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Visual Abstract

Investigation on influence of SiCp on three-body abrasive wear behaviour of glass/epoxy composites

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ABSTRACT. The study presents the influence of SiCp incorporation on three-body abrasive wear behaviour of glass/epoxy composites. The investigation was carried out using dry sand rubber wheel abrasive wear test apparatus. 2k factorial design of experiments was used to capture the experimental data. The parameters considered are abrading distance, load and speed. The wear rate was found to increase with the increasing values of wear parameters. The applied load has exhibited significant effect on wear rate. Incorporation of SiCp contributed to enhance wear resistance of glass/epoxy composites. The linear regression was also presented in the study to correlate abrasion parameters with wear rate. SEM image analysis of abraded surface revealed the occurrence of ploughing, micro-cutting, matrix removal and fiber breakage.

KEYWORDS. Polymer Matrix Composites; Wear; Statistical model; Scanning Electron Microscopy.

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INTRODUCTION

Polymer Matrix Composites (PMCs) are gaining popularity in many engineering applications like chute liners, gears, abrasive pumps, cams, bearings, bushes, bearing cages and other structural applications because of good mechanical and tribological characteristics. Abrasive wear plays a vital role in industrial applications like power plant chute liner, mining and earthmoving equipment [1]. The sliding of forced irregularly shaped hard particles against the soft matrix materials causes abrasive wear, which lead to severe damage and removal of the material by ploughing and rubbing mechanisms [2, 3].

During three-body abrasion, abrading medium is entrapped between two bodies which having relative motion between them. The asperities are free to roll and slide. Besides with the application of load, abrasive particles penetrate and detach material from the soft surface and produce crater. Abrasive particles size, sliding velocity, abrading distance and applied load are important parameters which highly effect the abrasion characteristic of PMCs [2]. Abrasive wear resistance increases with the increased fiber volume fraction of PMCs. Further, abrasive wear resistance improves with the increase in the modulus of the reinforced fibers almost linearly and polymer matrices within optimal range of volume fraction [4, 5]. Wear behaviour also depends on the orientation of fibers in the composites; fibers perpendicular to the sliding surface presents less abrasion [6].

Lee et al. [7] presented physical model for the two-body abrasive wear characteristic of composite materials. The model explains the abrasive wear mechanism possible in two-dimensional with reinforcement effect, but it has a limitation in explaining the mechanism possible in three dimensions. Torrance [8] presented a model for the two-body abrasive wear with progress approaching towards real process and concluded that a further development is needed to improve existing models to approach real process. Bijwe et al. [6] has reported that the aramid fiber reinforced polyetherimide exhibited good abrasive wear resistance, whereas carbon and glass fibers reinforcement show satisfactory results. Vasconcelos et al. [9] studied both reciprocating and abrasive wear of epoxy-based composites and concluded that wear rate decreases with increasing aluminum powder reinforcement, also as a result of reinforcement of carbon and glass fiber. Sakthivel et al. [10] presented the work on three body abrasive wear behaviour of sansevieria cylindrica fiber (SCF) and e-glass fiber (EGF) reinforced polyester (PR) composites. The composite containing 30% SCF, 20% EGF and 50% PR by weight fraction revealed better wear resistance compared to other studied composite specimens. Zhang et al. [11] stated that the wear loss and wear rate of alkali-treated eucalyptus/PVC composites due to three-body abrasion has relatively decreased in comparison to natural eucalyptus fiber. Further, micro-cutting and micro-indentations were prominent wear mechanisms of studied materials.

Addition of fillers into the polymer matrix composites enhances its desired characteristics. Cenna et al. [12] concluded that the incorporation of ultra-high-molecular-weight polyethylene (UHMPE) particles in PMCs decreases the wear loss due to abrasion. Prehn et al. [13] demonstrated that addition of SiCp particles has a positive effect compared to neat PEEK and epoxy resin material toward enhancement of abrasive wear resistance. Suresh and Chandramohan [3] reported that the SiCp filled composites showed better wear resistance. Also, they have illustrated that the graphite filled composites were observed to be not very beneficial. Rudresh et al. [14] noticed that PA66/PTFE/short glass fiber composites possess better abrasion resistance. Enhanced fracture energy and hardness of composites governed their wear resistance characteristics. Suresha et al. [15] investigated the three-body abrasive wear behaviour of high-density polyethylene (HDPE)/ UHMPE composites reinforced with glass fiber and Zirconia (ZrO_2). They have also demonstrated that specific wear rate increases with increase in filler/fiber content of composites. Jesthi and Nayak [16] presented a mathematical model to predict the specific wear rate. The micro-cutting, micro-ploughing and fiber breaking were dominant wear mechanisms of composites.

