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Tribo-mechanical behaviour of SiC filled glass-epoxy composites at elevated temperatures

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Abstract

Polymer matrix composites are a promising candidate in tribological applications due to possibility of tailoring their properties with special fillers. Several methods have been developed to improve their performance. For instance, the introduction of ceramics such (SiC, Al_2O_3, TiC, etc.) as within the matrix notably increases the friction coefficient and reduces the wear loss. While glass fibers enhance the toughness of the matrix, silicon carbide shows high hardness, thermal stability and low chemical reactivity, leading to superior friction properties. In this work an attempt was made to evaluate the mechanical properties and tribological behaviour of glass fabric reinforced- epoxy (G-E) composites and silicon carbide filled glass fabric reinforced-epoxy (SiC-G-E) composites. The fabricated wear specimens were tested by using pin-on-disk test rig at various temperatures viz., 30, 60, 90 and 120º C at normal applied loads of 10 N and 20 N. Sliding velocity of the disc of 1.5 m/s was maintained and test was continued for each sample up to a sliding distance of 5000 m. The wear loss in both the composites increases with increase in temperature/applied load and under the same conditions the specific wear rate increases. However, silicon carbide particulate filled G-E composite exhibits lower wear rate with higher coefficient of friction as compared to virgin G-E composite. The elemental composition of worn surface of filler filled composites was quantitatively analyzed by using energy dispersive X-ray spectroscopy. The features of worn surfaces of the specimens tested at higher and lower temperatures at applied normal load of 20 N were examined under scanning electron microscope and also micro mechanism of fractured surfaces were examined through SEM and discussed.

Keywords: Glass fabric-epoxy composites; Silicon carbide; Micro mechanism; wear rate and wear mechanisms.

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1. Introduction

Glass fiber reinforced epoxy matrix composites have been increasingly used for numerous engineering purpose such as seals, gears, rollers, cams, wheel, clutches and bearings due to high specific strength and high modulus, better tribological properties, wide varieties of availability and design flexibility as compared to metal based counterparts. The polymer matrix composites are produced without fillers and reinforcement using an epoxy resin as matrix, exhibit relatively high wear rates and better coefficients of friction when dry-sliding against hardened steel counter faces. This is basically due to the cross-linked molecular structure, which inhibits the formation of an efficient transfer film layer and results in a relatively high degree of brittleness. However, epoxy resins possess other favorable properties such as strong adhesion to many materials, good mechanical and electrical properties, relatively high chemical and moderate thermal resistance. Also epoxy in moulded or cast form has excellent dimensional stability and low shrinkage (Kalpakjain *et al.,* 2004; Kishore *et al.,* 2005). Mohan *et al.* (2010) incorporated jatropha oil cake to glass/epoxy composites to enhance their wear resistance by reducing their coefficient of friction. Suresha *et al.* (2008) found that wear resistance of glass/epoxy composites was enhanced by Cenospheres obtained from fly ash. Addition of abrasive fillers, however, enhances not only wear resistance, but, also coefficient of friction of glass/epoxy composites. If coefficient of friction increases, it may lead to heat buildup, which, in turn, might cause thermal degradation/aging of the polymer matrix. Hence, it is essential to reduce coefficient of friction by a judicious choice of filler(s). Glass fabric reinforcements in PMCs generally improve the creep resistance, stiffness and compressive strength and also result in enhanced wear resistance. Automotive applications is the new generation of control arm mountings or ball joints in the car chassis technology, in which higher loads and temperature are acting. In this case, PMCs will be operated at relatively high environmental temperature up to 120^0 C (Friedrich, 2005; Stachowiak, 2001). The improvement of the wear resistance of a polymer with the incorporation of fibers/fillers is well known. The incorporation of fiber has showed both positive and negative results on the tribological properties of a polymer (El-Tayeb and Yousif, 2007; Pihtili and Tosun, 2002). The reason to incorporate a filler into a polymer is twofold; (a) first to improve the wear resistance, mechanical and thermal properties and (b) to reduce the cost of the final product. In the last two decades, various filler and fiber materials have emerged as a subject of extensive research. Since 1893, silicon carbide (SiC) particulate filler has been mass produced to be utilized as an abrasive wear resistant material. SiC has been extensively used in abrasive machining processes such as grinding, honing, water-jet cutting and sandblasting due to its high hardness (Marco, 1997).

One of the limitations in the use of reinforced PMCs is their inferior thermo-resistant properties relative to metals and ceramics. During sliding, the mechanical energy is mainly dissipated as heat. This may lead to decomposition and deterioration of mechanical properties, which in turn often decreases the friction and wear performance. This limits the life time application of components made from PMCs. This is especially a problem in applications involving high contact pressures, high sliding velocities and high specific rate of energy dissipation. Hence, PMCs which are used in heavy duty applications at high temperature environment systems the heat decomposition and frictional heating are reduced by adding fillers (Thomas *et al.,* 2008; Mohan *et al.,* 2011). Additionally, if the PMCs are subjected to harsh environmental conditions such as chemicals, or moisture, the characterization of the material's performance is more essential before application because of the viscoelastic nature of polymeric composites. Above the glass transition temperature (Tg) fiber reinforced PMCs properties degrade significantly (Rudin and Hatakeyama, 1999). The glass transition temperature (Tg) of epoxy play a major role in selecting and designing suitable polymer composites for tailor made applications. Tg depends on the chemical structure of the epoxy and its cross linked density. Factors such as crosslink density, nature of hardener, amount of hardener, curing temperature, time, moisture content, plasticizer content, etc. play a significant role.

For engineering applications high Tg epoxy resins are required. Tg of epoxy can be altered by different routes, such as chemical or physical methods. The post cured epoxies generally possess high Tg as compared with low or room temperature-cured epoxy systems. Hence it is necessary that the application temperature for a polymeric composite is below the Tg in order to assure that the mechanical and tribological properties of the material is satisfactory and epoxy resin is limited to a maximum service temperature about 120^0C (Hand book of ASM. 2001). Most of the published studies on sliding wear of glass fabric reinforced-epoxy composites with and with out silicon carbide particulate filler dealt with coefficient of friction, specific wear rate under room temperature environmental conditions at different load and speed. Coefficient of friction and wear resistance are very important criteria for composites used in high temperature environmental components. That means coefficient of friction and wear resistance are no real material properties, but system properties, i.e., they depend on the system in which these materials have to function. Quit often sliding is the dominant wear mode, and the materials must be designed for low friction and low wear against smooth metallic counterparts components like bearing and gear etc. but some times high coefficient of friction and low wear is required in brake pads and clutches etc. In the present work mechanical and wear properties have been carried out for silicon carbide particulate filled glass reinforced-epoxy composite and unfilled glass reinforced-epoxy composite at different temperatures viz., 30, 60, 90 and 120^0 C and reported.

