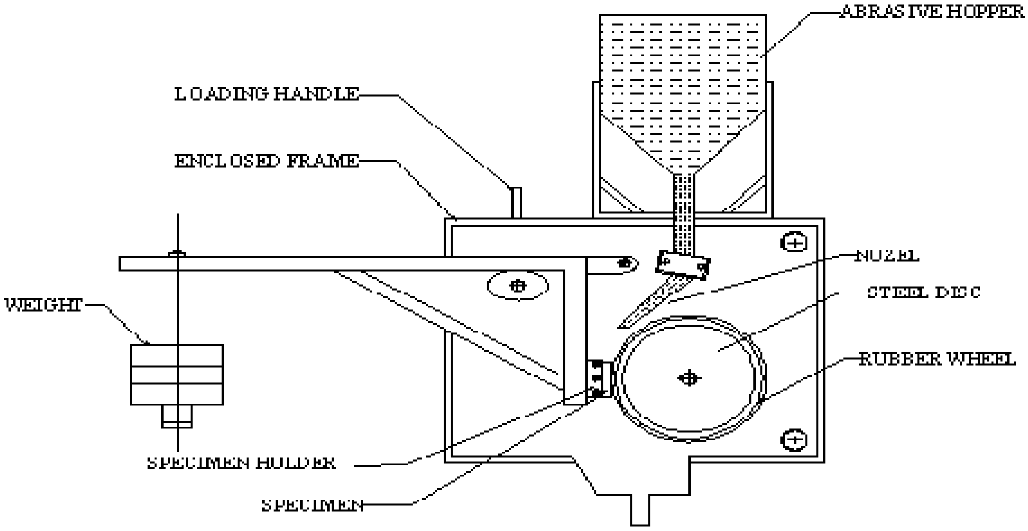


Figure 2.

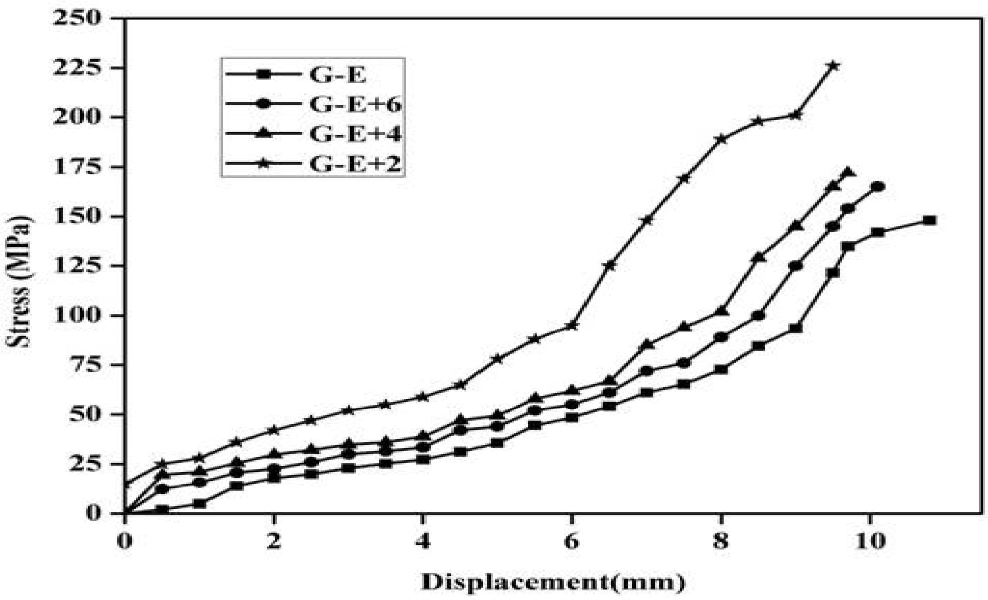


Figure 3.

