Three-Body Abrasive Wear Behaviour of Silicon Carbide Filled Glass-Fabric Reinforced Epoxy Composites Using Taguchi Method

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Abstract
The glass fabric-epoxy (G-E) composites with different loading of Silicon carbide filler were prepared using the hand lay-up technique followed by compression molding technique. The effects of Silicon carbide filler loading on the abrasive wear and worn surface features of G-E composites have been investigated. Three-body abrasive wear tests with different loads/abrating distances were performed at room temperature by using a rubber wheel abrasion apparatus. The results showed that among the filled G-E composites tested, 10 wt. % Silicon carbide filled G-E composites showed a promising trend. The Taguchi’s experimental design approach was applied to analyze wear behavior of selected composites. The systematic experimentation leads to identification of significant process parameters and material variables that are predominantly influence the specific wear rate. Further it is evident from Taguchi wear analysis that load plays a significant role followed by abrating distance, speed and material. Finally, the worn surfaces were examined using Scanning Electron Microscopy (SEM) to identify the various wear mechanisms.

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Key Words: Silicon carbide filler, Glass-epoxy, Three-body abrasive wear, Wear mechanisms, Scanning Electron Microscopy.

I. INTRODUCTION
Polymer can be considered to be one of competitive materials for tribological applications because of their low friction values against steel counterparts, good damping properties, and self-lubricating abilities. The advantages demonstrated by polymer matrix composites (PMCs), in addition to high strength, high stiffness, and low density, include corrosion resistance, long fatigue life, tailor made properties, and the ability to form complex shapes. This has given an impetus to the industrial production of newer materials, for example, bearing components in automotive industry [1]. Epoxy resin as matrix are widely used in the production of glass-fiber composites due to their wetting power and adhesion to glass fiber, low setting shrinkage, considerable cohesion strength, adequate dielectric characteristics, and thermal properties [2]. Bi-directionality of the fabric provides resistance to transverse forces or cracking and hence balanced properties are obtained. Particulate filled composites including nano particles possess good mechanical properties and these fillers are added from the techno economics angle [3].

The importance of the tribological properties convinced various researchers to study the wear behavior and to improve the wear resistance of polymers and fiber-reinforced polymeric composites. Among the wear types, the abrasive wear situation encountered in industries connected with power, automobile, pumps handling industrial fluids, and earth moving equipment has been receiving increasing attention. Reports of application of PMCs in mechanical and tribological components such as gears, cams, wheels, and impellers are cited in literature [4-8]. Woven fabric reinforced PMCs are gaining popularity because of their balanced properties in the fabric plane as well as their ease of handling during fabrication. Also, the simultaneous existence of parallel and anti parallel fibers in a woven configuration leads to a synergetic effect on the enhancement of the wear resistance of the composite [9]. Three-body abrasion is generally considered more practical; it appears to have received less attention than a two-body problem. In the last few years, some studies on polymer composites subjected to abrasive wear are available. Cirino et al. [10, 11] investigated the sliding and
abrasive wear behavior of PEEK polymer with different types of continuous fibers. Cenna et al. [12] studied abrasion resistance of vinyl ester based composites and reported that UHMWPE reinforcement enhanced the wear resistance against both coal and mineral ignimbrite abrasives. Suresha et al. [13-16] investigated the sliding and abrasive wear behavior of epoxy/vinyl ester filled with or without particulate filler and glass/carbon fabrics and concluded that particulate filled composites improves wear behavior compared to unfilled composites.

\[ S/N_i = -10 \log \left( \frac{1}{N} \sum_{j=1}^{N} S_j^2 \right) \]

Design of experiments (DOE) using Taguchi approach is a standardized form of experimental design technique. DOE is an experimental strategy in which effects of multiple factors are studied simultaneously by running tests at various levels of the factors. Glen [17] found that the Taguchi approach to experimentation provides an orderly way to collect, analyze, and interpret data to satisfy the objective of study. Taguchi [18] proposed that the most important stage in the plan of experiments is selection of factors. Taguchi technique creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiments. The experimental results are analyzed using analysis of means and variance to study the influence of factor.

To evaluate the possibility of improving the abrasive wear of glass fabrics reinforced epoxy composites and elucidate the abrasive wear mechanisms, in the present study, the three-body wear behavior of epoxy based composites, reinforced by glass fabrics (balanced mat) and ceramic filler Silicon carbide (SiC), were investigated under different loads/abrating distance. Further, Taguchi’s experimental design approaches were applied to identify the significant control factors and their interactions predominantly influencing the abrasive wear of the Glass-epoxy composites filled with Silicon carbide particulates.

II. EXPERIMENTAL DETAILS

The Glass-epoxy (G-E) samples were prepared by hand layup technique using epoxy resin as the matrix material and glass fiber woven cloth as the reinforcement. The ceramic filler Silicon carbide (SiC) of average size of about 5 to 10 µm was employed as fillers.