2. Experiment

2.1. Materials: A bidirectional E-Glass woven fabric of 210 g/m^2, 8 mill bidirectional with fiber diameters of 5-10 μm (Figure1) procured from M/s. Reva composites was used as reinforcement. Bifunctional epoxy (diglycidyl ether of butane diol, LY-5052) resin, its viscosity at 25^0C is 1000-1500 mPa and specific gravity is 1.17 g/cc and hardener cyclo aliphatic amine (HY-5052) (room temperature cure system) is a liquid and its viscosity is 40-60 mPa and specific gravity is 0.94 g/cc were obtained from M/s. Huntsman Advanced Materials was used as resin system. The commercially available silicon carbide powder was obtained from M/s. Silicarb Recrystalized Pvt. Ltd., Bangalore. Its particle size ranged from 20-75 μm was used as filler material.

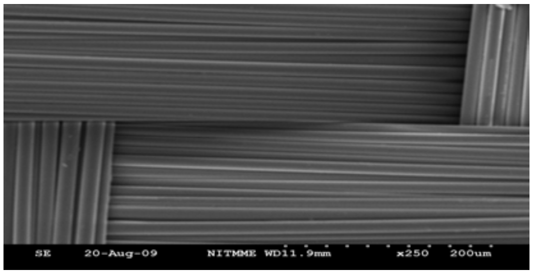

Figure 1. SEM photograph of dry glass fabric

Table 1 Formulations of composite samples

Designation	Sample Code	Glass Fabric (wt. %)	Matrix (wt. %)	SiCp Filler (wt. %)
Unfilled Glass-epoxy composite	G-E	50	50	-
Silicon Carbide filled Glass-epoxy composite	SiC-G-E	50	44	6

***2.2. Fabrication of composite specimens**:* A resin mixture of epoxy and hardener was prepared in the ratio 100:38 by weight by using magnetic stirrer. A releasing agent is applied on the smooth surface of the mold for easy removal of the composite stack and to obtain better surface finish. A bidirectional E-glass woven fabric cut as per the required dimension and placed one above the other in the mould, for each placement of fabric a well stirred mixture of resin and hardener is applied between the fabrics by using roller and brush. The exposed side of the stack was covered by cellophane membrane and sealed round the periphery by using suitable sealant. The weight percentage of glass fabrics in composites is maintained around 48 + 2 %. The laminate was cured under a pressure of 14 psi up to 24 hours, at room temperature and post cured up to 100^0 C for one hour in a controlled oven. The formulations of the composites are listed in Table 1. To prepare filler filled composite, 6 wt.% of SiC filler is incorporated to the resin mixture and stirred well before application of resin to the fabric surface. The laminate is fabricated to the dimension of 200 mm x 200 mm x 2.5 mm and the specimen was obtained by required dimension by using a diamond tipped cutter. Density of the composites specimens was determined using a high precision digital electronic weighing balance of 0.1 mg accuracy by using Archimedes principle.

2.3 Techniques: The tensile, compression and flexure properties of the composites were evaluated using an Instron universal testing machine (UTM, UK) as per ASTM D 3039. The test was conducted at a cross head speed of 10 mm/min. The surface hardness of the composite was measured using shore D Durometer (M/s. P.S.I Sales Pvt. Ltd., India) as per ASTM D 2240 specification five samples were tested for each composition of the composites.

A high temperature pin-on-disc (HT-POD) setup was used for the sliding wear tests as per ASTM-G99 standard (Figure 2). The cut sample from fabricated composite laminates of 5mm x 5 mm x 2.8 mm was fabricated to a square pin of 5mm x 5mm of 25mm length and fitted in the pin holder mounted in the HT-POD lever-arm such a way that which comes in contact with a hardened alloy steel disc of the machine. The hardness value of the EN-32alloy steel disc is 55 HRC and surface roughness (Ra) of 0.65µm. the test was carried out at normal load of 10 N, sliding velocity of 1.5 m/s and at varying temperatures viz., 30, 60, 90 and 120^0C. For every sample the surface is cleaned with a soft paper soaked in acetone and compressed air before and after testing. The specimen weight is recorded using digital electronic balance 0.1 mg accuracy. The difference between initial and final weight of the specimen was a measure of slide wear loss. A minimum of three trials were conducted to ensure repeatability of test data. The frictional force is measured by attaching a force transducer on the machine. The friction coefficient was recorded continuously and gets displayed on a computer interfaced with the high temperature pin-on-disc (HT-POD) machine (Figure 2). Experimentation was repeated for anther set of samples at 20 N applied normal load. The tests conditions adopted in the present study are listed in Table 2. A scanning electron microscope was used to analyze the micro mechanism of fracture of the composites.

Table 2 Details of the sliding wear test conditions.

Test conditions	Parameters
Dimension of the specimen holder (mm^3)	5 x 5 x 25
Dimension of the composite specimen(mm)	5 x 5 x 2.8 $\underline{+}$0.3
Applied load (N)	10 and 20
Angular speed (rpm)	716.5
Sliding diameter (mm)	40
Sliding Distance (m)	5000
Sliding Velocity (m/s)	1.5
Temperature (^{0}C)	30, 60, 90 and 120
Steel disc hardness and roughness (HRC and Ra)	55, 0.65

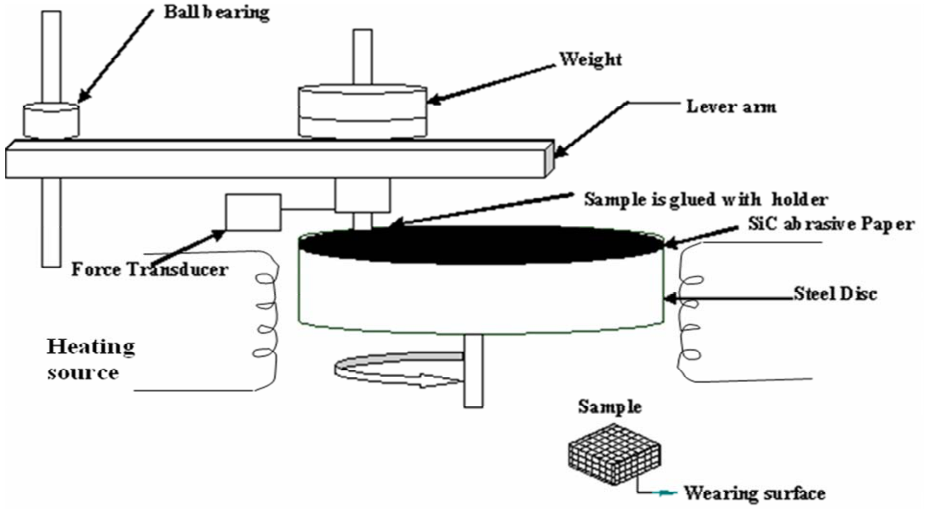

Figure 2 A schematic representation of high temperature pin-on-disc machine setup