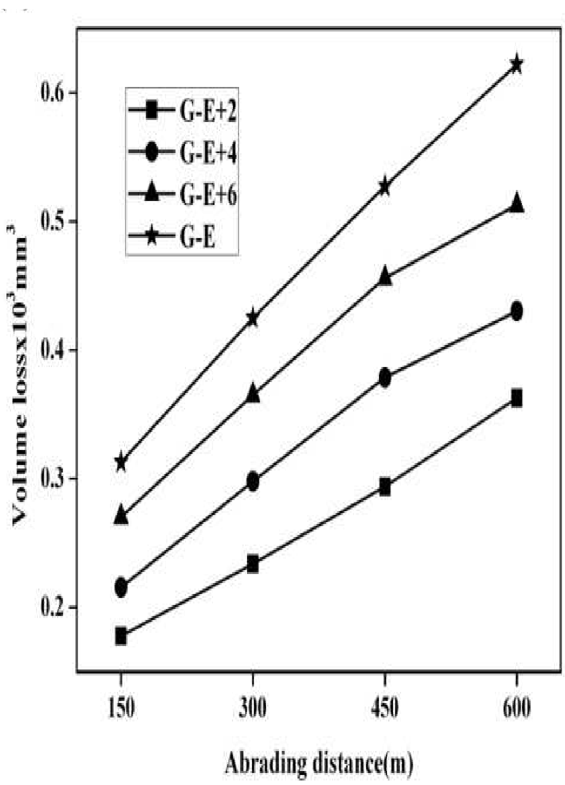
2.4. Scanning Electron Microscopy

After the conduction of experiments, the required surface area is cut by using diamond tip cutter. Before the microscopic examination, a thin gold film was deposited on the worn surface of the TiC filled and unfilled G–E composites by using sputtering technique. Using a scanning electron microscope (LEICA S440i, Model 7060, and Oxford) the worn surfaces were analyzed.

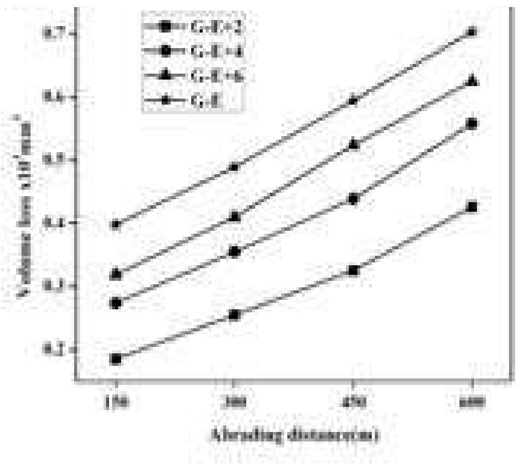
3. Results and Discussion

3.1. Volume Loss and Specific Wear Rate

Volume loss for the unfilled and TiC filled glass fabric epoxy composites as a function of abrading distance at two different loads of 22 N and 32 N are shown in Fig. 4a and 4b, respectively. It is observed that, there is a linear trend of volume loss with an increasing abrading distance. It shows a constant wear rate for all the composites. The highest volume loss is seen with unfilled composites while the lowest is seen for 2 wt % TiC filled G-E composite. The volume loss is higher in (4 and 6 wt %) TiC filled G-E as compared to 2wt% TiC filled epoxy composite, indicating the good bonding between filler and matrix. With the in-crease in filler weight fraction, the volume loss of the composites also increases. 6 wt% TiC filled G-E have highest material loss among all the composites. G-E composite shows 41.67% higher wear than G-E+2 composites. Wear resistance is better in G-E+2 composite due to the uniform dispersion of TiC particles in the matrix. Higher filler content of TiC in the epoxy did not protect the fibers from damage and hence increase in the volume loss.