Sahin [17] and Mondal et al [18] has reported that 2^k factorial design of experiments can be employed for describing the abrasive wear behaviour of composites. Sahin [17] has employed 2^3 factorial design of experiments where 3 corresponding to abrading distance, applied load and abrasive size. Mondal et. al [18] have employed 2^2 factorial design of experiments, k=2 corresponding to abrasive particle size and applied load. Further, it was inferred from the studied that, factorial design of experiments is useful for establishing the linear relationship to predict the wear behaviour within the selected experimental conditions. The design of experiments by Taguchi approach can be adopted successfully to analyze the friction and wear behaviour of composites [19-21]. Hemant et al. [22] employ L9 Taguchi orthogonal array to study abrasive wear behaviour of hexagonal boron nitride incorporated polyetherketone (PEK) composites. The study shown that filler incorporation diminished the wear resistance of PEK material under three-body abrasion due to reduction in hardness and impact strength. The retrospection on available literature revealed that the presence of scope for to studying the three-body abrasive wear behaviour of PMCs with varied SiCp filler. Thus, the current research pays attention on the investigation of three-body abrasive wear behaviour of glass/epoxy composites with varied volume fraction of SiCp filler using factorial design of experiments.

EXPERIMENTATION

Materials

The medium viscosity epoxy was used as matrix with trade mark of LAPOX L-12. The curing agent used in the study is polyamine hardener K-6. The reinforcement used was 7-mil E-Glass fiber. SiCp passed through 400 mesh sieves was used as filler material, since it is hardest and is expected to the improve the abrasive wear resistance of composites.

The hand lay-up technique was used to produce specimen as per details provided in Tab. 1. The composite laminates were prepared as reported by Basavarajappa et al. [23]. The cured laminates were cut to obtain desired specimen of size 76mm×25mm×3mm as per ASTM G 65 standards [24]. The details of the composite specimens prepared and char tested are given in Tab. 1.

Matrix	Volume%	Reinforcement	Volume%	Filler	Volume%
Epoxy	50	Glass Fiber	50	--	--
Epoxy	45	Glass Fiber	50	SiCp	5
Epoxy	40	Glass Fiber	50	SiCp	10
Epoxy	35	Glass Fiber	50	SiCp	15

Table 1. Details of samples prepared.

Plan of experiments

The 2^k factorial design of experiment was employed in current research, where 'k' denotes number of parameters and '2' denotes number of levels. The parameters considered were abrading distance, load and speed. The 2^k factorial design of experiments can be successfully employed to capture the experimental data in systematic manner. Also, it aids to establish relationship between experimental parameters with responses [17, 18]. Eight experimental runs were repeated twice and average reading was analyzed alike in reported literatures [17, 23]. The experiments were conducted as per the experimental design given in each row and corresponding uncoded values of parameters are illustrated in first 3 columns of Tab. 3. The regression model of obtained result is expressed as

$$W = a_0 + a_1 x + a_2 y + a_3 z + a_4 xy + +a_5 yz + a_6 xz + a_7 xyz \tag{1}$$

where W is the wear rate, a_0 is the response parameter of wear at base level, with a_1, a_2 and a_3 are correspondingly coefficients of load, speed and abrading distance.

Abrasive Wear

Three-body abrasive wear experiments were performed on dry sand rubber wheel abrasive wear test (RWAT) rig to study the abrasive wear behaviour of composites. The test set up and experiment was conducted according to ASTM G 65 standards.

Three-body abrasive wear experiments were performed on dry sand rubber wheel abrasive wear test (RWAT) rig in accordance with ASTM G 65. The Chlorobutyl rubber wheel and quartz abrasive particles with approximately 200μm size were employed in experimentation. The flow of abrading particles was attained between rotating wheel and specimen at 372 g/min and the wheel was rotated at desired speed (75rpm and 100rpm). The specimens were cleaned using acetone, the initial and final mass loss were measured with the help of digital balance with an accuracy of 0.1mg. The mass loss was then converted into wear rate using measured density data. Further, applied load and abrading distance were varied at two levels viz. 75N and 100N load and 75m and 100m distance respectively.