3. Results and Discussion

***3.1. Mechanical Properties**:* The effect of Silicon carbide on Mechanical properties such as tensile, flexural, compression and hardness of the composites has been studied. The mechanical properties depend to a greater extent on the reinforcement/filler and lesser extent on the matrix material and the interface/interaction between them. A good interfacial bond is required for effective stress transfer from the matrix to the fiber whereby maximum utilization of the fiber strength in the composites is achieved is cited in literature (Suriani e*t al.,* 2007; Sastra *et al.,* 2005). The measured density and mechanical properties of SiC filled and unfilled composites in room temperature conditions are recorded in Table 3. A comparison of the results revealed that the unfilled composites show the lower value of mechanical properties as compared to SiC filled composites, confirming the effect of SiC filler in G-E composites. From the table 3 it is clearly evident that Tensile strength, Tensile Modulus, Flexural Strength, Flexural Modulus, Compression Strength, and Surface Hardness of SiC-G-E composite system increased by 13, 85, 29, 90, 81 and 3.5% respectively. Addition of fillers in polymer matrix composites increases mechanical properties are reported (Mohan *et al.,* 2013; 2014; Kim *et al.,* 2004; Unal, 2004). The test shows brittle type of fracture of composites leading to increased tensile strength, tensile modulus and lowers the elongation (56% reduction) at fracture and increased surface hardness meaning better dimensional stability and increased flexural strength meaning higher fracture toughness of the epoxy matrix, which is filled with SiC filler. The improvement reported for the mechanical properties of composites is mainly due to the enhancement of good interfacial adhesions among the fibers, matrix and SiC filler.

Table (3a) Mechanical properties of G-E and SiC-G-E composites tested at 120^{0}C

Properties	G-E	SiC-G-E	% change in properties
Density g/cc	1.30	1.36	
Tensile strength, MPa	185	209	13
Standard Deviation	1.58	2.54	-
Tensile Modulus MPa	9651	1411	85
Standard Deviation	28.16	11.4	-
Percentage elongation at break	3.9	2.5	56(reduction)
Standard Deviation	0.082	0.031	-
Flexural Strength, Mpa	299	388	29
Standard Deviation	8.24	3.16	-
Flexural Modulus, Mpa	1220	2320	90
Standard Deviation	12.54	14.56	-
Compression Strength, Mpa	54	98	81
Standard Deviation	2.23	1.58	-

Table (3b) Surface Hardness of GE and SiC filled GE Composites at elevated temperature:

Temperature in Degree Celsius	G-E	SiC-G-E
30	89	92
60	80	90
90	81	89
120	85	88

3.2. Micro mechanism of fractured surfaces:

3.2.1 Tensile fracture: The SEM images in Fig 3 to 8 shows the micro mechanism of fractured surface of fiber-matrix interface and matrix-filler interface of G-E and SiC-G-E composite systems respectively. The SEM images of tensile tested G-E composites (Figure 3) revealed that brittle type fracture and could be explained by the plastic deformation of the matrix after fiber breakage. The fracture is due to delamination between the fiber and matrix was seen that a gap has occurred between a fiber and matrix at microns level and extensive fibers pull out along with instant multiple fractures in transverse direction is shown in Figure 3a. In Figure 3b indicates fiber fracture, cohesive matrix fracture and fiber-matrix debonding. Generally matrix fracture was found to initiate at parallel to the surface of fibers and propagates into the matrix on either side, where cracks extend from the surfaces of neighboring fibers simultaneously in longitudinally. The SEM images Figure 3b support the evidence of brittle type of failure because of fibers on fractured surfaces are neat and clean and there is no reduction in cross sectional area at fiber ends and no adhere of matrix at the fractured surface.

SEM images (Figure 4a and b) of SiC filled G-E composite system shows the good interfacial adhesion between fiber and matrix and less voids due to the presence of SiC filler. From Figure 4a it was observed that interfacial bond strength was high, causing strong stress concentration and a tendency for cracks to pass through large bundles of fibers stepped across thickness without much deviation. Figure 4b indicates elongation of matrix, simultaneous breakage of fiber and matrix with fillers on the fractured surface and show good interfacial adhesion between fiber and matrix.

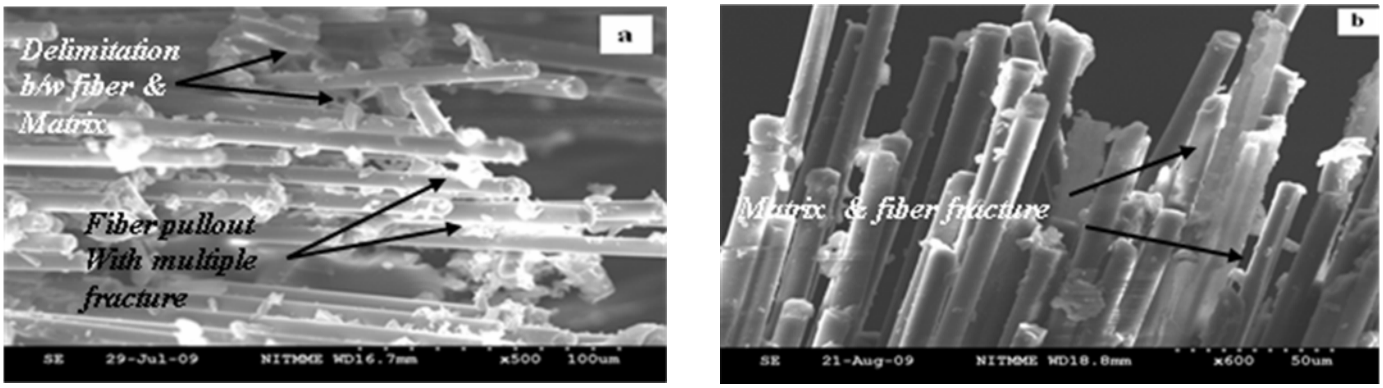

Figure 3 SEM images of tensile fracture surface of G-E composite (a) 500 x and (b) 600 x

In unfilled G-E composite tensile fracture surface shows a long length of fibers are pulled-out and a large region of fiber separation exists at the interfaces (Figure 3). This can be probably attributed to the inter-fiber and inter-layer pores present in the composites. The fracture surface of SiC filled composite under tensile fracture (Figure 4) are rough and rapture across the thickness with the extensive of shorter pulled-out broken fibers this is due to the effect of filler in the matrix resist the higher tensile loads.