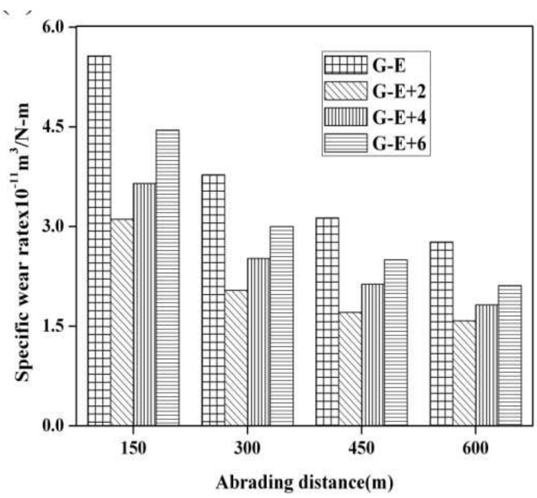


(a)

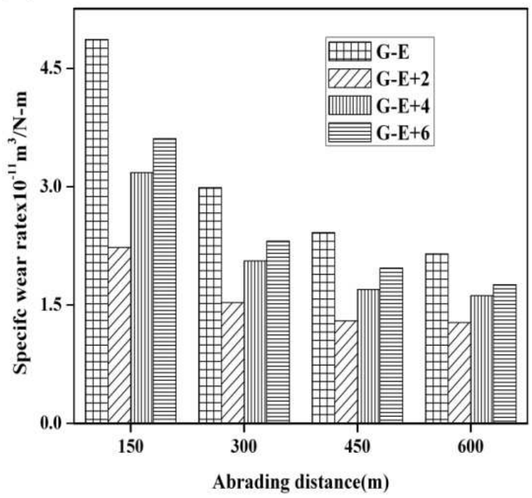


(b)

Figure 4.



(a)



(b)

Figure 5.

The results of specific wear rate as a function of abrading distance of unfilled composites and filled composites are shown in Fig.5a and 5b, respectively. For all the composites tested, it is observed that the specific wear rate decreases with increase in abrading distance. At all abrading distances the highest specific wear rate is for unfilled, with a value of $5.57\times 10^{-11} m^3/N\text{-}m$ and the lowest value of $1.28\times 10^{-11} m^3/N\text{-}m$ for 2wt % TiC filled G–E composite. Initially the specific wear rate is high, subsequently specific wear rate decreases until an abrading distance of 300 m and reaches to an almost constant value in the abrading distance range of 450–600 m.Also the specific wear rate is very high initially, and reaches an almost steady state with increase in filler wt %. The specific wear rate strongly depends on the applied load and abrading distance for all the composites. With an increase in applied load from 22N to 32N there is a reduction in the wear rate, due to the fact that the apparent contact area is greatly increased at higher applied loads. Since there is an increase in contact area, it allows a large number of sand particles to encounter the interface and share the stress. This, in turn, leads to a steady state or reduction in the wear rate. Among the composites studied, the abrasion resistance is higher for 2wt % TiC filled epoxy and lower for the unfilled one. This is attributed to the fact that, in 2wt % TiC filled G–E composite, the dispersion of filler is uniform and a better adhesion is established be-tween the matrix and the filler. Due to the poor adhesion between the filler and epoxy in 4wt% and 6 wt% of TiC filled composites, volume loss is increased.

The correlations of volume loss with respect to selected mechanical properties of composites such as (σe) factor (where, σ is the ultimate tensile strength and e is the ul-ti-mate elongation), Hardness (H) have been reported for single-pass studies of polymers without fillers and compo-sites [14, 15]. Lancaster [14] stated that the product of σ and e is related to the area under the stress-strain curve. Gener-ally fiber/filler reinforcement increases the tensile strength (σ) of neat polymer; there is usually a corresponding reduc-tion in the elongation to break. Similar results are obtained and given in Table 1. The model proposed by Ratner et al. [15] state that the rate of material removal is inversely proportional to the product of stress and strain at rupture. In the present work, for G–E composites and TiC filled com-posites volume loss due to wear decreases with increase in (σe) factor. However, inclusion of TiC greater than 2wt % (i.e., 4 wt & 6 wt %) in epoxy showed an increase in the wear volume loss in spite of an increase of the σe factor. Similar results were observed by Poomali et.al [16].