Trial No.	Sliding Speed (rpm)	Abrading Distance (m)	Applied Load (N)	Wear Rate ($\times 10^{-6}$ mm^3/N-m)			
				G-E	G-E+ 5%SiCp	G-E+ 10%SiCp	G-E+ 15%SiCp
1	75	75	75	66.916	49.582	42.951	40.018
2	100	75	75	75.573	62.151	56.622	52.284
3	75	100	75	64.973	50.773	45.320	42.507
4	100	100	75	77.320	54.413	52.093	48.493
5	75	75	100	73.680	52.573	48.093	46.413
6	100	75	100	87.120	56.227	51.667	49.173
7	75	100	100	71.150	45.390	41.680	39.710
8	100	100	100	78.050	47.710	43.290	41.380

Table 2: Experimental results.

RESULT AND DISCUSSION

Three-body abrasive wear behaviour of glass/epoxy composites was investigated with the aim to correlate load, speed and abrading distance with wear loss due to abrasion of composite. The experiments are conducted as per 2^3 factorial design of experiments. The experiments are repeated twice and average values are considered for the analysis and are shown in Tab. 2.

The linear regression model was developed using MINITAB – R15. The linear regression models are presented as Eq. (2) to (5) respectively representing wear equation of unfilled, 5% SiCp, 10% SiCp and 15% SiCp filled glass-epoxy composites.

$$W_0 = -0.537 + 0.00488L + 0.00325D + 0.00027\mathrm{S} + 0.000016(\mathrm{L}\times\mathrm{D}) + 0.000023(\mathrm{L}\times\mathrm{S}) + 0.000010(\mathrm{D}\times\mathrm{S})$$

R-Sq. =99.5%   R-Sq.(Adj.)=96.3%   (2)

$$W_5 = -1.12 + 0.00979L + 0.00926D + 0.00814\mathrm{S} - 0.000036(\mathrm{L}\times\mathrm{D}) - 0.000038(\mathrm{L}\times\mathrm{S}) - 0.000038(\mathrm{D}\times\mathrm{S})$$

R-Sq. =99.3%   R-Sq.(Adj.)=95%   (3)

$$W_{10} = -1.49 + 0.0138L + 0.0109D + 0.0102\mathrm{S} - 0.00006(\mathrm{L}\times\mathrm{D}) - 0.000064(\mathrm{L}\times\mathrm{S}) - 0.000034(\mathrm{D}\times\mathrm{S})$$

R-Sq. =99.8%   R-Sq.(Adj.)=98.6%   (4)

$$W_{15} = -1.37 + 0.0135L + 0.00939D + 0.00883\mathrm{S} - 0.000055(\mathrm{L}\times\mathrm{D}) - 0.000061(\mathrm{L}\times\mathrm{S}) - 0.000022(\mathrm{D}\times\mathrm{S})$$

R-Sq. =99.8%   R-Sq.(Adj.)=98.6%   (5)

wWhere W_0, W_5, W_{10} and W_{15} represents the wear rate of the composites with unfilled, incorporated with 5%, 10% and 15% SiCp respectively. The terms L, S and D represents the applied load, speed and abrading distance parameters. The coefficients of load, abrading distance and speed in the Eqns. (2) to (5) are positive, suggesting increased wear rate with increasing values of parameters. The R-Sq value indicates the coefficient of determination of respective regression model. The obtained R-Sq values for all regression models are above 0.98. It confirms that obtained models give good results within the experimental conditions ranging from 75rpm to 100rpm of sliding speed, 75m to 100m of abrading distance and 75N to 100N load.

The constant values of model for unfilled and SiCp filled G-E composites are negative. The a_0 represents the point of intercept of regression plane and is a mean response value of experimental trials carried out [25 - 27]. It depends mainly on the important parameters considered in this study and also associated with experimental abnormalities like environmental conditions, machine vibrations, so on. The values of a0 and experimental results illustrates that SiCp filled G-E composites have better wear resistance than the unfilled G-E composites. The abrasive wear resistance increases with the increase in the filler volume fraction equal to 10%. Further increase in filler volume fraction has not found much effect on the abrasive wear resistance of the composites and there may be chances of detrimental effect.