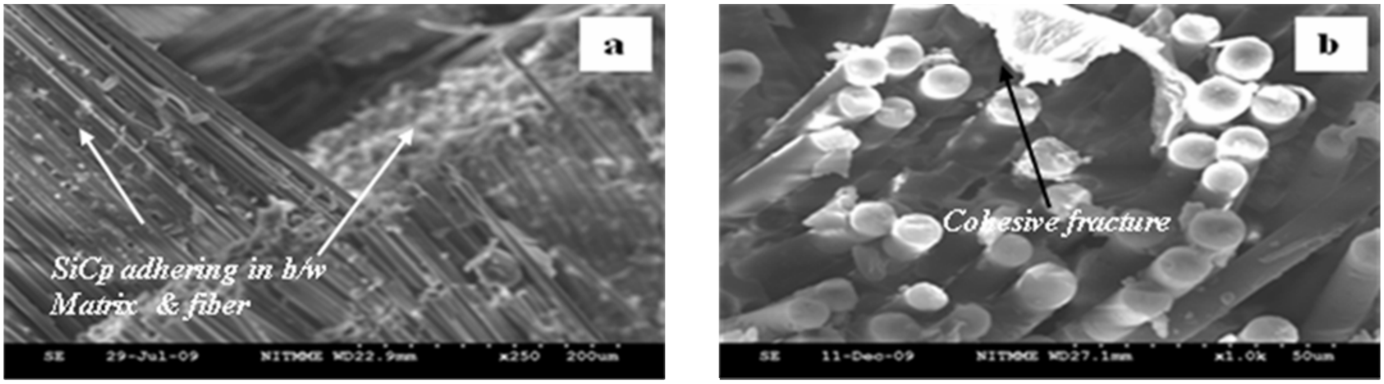

Figure 4 SEM images of tensile fracture surface of SiC-G-E composite (a) 250 x and (b) 1000 x

Generally composites are filled with inorganic fillers. The thermal micro-cracks may be produced after the processing as a consequence of the different coefficient of thermal expansions of fillers in matrix. It is thus very likely that the partial re-opening of the thermal micro-cracks contributes to the non-linear stress-strain behavior at the lower loads. The non-linear behavior can also be possibly attributed to multiple debonding at the fiber-matrix and filler-matrix interfaces, crack formation, crack propagation and deflection, when the tensile/compressive loads increasing, since the interfaces mainly depend on the mechanical bonding has discussed many researches (Suresha *et al.,* 2010; Zhang *et al.,* 2002; Qin *et al,,*2003; Anthony ,2001).

The SEM images shows possible failure mode in the laminate with SiC filler is as shown in Figure 4, On the possible fiber-broken section, there is only a slight hint of fibers debonding. The mode of fiber failure in tension is fiber breakage and compression is fiber buckling was observed in the failed sample (Figure 3, Figure 5 and Figure 7). The fiber breakage appeared to be a brittle type of fracture. These fiber fractures were observed at matrix cracks as shown in Figure 3 the final failure of specimen occurred when localized areas of damage merged, increasing the stress on neighboring undamaged areas. The increased stress accelerated the accumulation of damage until the specimen failed.

3.2.2 Fracture at bending: The SEM images in Figures 5 and 6 show the fractured surfaces (obtained by three point bending test) of the unfilled and SiC particulate filled composite systems, respectively. The SEM images revealed that brittle type of fracture along with instant multiple fractures. This is due to delamination between fiber and matrix due to bending action. The main delamiantion was produced by interlaminar stresses and failure was observed at middle of the specimen. In Figure 5a indicates fracture surface of unfilled G-E composites under three point bending action. It is very clear from the SEM image that debonds and broken fibers were essentially localized in the vicinity of rollers where the compressive stresses and tensile stresses are higher. The bonding was weaker, extensive fiber pull out, fiber breakage, and kink band formation in the fiber due to higher tensile stress at the bottom region. The SEM images shown in Figure 5b supports poor interfacial adhesion between fiber and matrix including bending and cutting of fibers along longitudinal direction due to higher compressive stress at top region of the specimen.

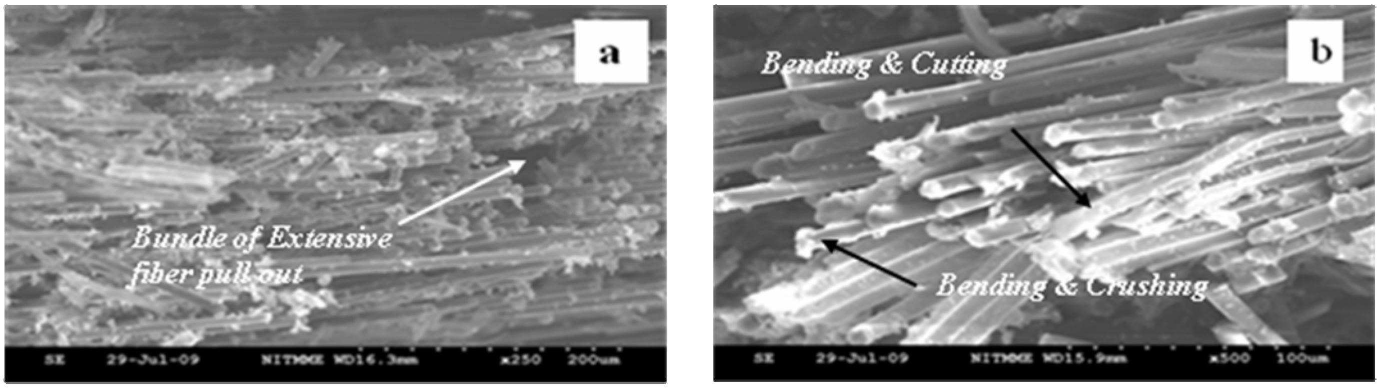

Figure 5 SEM images of flexural fractured surface of G-E composite, (a) 200 x and (b) 500 x

SEM images of the SiC filled G-E composite fractured surface (obtained by three point bending test) revealed very different fracture morphologies than that of unfilled G-E composite as shown in Figure 6a and 6b. The SiC filled G-E composites revealed that simultaneous breakage of fibers and matrix, less delamination and less fiber breakage led to a resist the flexural strength which evidenced better interfacial adhesion is shown in Figure 6a .The hard SiC particles in the matrix were attributed to the improvement in bending strength. Other important failure features, a lot of hackles in the epoxy matrix, due to shearing action of fiber/matrix and broken fibers and good fiber matrix bonding and it posses high strength under bending loads, which is evidenced by a less fiber bends at lower region and fiber breakage / cutting at single action at top region and a bundle broken fibers are straight at middle regions are show in Figure 6b.