3.2. Surface Morphology Studies Using SEM

In general, four different wear mechanisms were observed on the wear surfaces of the composite materials. They are 1) matrix wear,2) fiber wear,3) fiber fracture 4) fiber-matrix interfacial debonding.

SEM images of shorter abrading and longer abrading distance for unfilled and TiC filled G–E composites at higher loads are shown in Fig. 6-9, respectively.

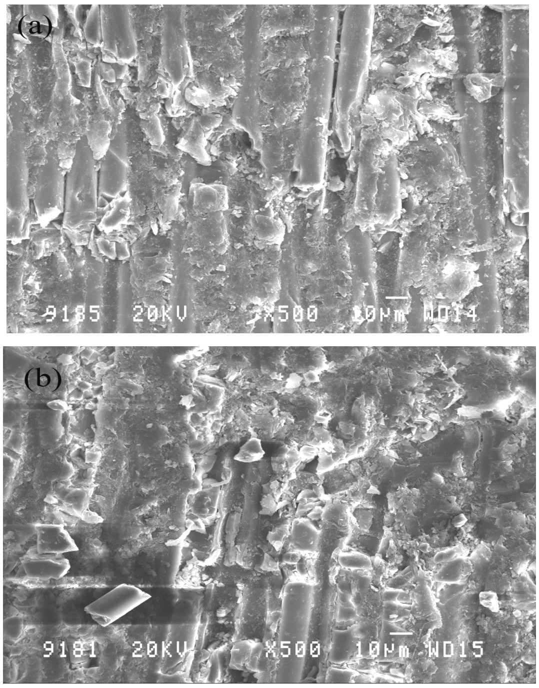


Figure 6. SEM images of unfilled G–E composites at (a) 32 N, 150 m, (b) 32 N, 600 m.

Fig. 6a and 6b shows the worn out surfaces of unfilled G–E composite at a load of 32 N, 150 m and 600 m abrading distance, respectively. Fig. 6a infers the fiber damage, with matrix debris concentrated at certain regions; and the re-maining regions are dominated by the presence of broken fibers. In the case of unfilled G-E composites, at the initial stage of abrasion, the particles penetrate the soft outer layer of the epoxy matrix due to the low hardness. Matrix layer removal, debonding and pull-out of fibers have been ob-served. Fiber fractures and pits of glass fibers are also visible on the worn surfaces of the composites. This result is in agreement with the SEM micrograph 6 (a), where fibers apparently are not well bonded to the matrix material. Fur-ther, more matrix debris formation occurs with plough-ing and fragmenting of fibers, are noticed. At low distance, matrix debris adhered to the broken end of the fibers clearly visible. At high abrading distance, severe damage to the matrix, fiber breakage and fibers pull-out from the surface is also observed. The worn out surface of the unfilled G-E composites show fractured glass fibers. Also from the Fig. 6a, it is observed that the brittle fractures of the material due to the cutting action by the abrasive particles are apparent and the extent of damage to the matrix and fiber is severe. From Fig. 6 b fiber-matrix de-bonding and inclined end fractures of fibers are visible. The movement of the abrasive particles determines the mechanism of material. Fibers are exposed to the abrasive environment due to the continuous wear of the particles. Due to this inadequately supported fibers are de-bonded and/or fractured from the surface. During the final stage of abrasion, the depth of the groove and length of wear track increases. Because of the cyclic stress at fiber resin interfaces leads to large-scale fiber separation. These separated individual fibers fracture more easily owing to the bending and mechanical pulling action. SEM features of 2 wt % TiC filled epoxy composites subjected to different abrading distances at a load of 32N are displayed in Fig. 7a and 7b, respectively. The 2 wt % TiC-filled G-E system shows less of matrix phase wear out. This is due to the presence of TiC filler in the epoxy which protects the fiber from damage. Since G-E+2 composite contain a combination of hard and soft phases, severity and extent of damage on the surface are less. The hard phases/regions offer resistance to the damaging action of the abrasive. The spread of the matrix is distinctly seen in Fig.7 (b). At a shorter abrading distance fiber breakage is less, compared to longer abrading distance. Development of cracks in composites can cause the removal in the form of TiC debris, which resulted because of the debonding between epoxy and TiC and the brittle nature of epoxy; TiC particles which are clearly visible in Fig. 7(b). These figures show less matrix wear and less distortion when compared to unfilled one. From the above result it is indicated that wear rates are dominated by the wear mechanisms associated with the filler filled matrix. The hard TiC filler in epoxy hinders the crack propagation during the abrasion process. This may be the reason for improved wear resistance in G-E+2 composite.