The positive values of the coefficients of load, abrading distance and speed reveal that wear rate increases with increase in the associated parameter. The negative value of coefficients suggests an opposite effect. From the Eq. (2)-(5), it is observed that applied load, abrading distance and sliding speed has more effect on the abrasive wear of the composites. However, interaction among the parameters is not statistically significant.

The coefficients of associated parameter for applied load possess highest magnitude; it demonstrates that applied load has greater significance followed by abrading distance and least significance was found to sliding speed. Hence, wear rate of the composites increases with the increase in applied load and abrading distance and slightly lower for sliding speed in the range of parameters considered in the study. While load is applied on the specimen, it induces high stress on the counterface of the rubber wheel and concurrently stress is transferred to abrading particles. The free-flowing abrasive particles penetrate into soft matrix material, which produces groove. The penetrated abrasive particles execute ploughing of matrix layer, later performs microcutting of high modulus glass fibers. However, the depth of the penetration of abrading medium is subjected to various parameters such as abrasive type, size and hardness of abrasive particles, load environment and matrix material hardness [13]. As a result, greater wear rate of the material is due to the abrasive wear.

The increase in sliding distance increases the encounter of specimen surface with abrasive particles and the rubber wheel. Successively more stress is transferred from rubber wheel to the abrasive particles. Thus, depth of groove increases with the increase in sliding distance. As the sliding speed increases, sliding abrasive particles generates heat at the counterface of rubber wheel and composite which softens the matrix layer. Further increase in speed helps the abrasive particle to plough matrix material from the surface. Instantaneously glass fibers are subjected to microcutting and however, glass fibers withstand for the increased temperature. In PMCs the penetration of abrasive particles mainly depends on hardness of the surface and on later the modulus of the glass fibers. The plastic deformation of matrix is low and hence less energy is required to plough the matrix layer. The maximum energy is spent during the later stages for microploughing and microcutting of glass fibers.

In the presence of SiCp filler, the penetration of abrasive particles into matrix is reduced because of the increased hardness. Due to continuous abrasion, the abrasive particles penetration is resisted by the incorporated filler materials, thus increases the abrasive wear resistance of the composites. Further wear resistance is increased by increasing the filler volume fraction, thus decreases the wear rate of the composite due to wear. The increase in SiCp content further would lead to decrease in crosslinking density of the epoxy polymer, thus interfacial bonding strength decreases. The agglomeration of the matrix takes place due to poor adhesion, subsequently filler particles comes out easily [28]. The loose abrasive particles convene with the pulled-out filler particles and together acts as abrasive particles. The increased wear resistance is sufficient for the abrasion of these particles. Hence less difference in wear rate was observed between the 10% and 15% filler content specimens. Hu et al. [29] reported that increase in volume fraction of reinforcement enhance the wear resistance of the composite. However, there is a critical volume fraction above which the resistance offered by composites decreases. Similarly, in the current study there was a critical volume fraction of filler above which relatively less improvement in the abrasive wear resistance was observed. Besides, higher SiCp content in the matrix forms more interfaces that acts as weak points. It contributes for ploughing of composites and pullout of fibers. Hence, it can be concluded that an increase of SiCp content in composites has improved its abrasive wear resistance till 10% while a further increase in SiCp has not found to be relatively lucrative.

The evaluation of the equations was done by conducting the confirmation test. Tab. 3 shows experimental conditions used in the confirmation tests and predicted values by the modeled developed and experimental results. The comparison of results obtained from the experiments and the models in Eqns. (2) to (5) shows a good agreement with deviation within 5%. Hence, Eqns. (2) to (5) are demonstrated as feasible within the experimental conditions as similarly stated by previous literatures [12-14, 18-20].

Composite	Applied load (N)	Abrading distance (m)	Sliding speed (rpm)	Wear Rate (mm^3/N-m) (from expt.)	Wear Rate (mm^3/N-m) (from eqn.)	%age of error
G – E	87.5	87.5	87.5	74.86171	74.66094	0.27
G–E–5%SiCp	87.5	87.5	87.5	52.4578	52.38125	0.15
G–E–10%SiCp	87.5	87.5	87.5	46.24457	47.73125	3.21
G–E–15%SiCp	87.5	87.5	87.5	45.57584	44.8875	1.51

Table 3: Comparison of obtained results with the experimental results.