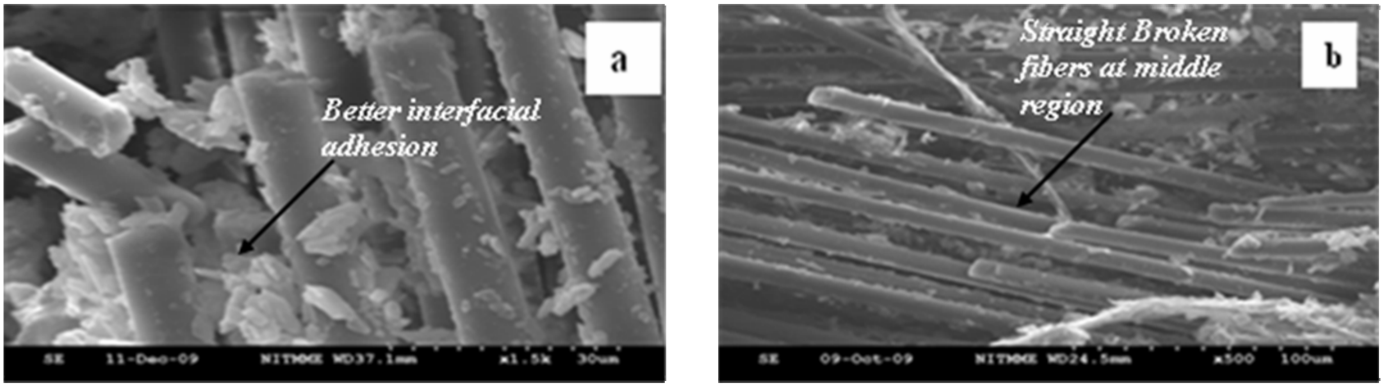

Figure 6 SEM images of flexural fractured surface of SiC-G-E composite, (a)1500 x and (b) 500 x

***3.2.3 Compression fracture**:* The SEM image (Figure 7 and Figure 8) reveal that axial compressive failure of G-E and SiC-G-E composite specimen. The failure of composites in axial compressive is mainly due to plastic micro buckling. Fiber kinking and fiber breakage are the two modes of fiber breakages were observed in compressive fractured specimen. The fractured surface shows a lot of hackles in the epoxy matrix with debonding between fiber-matrix and broken fibers appearance to be a brittle fracture.

Two modes of fiber breakage were observed in the failed composite samples. In Figure7a fiber kinks and warp tows kinked back. This fiber kinking occurred close to the fracture surface, most likely at or near the time of final failure. As the warp fibers kinked, an additional localized load was developed which pushed the broken fibers into the neighboring fill tows (Figure 7b) and. fiber breakage appeared to be a brittle fracture. These fiber fractures were observed at matrix cracks as shown in Figure 7b, and were more frequent and wide spread than the fiber kinking failures. The final failure of specimen occurred when localized areas of damage merged, increasing the stress on neighboring undamaged areas. The increased stress accelerated the accumulation of damage until the specimen failed and breaking of the fibers gradually depending on the fiber orientation. When SiC filled composites (Figure 8) revels that the improves the interfacial bond strength reduces the debonding of the composites this is an evidence in SEM images of SiC filled composite shows less fiber matrix damage

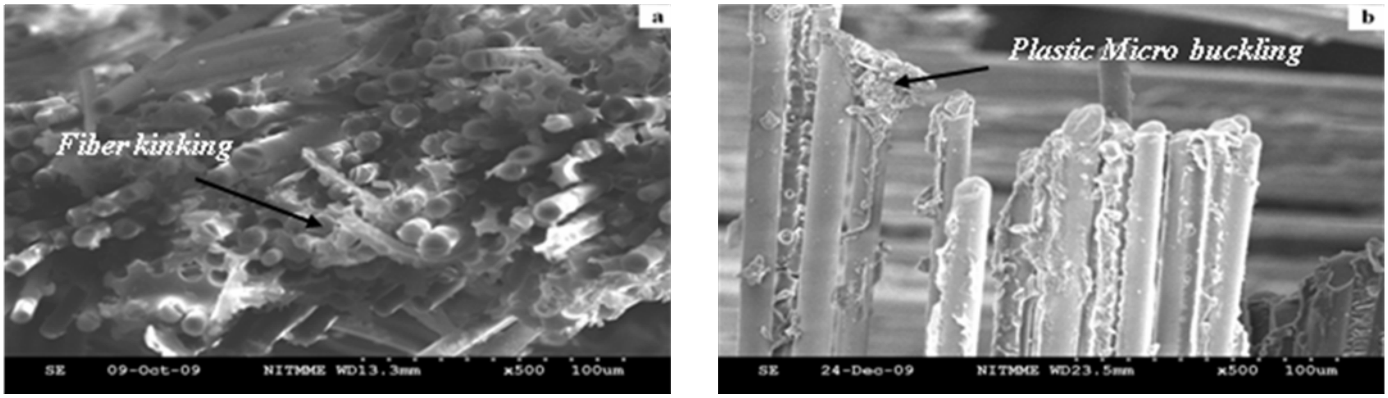

Figure 7 SEM images of Compression fractured surface of G-E composite, (a) 500 x and (b) 500 x

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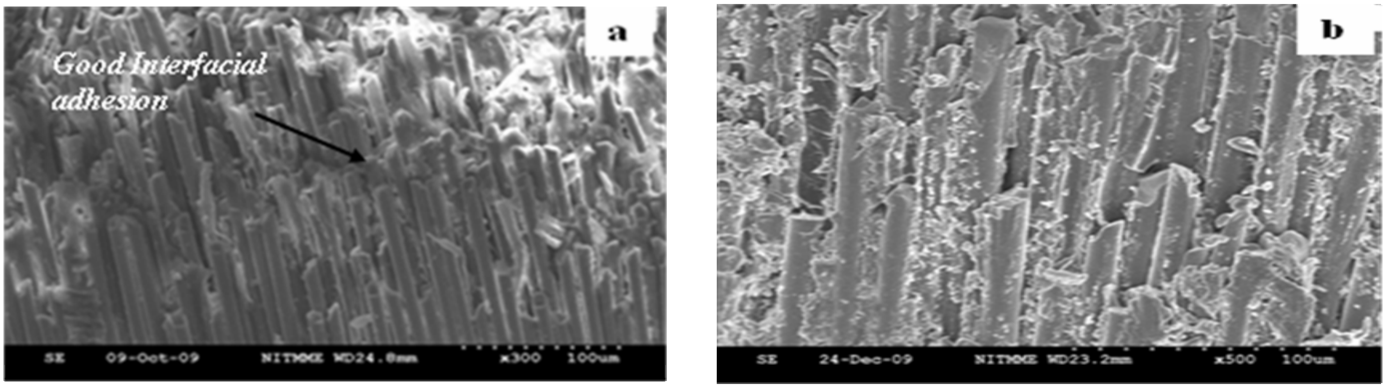

Figure 8 SEM images of compression fractured surface of SiC-G-E composite (a) 300 x and (b) 500 x

3.3 Wear loss and specific wear rate:

The plot of wear loss as a function of temperature for unfilled and silicon carbide filled G-E composites at 10 and 20 N loads are shown in Figure 9a and 9b respectively. It is observed that the wear loss of composites increases with increase in applied load and temperature. Due to thermal softening, initially in both type of composites the epoxy matrix was detached from the composite surface and after certain sliding distance shear deformed polymer matrix containing broken pulverized matrix powder which spreads on the counter surface. This remains there some time as a transfer layer on the steel counter face and Fig.9c show the supportive evidence of wear track on steel disc. In case of unfilled glass-epoxy composite the broken pulverized glass particles can act as a third body abrasive leading to enhanced roughening of the counter surface. Hence, the soften epoxy matrix dig into the surface of the composite specimen and enhances the wear loss.