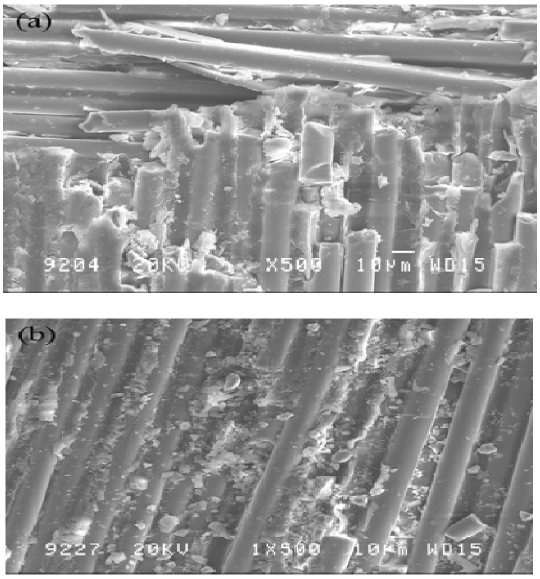


Figure 7. SEM images of 2wt %TiC filled G–E composites at (a) 32 N, 150 m, (b) 32 N, 600 m.

Fig. 8(a) indicates wear of matrix on the surface of the 4wt% TiC filled G-E composites. From Fig.8 (b), long cracks in matrix fiber cutting, pull out of fibers and fiber de-lamination are observed. More fiber damage is the result of surface fatigue due to the failure of protection given by TiC particles in the epoxy resin. A layer of resin seems to be removed by micro cracking resulting again from surface fatigue. Also, the fiber fracture is due to abrasion and transverse bending by sharp abrasive particles, resulting in fragments of fibers. From Fig. 8b at a longer abrading distance of 600 m, the glass fiber gets exposed and cracks are formed on the surface of the fibers. However, cracks on the matrix, fiber removal, fiber–matrix debonding and fiber breakages are more in G-E+4 composite than in G-E+2. Thus this observation accepts that the presence of TiC particles allow less of matrix wear during abrasion which in turn leads to lower fiber breakage and torn off from the matrix.

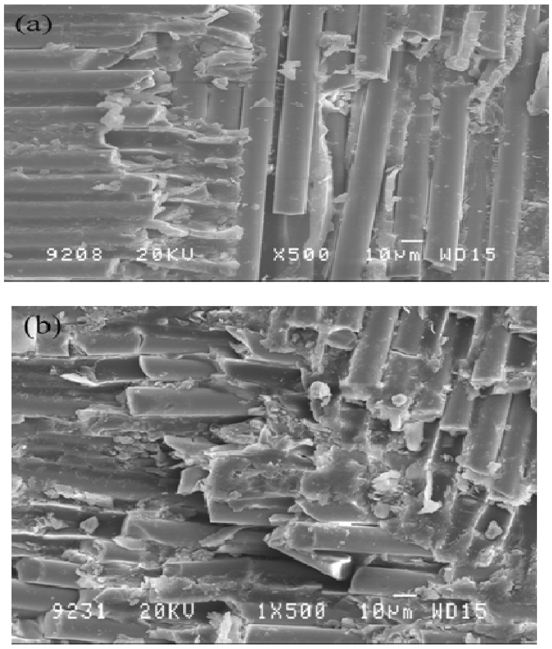


Figure 8. *SEM images of 4 wt % TiC-filled G-E composites at (a) 32 N, 150 m, (b) 32 N, 600 m.*