WORN SURFACE MORPHOLOGY

In order to investigate the abrasive wear mechanism for filled and unfilled G-E composites, the worn out surfaces at different wear regions were examined using SEM. The direction of abrasive particles flow from the upside to the bottom side as depicted in Fig. 1.

Fig. 2(a) depicts the SEM features of worn out surface taken at upside of the specimen at low magnification for unfilled G-E composite. It indicates that the matrix has relatively greater damage when compared to the glass fibers at upside as same as the bottom side~~. It perhaps~~, upside of the specimen is subjected to large contact stress resulting in severe peeling off and damages. The magnified worn microstructure (Fig. 2b and c) evinced the occurrence of macro cutting, fiber breakage, matrix removal and ploughing of fibers under compression and shear stress. Similar observations were made by Suresh et al. [30]. The fibers were fractured into small fragments by the hard-abrasive particles, which were plough out during further abrasion leading to high wear.

On the central area of worn surface, the hard asperities have penetrated into the depth of specimen causing the deep craters. In addition, matrix removal phenomenon demonstrated the characteristic of steady state wear. Fig. 3(a) has also revealed the formation of many pits attributed to the micro-ploughing action of abrasive particles and pull-out of fibers with larger diameter craters. Extensive debris formation with large number of broken fibers were clearly observed through closer inspection (Fig. 3b and c). The well dispersion of matrix material was illustrated in Fig. 3. On contrary, the worn surface of the bottom side of the specimen is smooth; pulling-out and exposure of the glass fibers are nearly invisible (Fig. 4a). At higher magnification (Fig. 4b and c), the worn surface was evinced relatively with lesser matrix and fiber removal; associated with phenomenon of more abrasive particle around the fibers. Harsha et al. [31] reported that worn surface morphology at the entrance and exit zone were similar and uniform. It was perhaps due to the low pressure applied on abrasives, resulting in rolling action of abrasives instead of penetration or ploughing.