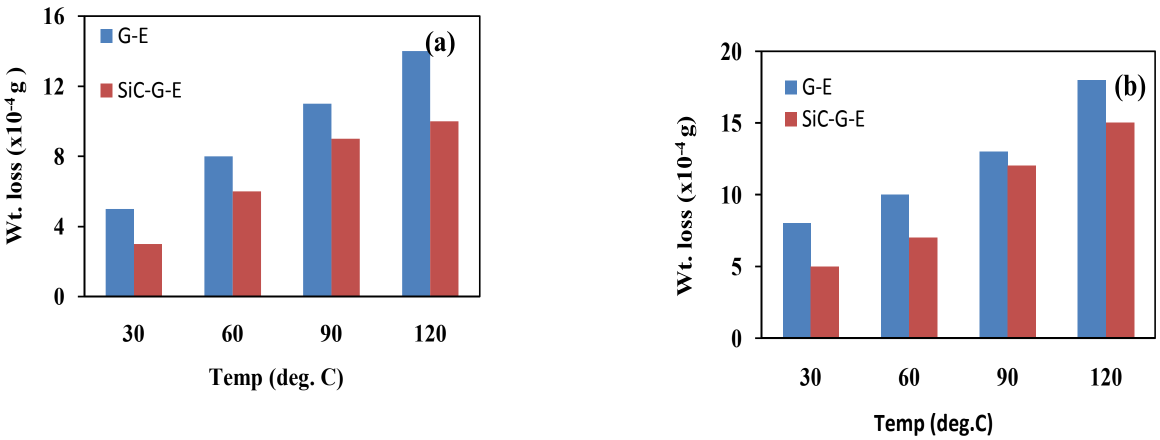

Figure 9(a) and (b) The plot of wear loss as a function of temperature at load of (a) 10 N and (b) 20 N

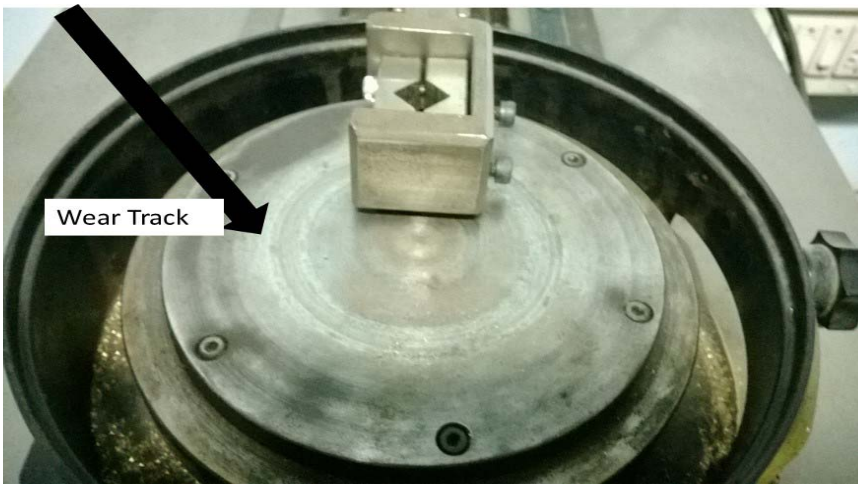

Figure 9(c) Wear track of SiC filled G-E Composites on En 32 steel disc

While in the case of SiC filled G-E composite exhibited the higher wear resistance under different temperature. This behaviour can be attributed to the presence of SiC particles on the counter surface, which resists the plastic deformation and effective barriers to prevent large-scale fragmentation. This phenomenon is more effective at lower temperature, but at higher temperature due to softening effect of polymer reduces the debris formation and failure of surface more on plastic deformation and deep scratches.

Hence, the wear loss of unfilled G-E is much higher than those of SiC filled G-E composite at elevated temperatures. Better wear resistance of SiC filled G-E composite due to SiC is comprising of tetrahedral crystals of carbon and silicon atoms with strong bonds in the lattice. This exhibits a very hard and strong material that has the ability to provide reinforcement. It is evident that the SiC filled composite showed higher wear resistance, higher the mechanical properties confirming the effect of silicon carbide as filler.

The lowest wear loss of 3 x 10^{-4} g was observed in SiC filled glass-epoxy composite at 30^0 C and highest wear loss of 14 x 10^{-4} g was observed in unfilled glass-epoxy composite at 120^0 C temperatures and at applied load of 10 N. Furthermore, higher wear loss of 18 x 10^{-4} g was noticed in unfilled Glass-epoxy composite at 120^0 C and at applied load of 20 N. As compared to SiC filled composite, unfilled Glass-epoxy composite shows more wear loss at all conditions. In case of SiC filled Glass-epoxy composite, wear loss increased with the increase in applied load and temperature. This is due to energy barrier created at the specimen surface is greater due to the reinforcement of SiC particles into the matrix. Hence at even higher loads and higher temperature, energy generated by third body particles at counter face is not sufficient as a result particles cannot get penetrate deeper into the matrix material and which acts as a transfer layer and only a micro fracture of matrix material. The wear data of the composites reveal that the wear loss strongly depends on the applied load and temperature.

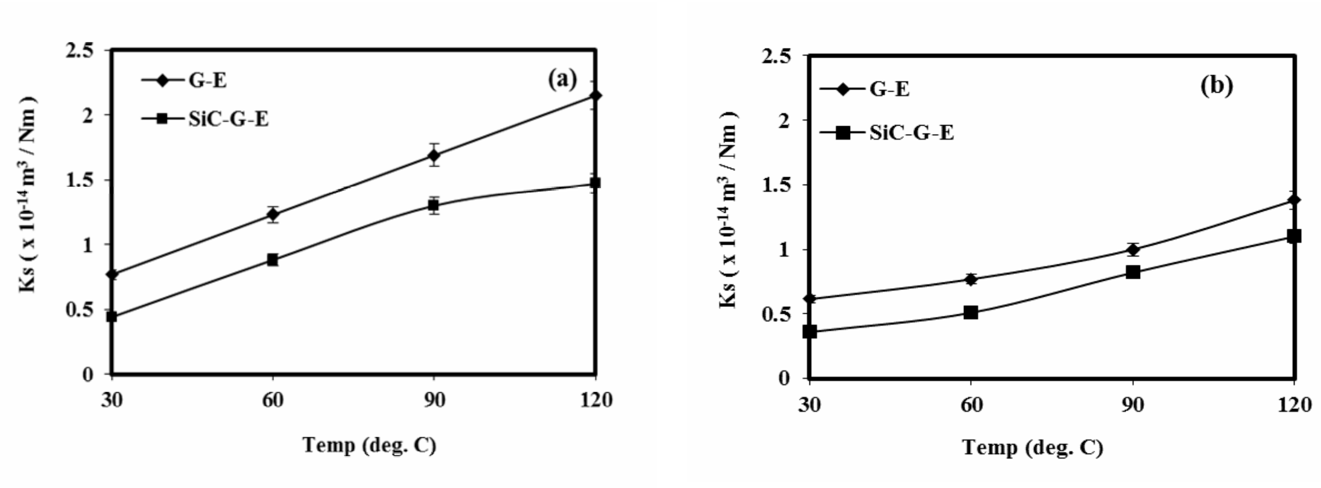

Figure 10 Specific wear rate versus temperature of G-E and SiC-G-E composites at (a) 10 N and (b) 20 N loads

The plot of specific wear rate (K_s) as a function of temperature is as shown in Figs 10a and b. The specific wear rate increases with increase in temperature and decreases with increase in applied load. The lowest K_s (0.3 x 10^{-14} m^3 / Nm) for SiC filled Glass-epoxy composite and highest K_s (2 x 10^{-14} m^3 / Nm) for unfilled Glass-epoxy composite were observed. As compared to unfilled G-E composite the SiC filled composite shows low specific wear rate at all condition due to matrix used in this work is thermoset and the reduction in specific wear rate after incorporation of SiC filler in GE composite and which acts as a anti wear additive.