From Fig. 9a at a shorter abrading distance of 150 m, for G-E+6 composite, SEM images shows broken fiber debris on the surface, matrix damage and exposure of glass fibers. The exposed fibers can easily remove due to inadequate support of matrix. At longer abrading distance (Fig. 9b) there is an evidence of fiber breakage and cracking of fibers which indicates that fillers in G-E composite have poor interfacial adhesion. The matrix fragmentation and fiber damage were relatively high as compared to G-E+2, G-E+4 composite.

Based on the previous reviews, fine particles of inorganic materials seem to contribute better wear property than larger particles. Reducing the filler size from macro to a micro scale level is proposed to have a better wear resistance for the filler filled composites [17]. In this work also the results showed a similar trend. It was found that well dispersed micro-particles could significantly improve both the mechanical and the tribiological properties of the thermo-setting matrix composites. Once the particle sizes are diminishing down to micro-scale, significant improvements of the wear resistance of polymers were achieved at very low filler content. Also good particle distribution is an important factor in the improvement of the abrasive wear resistance. Hence the better result was observed in 2 wt % TiC filled composites as compared to 4wt % and 6wt % TiC filled composites. Thus in the present work, the TiC filled and unfilled G-E composite exhibits an increase in volume loss with increase in filler weight percent which is in line with the findings reported in the literature [18].The order of failure was matrix failure and its removal lead to exposure of fibers and ultimately their breakage and removal.

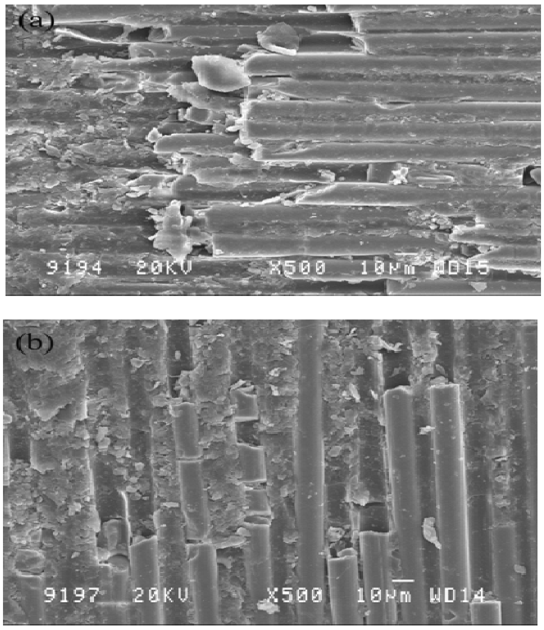


Figure 9. *SEM images of 6 wt % TiC filled G-E composites at (a) 32 N, 150 m, (b) 32 N, 600 m.*

4. Conclusions

The three-body abrasive wear behavior of TiC filled at different weight percent (2, 4 and 6 wt %) were investigated. Among the composites tested, wear resistance is higher in 2wt% TiC filled composites than the unfilled and 4wt %, 6wt %TiC filled G-E composites. The volume loss of the composites increases with the increase in the filler content. Higher wt % of TiC filler (4, 6 wt %) were observed to be not beneficial to resist the abrasive wear. The worn out surfaces of the composites, using SEM, indicated severe dam-age to the matrix for unfilled composites. Exposure of fibers and fiber breakage are the dominant mechanisms for the com-posites tested.

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