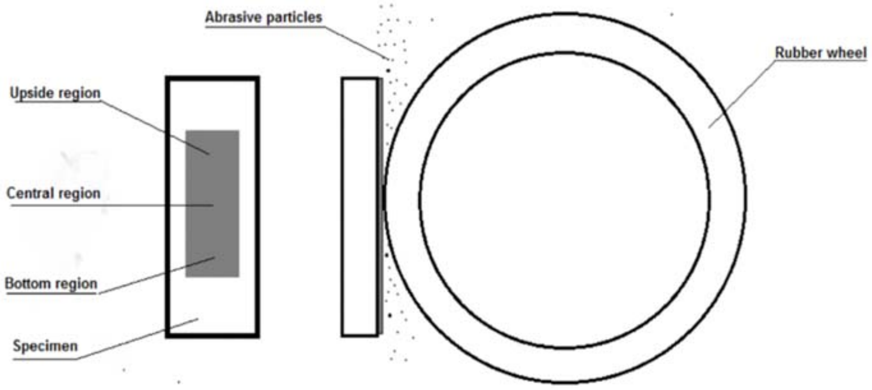

Figure 1: Schematic diagram of different worn region in abrasive wear

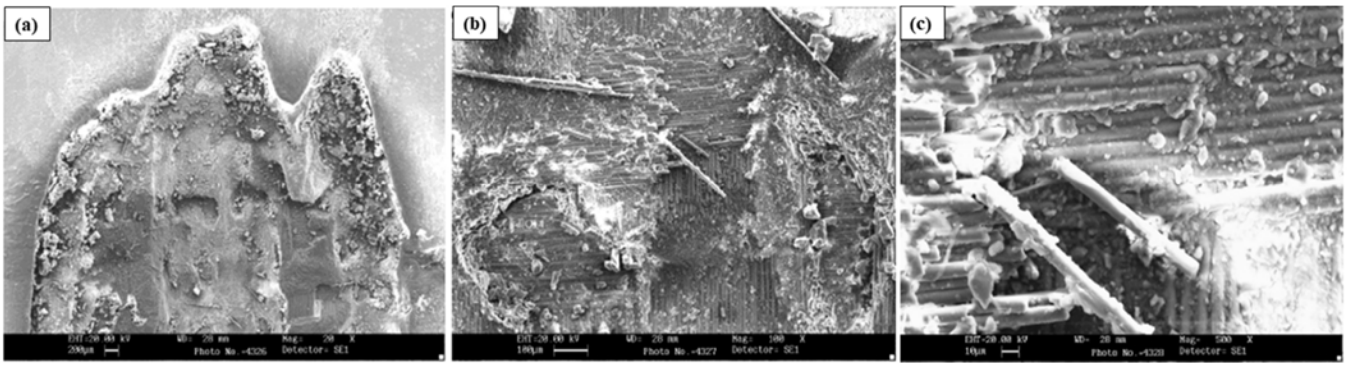

Figure 2: SEM image of unfilled GE composite upside region (a) Low magnification, (b) Moderate magnification, (c) High magnification.

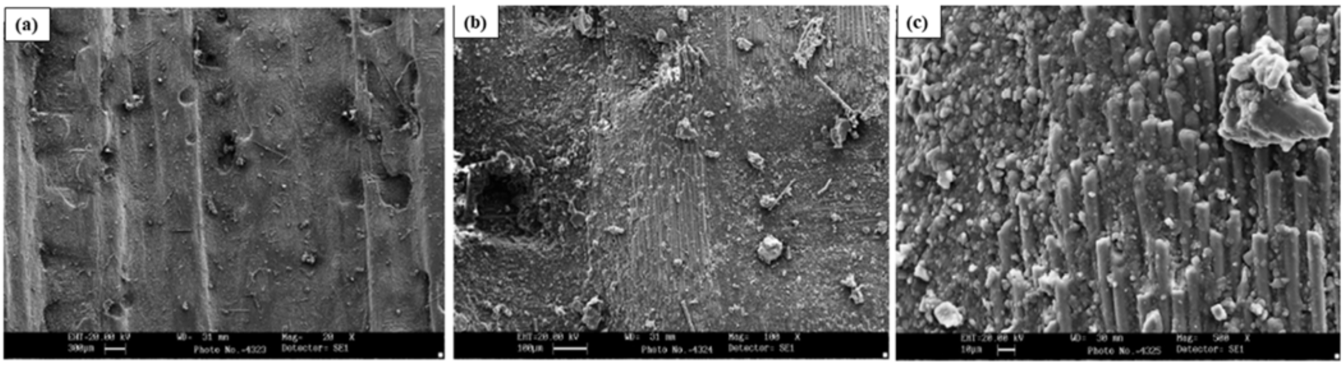

Figure 3: SEM image of unfilled GE composite central region (a) Low magnification, (b) Moderate magnification, (c) High magnification.

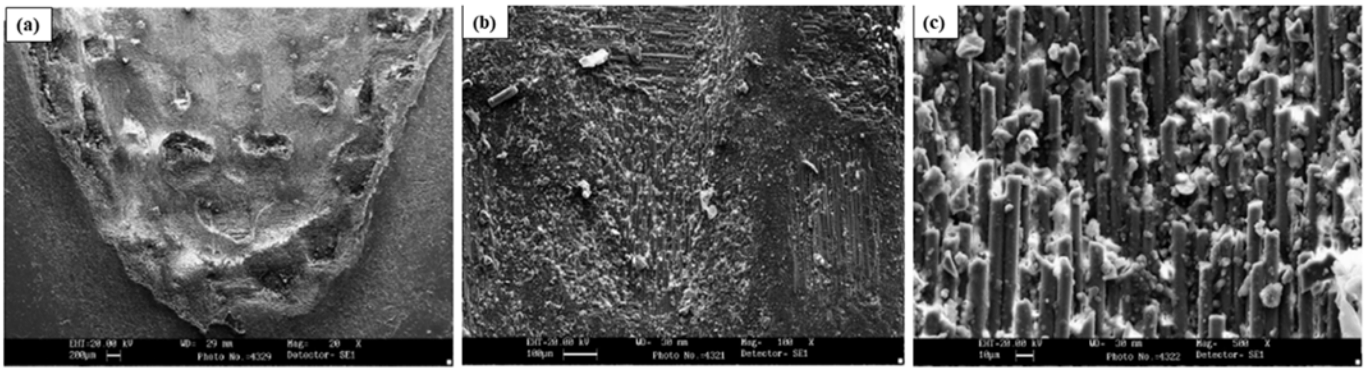

Figure 4: SEM image of unfilled GE composite bottom region (a) Low magnification, (b) Moderate magnification, (c) High magnification