3.4 Coefficient of friction:

The main mechanism of frictional energy dissipation will be shear of a few nanometers thin zone of the composite at the interface. If the sheared layer of composite film may be deposited on the smooth counter surface which acts as a transfer layer and subsequently the frictional energy dissipation mainly takes place either in the transfer film or in a very thin layer [23].The detached thin layer from the matrix was directly contact with the counter surface. The plot of coefficient of friction (μ) as a function of temperature for unfilled G-E composite and SiC filled G-E composite are shown in Figure 11(a) and (b).

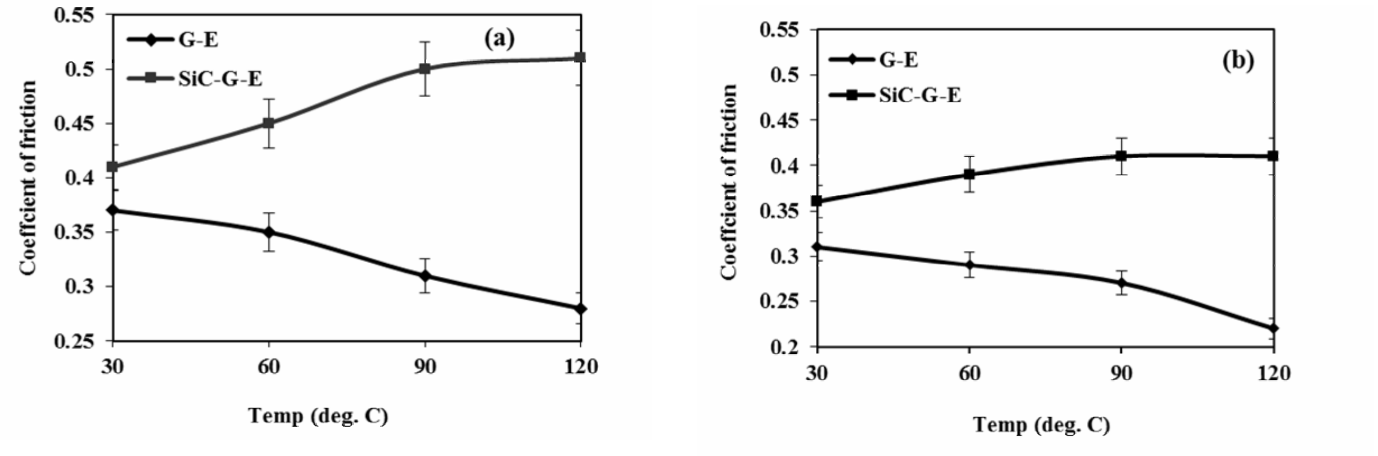

Figure 11 Coefficient of friction versus temperature at a load of (a) 10 N and (b) 20 N

It was observed that the coefficient of friction decreases as increase in temperature and applied load for G-E composite. As compared to unfilled G-E composite the SiC filled G-E composite shows higher coefficient of friction and the friction coefficient was increases with increasing temperature and applied load. (Fouquet *et al.,* 2007) reported that the presence of silicon in the composite matrix greatly influences the third body morphology and generates adhesive friction due to increase in coefficient of friction there by leading to less wear and similar observation was found in the present investigation.

3.5 Energy Dispersive X-Ray Spectroscopy and Worn Surface Morphology of composite specimen

The surface morphologies shown in Figure 12 to 13 of the SiC_P filled and unfilled glass epoxy composite specimen were characterized using a Hitachi S- 4700 field emission gun scanning electron microscope (FEGSEM) equipped with an energy dispersive X-ray spectrometer (EDS), manufacture by EDAX Inc., US. EDS is accurate for the presence of elements qualitatively and it may be the same quantitatively also. The detection error of EDS is within the limits of 2% in all cases irrespective of spot size, magnification and current.

The EDS analysis is done to indicate the composition of elements presents in the worn out SiCp G-E specimen. The obtained values of chemical composition are given in Table 4. From Fig.12c among all the elements the presence of silica are rich in the composites specimen and a very small amounts of iron oxides this is due to the rubbing action of specimen against steel disc.

In glass fabric reinforced-epoxy composites the process of material removal in dry sliding condition is dominated by four wear mechanisms, viz., matrix wear, fiber sliding wear, fiber fracture and interfacial debonding. The matrix wear occurs due to plastic deformation and fiber sliding wear occurs due to fiber rubbing, fiber rupture, fiber cracking, and fiber pulverizing (Friedrich, 1985).

The SEM photographs of worn surfaces of unfilled and SiC filled composite samples at 20 N load, constant sliding velocity of 1.5 m/s and for an sliding distance of 5000 m at two different temperatures of 30^0 C and 120^0 C are shown in Figures 12-13. Figure 12a and b represent the worn surface features of unfilled glass-epoxy composite. At lower temperature (30^0C) SEM image (Figure 12a) indicate some of the matrix enveloping the glass fiber and protects the fiber from damage and micro crakes and matrix fracture takes place in the form of brittle manner and formation of debris was observed. With increase in temperature from 30^0 C to 120^0 C, worn surface shows more fiber and matrix was removed from the surface and detachment of matrix in between the fiber and also more voids formation due to thermal softening of the matrix (Figure 12b).