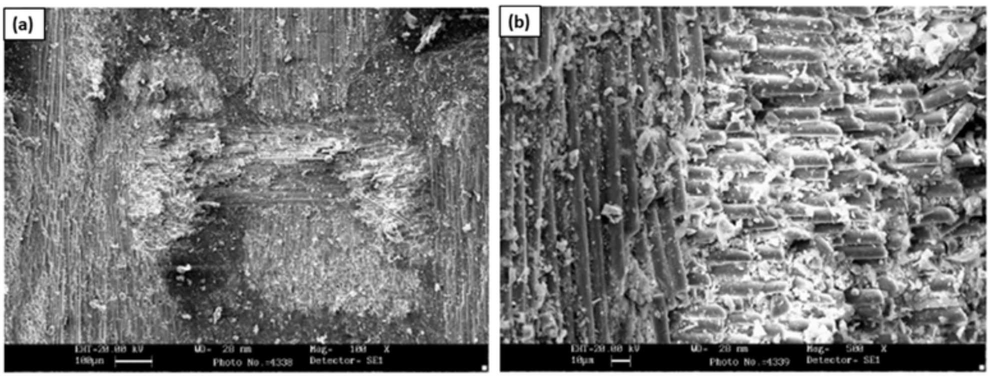

Figure 5: SEM image of SiCp filled GE composite upside region (a) Moderate magnification, (b) High magnification.

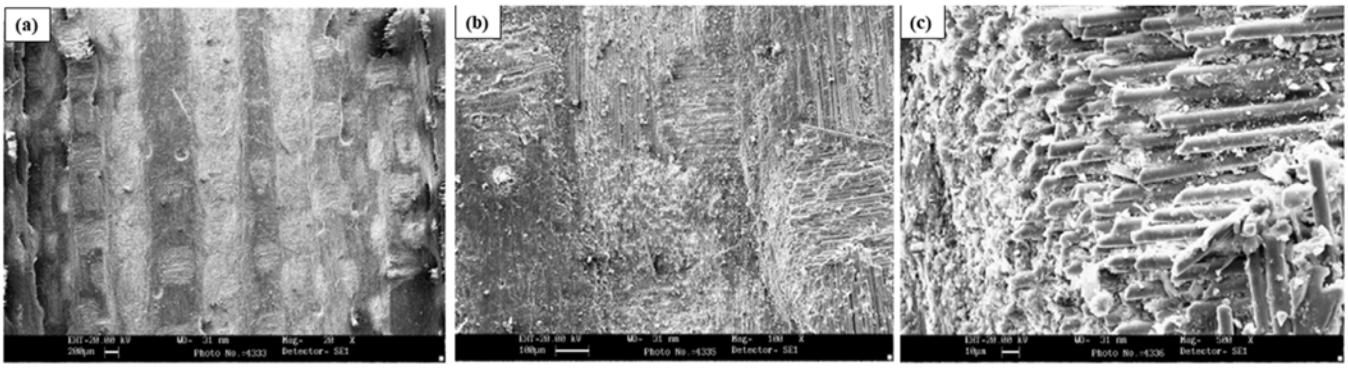

Figure 6: SEM image of SiCp filled GE composite central region (a) Low magnification, (b) Moderate magnification, (c) High magnification.