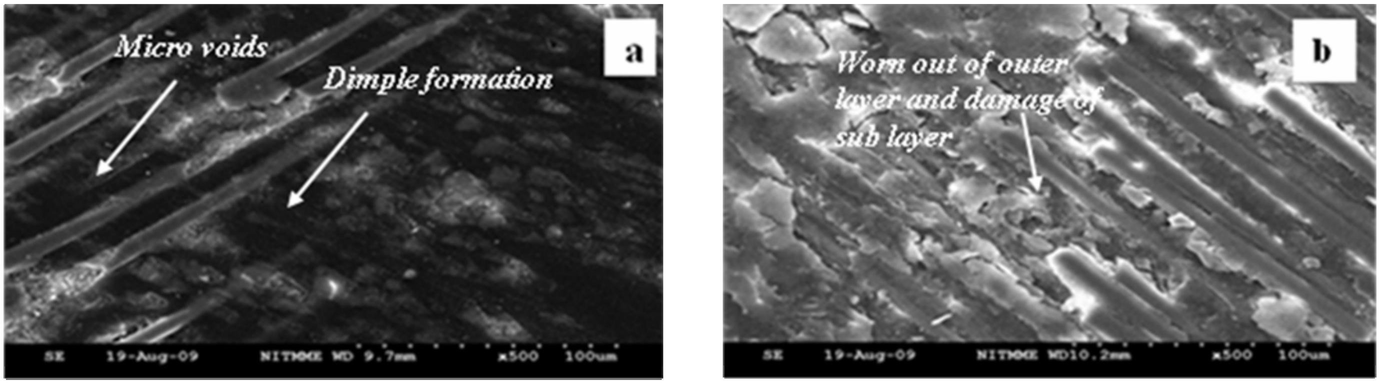

Figure12 SEM images of unfilled glass-epoxy composite at 20 N load and at (a) 30^0 C and (b) 120^0C

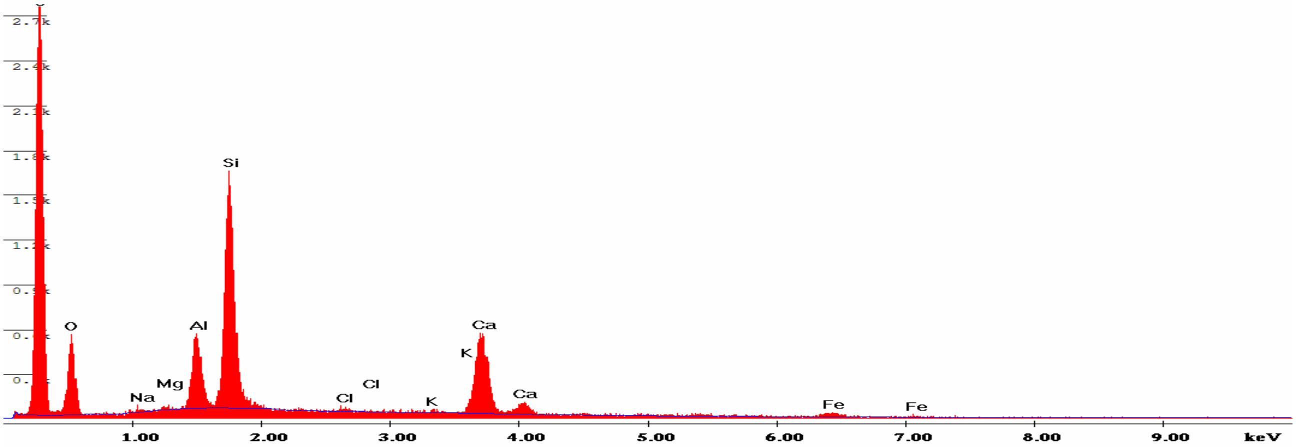

Figure12(c) EDS spectra of elemental composition of worn surface of SiC G-E Composite specimen at 120^0 C

Table 4 Chemical composition of worn SiC filled G-E composite specimen

Element	C	O	Na	Mg	Al	Si	Cl	K	Ca	Fe
Wt. %.	64.67	11.06	0.18	0.16	2.95	10.27	0.24	0.23	8.49	1.74

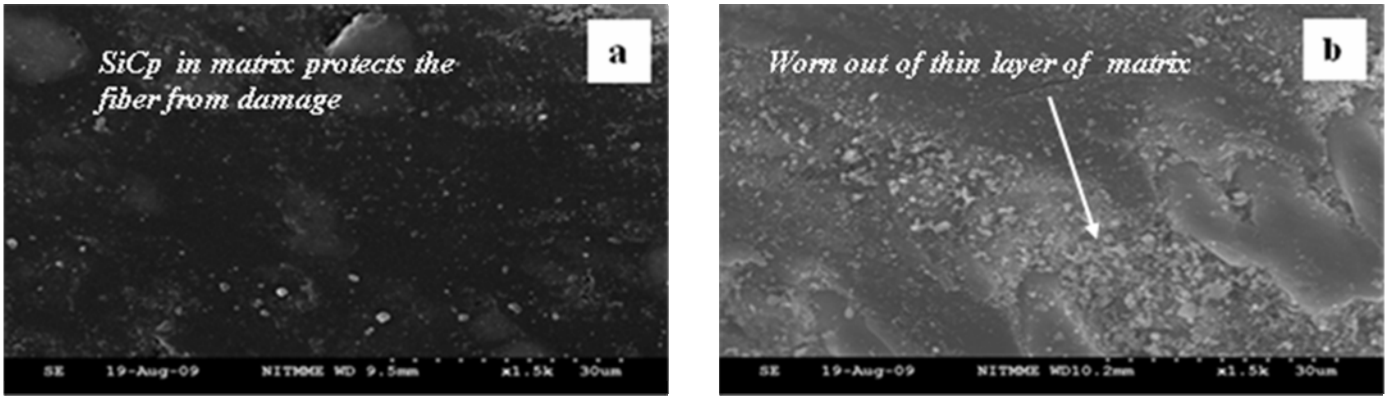

Figure 13 SEM images of SiCp filled glass-epoxy composites at 20 N and at (a) 30^0 C and (b) 120^0 C

In SiC filled glass-epoxy composite (Figures. 13a and b) the SiC particles are well protects the fiber from damage and worn surface was relatively rough and less damage to the fiber and matrix was observed. In Figure13a at lower temperature the SEM photograph indicate the worn surfaces are much smoother and the glass fiber detachment was limited and no exposure of fiber and damage was thin. At higher temperature in Figure13b shows a thin layer of matrix was eroded including a parting up of top and bottom layer and less exposure of fiber was observed.

As compared to unfilled G-E composite (Figure 12(a)) in silicon carbide filled composite (Figure 13(b)) shows less damage of matrix and fibers are observed. The presence of silica particles in the epoxy matrix acts as a anti wear properties and led to an enhanced load-bearing capacity of the composite. These hard silica particles in the matrix show lower specific wear rate and higher wear resistance and higher friction coefficient.

4. Conclusions

The following conclusions were derived from the results of the investigation.

- Incorporation of silicon carbide particles into glass fabric/epoxy as a secondary reinforcement composites leads to an enhancement of their mechanical properties, such as Young's modulus, tensile strength, flexural strength and compression strength. The SEM images of the specimen reveals micromechanism of fractured surface.
- The sliding wear loss in both type of composites increases with an increase in temperature and applied load.
- The wear performance of unfilled glass-epoxy composite possesses strong relation with the applied load and temperature. The enhancement on the wear resistance of silicon carbide filled glass-epoxy composite is associated with less fiber matrix loss.
- The increase in temperature leads to a reduction in coefficient of friction at higher loads and it causes a reduction in the friction performance and higher the friction coeffiecnet was observed in SiC filled composites.

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