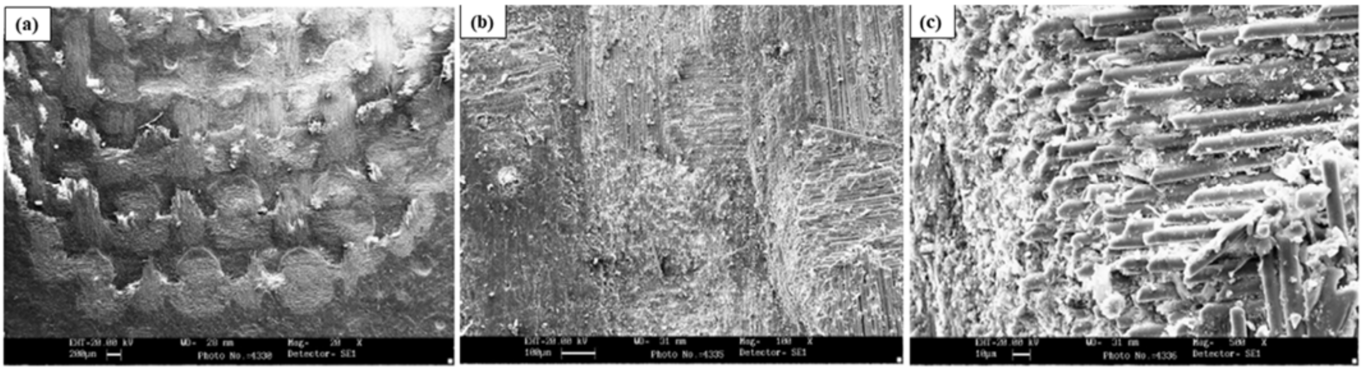

Figure 7: SEM image of SiCp filled GE composite bottom region (a) Low magnification, (b) Moderate magnification, (c) High magnification.

The extent of damage to the matrix and fiber was relatively less in SiCp filled GE composite compared to unfilled GE composite under similar experimental conditions. Worn surface of SiCp filled GE composite depicted distinct worn morphologies relative to unfilled GE composite. At low magnification (Fig. 5a), worn surface illustrates the occurrence of severe ploughing, cutting action by abrasives. While, wear pattern has revealed that the circumstance associated with relatively reduced particle rolling. Perhaps, abrasion particles tend towards sliding instead of rolling. Substantially, it indicates that dominant wear regime begin to shift from macro cutting of fibers and debris to micro cutting of fibers and fine debris. Although, the surface of filler incorporated composite shown highly damaged regions and ruptured fibers (Fig. 5b); the resistance to material removal from its subsurface was enhanced. Thus, material pull-out and ploughing due to abrasives penetration was reduced. The worn surface at central region demonstrated less damage to matrix and fibers as shown in Fig. 6a. This is due to incorporated hard SiCp particles present along with matrix on surface of the composite specimen, which acts as antiwear additive, hence retarded the wear loss. The matrix phase around the SiCp particles has evidently worn out with SiCp particles (Fig. 6b). As a result, substantial SiCp particles at this region were exposed directly to abrasives.

Later, the removal of SiCp particles occurs followed by subsequent pulling out of abrasive particles. Few craters were also noticed on the worn surface, possibly formed due to the dislodging of SiCp particles. At higher magnification (Fig. 6c), worn surface pronounced with a distinct evidence of fiber breakage and, also damage to the epoxy resin matrix with SiCp particles protruding action. Fig. 7a depicts the additionally stepped appearance of glass fibers aided with ploughing marks on the surface, and inclined fracture end of fibers. Besides, at higher magnification significant amount of loose wear debris were seen on the surface and filler matrix debonding were also observed (Fig. 7b and c). However, it might not have occurred as easily in the case of unfilled GE composite.

The wear loss of unfilled GE composite is greater than SiCp filler incorporated GE composites. It may be due to the exposure of soft matrix to abrasion. The GE composite exhibited severe matrix wear at the beginning of abrasion. Further, hard abrasive particles were in contact with matrix which is softer in nature leading to severe matrix damage, as a consequence wear loss was greater. The improvement in wear resistance of GE composite filled with SiCp particles could be attributed to the ability of SiCp particles to undertake greater contact stress, as well as to protect the glass fiber from being gouged out during the wear process.

CONCLUSIONS

An experimental study of the abrasive wear behaviour of unfilled and filled GE composites was evaluated. The inclusion of SiCp filler in the GE composite has significant potential for improving the abrasive wear resistance. Further, the study suggests that, applied load and abrading distance are the main factors which are affecting the abrasive wear of composites. The increase of SiCp content in composites has improved its abrasive wear resistance till 10%, further increase in SiCp has not found to be relatively lucrative. An examination of worn surface morphology suggested that the abrasive wear behaviour of filled and unfilled GE composites was dominated by ploughing, microcutting, matrix removal and fiber breakage.

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