A. Mechanical Test

Tensile properties were measured using a Universal testing machine in accordance with the ASTM D-3039 procedure at a cross head speed of 5 mm/min and a gauge length of 50 mm. The load was recorded using a software and data acquisition computer. Hardness (Shore-D) of the samples were measured as per ASTM D2240, by using a Hiroshima make hardness tester (Durometer).

B. Three-Body Abrasive Wear Tests

The three-body abrasive wear tests were conducted using a dry sand/rubber wheel abrasion tester as per ASTM G-65 [19]. The details of the wear testing procedure described elsewhere [19]. The sample was cleaned with acetone in an ultrasonic cleaner, dried and its initial weight was noted in a high precision digital balance (0.1 mg accuracy, Mitutoyo; Japan) before it was mounted in the sample holder. At the end of the test, the sample was removed, thoroughly cleaned and again the final weight determined. The difference in weight calculated is a measure of abrasive wear loss. The experiments were carried out at two different loads (23 and 36 N) under different abrating distances (250 m to 1000 m). The wear was measured by the loss in weight, which was then converted into wear volume using the measured density data. The specific wear rate \( K_s \) was calculated from the equation:

\[ K_s = \frac{V}{L \times D} \text{ m}^3/\text{Nm} \]

where \( V \) is the volume loss in m\(^3\), \( L \) is the load in N and \( D \) is the abrading distance in m.

C. Design of Experiments

Design of experiments (DOE) using Taguchi approach is a standardized form of experimental design technique. DOE is an experimental strategy in which effects of multiple factors are studied simultaneously by running tests at various levels of the factors. Factor is a variable or a parameter that has a direct influence on the output (quality characteristic). Levels are the descriptions that define the condition of the factor held while running the experiments. The wear tests are carried out under operating conditions given in Table 1.

<table>
<thead>
<tr>
<th>Control factors</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed(rpm)</td>
<td>100 150 200</td>
</tr>
<tr>
<td>Load(N)</td>
<td>12 24 36</td>
</tr>
<tr>
<td>*Material</td>
<td>1 2 3</td>
</tr>
<tr>
<td>Distance(m)</td>
<td>250 500 750</td>
</tr>
</tbody>
</table>

*Material 1-5%SiC-G-E, 2-7.5%SiC-G-E, 3-10%SiC-G-E

The tests are conducted at room temperature as per experimental design. Taguchi design of experiment methods are used to optimize the experimental design based on the number of control factors and the number of levels. Two orthogonal array designs \( L_{9} \) and \( L_{27} \) can be used. In this present work the \( L_{9} \) array design is used as the experimental design.

The experimental observations are transformed into signal-to-noise (S/N) ratios. There are several S/N ratios available depending on the type of characteristics. The S/N ratio for minimum wear rate coming under smaller is better characteristic, ........................(2)

which can be calculated as logarithmic transformation of the loss function as shown below.

Smaller is the better characteristic: Where \( i \) is experimental number, \( u \) is trail number and \( N_i \) is the number of trials for experiment \( i \). “Lower is better” (LB) characteristic, with the above S/N ratio transformation, is suitable for minimization of wear loss.

III. RESULTS AND DISCUSSION

A. Measurement of mechanical properties

The physico-mechanical properties such as density, tensile strength, tensile modulus and hardness data of unfilled and particulate filled G-E composites are given in Table 2. The results revealed that particulate filled G-E composites showed better mechanical properties than that of unfilled G-E composites. Comparing the results it was observed that inclusion of ceramic fillers into G-E showed higher density. The incorporation of SiC filler in G-E composites increased

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the tensile strength. Elongation properties decreased with the presence of filler that indicates interference by the filler in the deformability of the matrix. SiC filled G-E composites showed improved mechanical properties compared to unfilled G-E composites. It should be pointed out that the presence of SiC filler improved adhesion and it has been proved to be beneficial in glass fiber reinforced epoxy composites.

**TABLE 2: MECHANICAL PROPERTIES OF UNFILLED AND FILLED G-E COMPOSITES.**

<table>
<thead>
<tr>
<th>Sample code</th>
<th>G-E</th>
<th>5% SiC-G-E</th>
<th>7.5% SiC-G-E</th>
<th>10% SiC-G-E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, (g/cm³)</td>
<td>1.984</td>
<td>2.15</td>
<td>2.35</td>
<td>2.42</td>
</tr>
<tr>
<td>Hardness (Shore-D)</td>
<td>63</td>
<td>67</td>
<td>71</td>
<td>74</td>
</tr>
<tr>
<td>Tensile strength, σ (MPa)</td>
<td>254</td>
<td>342</td>
<td>361</td>
<td>372</td>
</tr>
<tr>
<td>Tensile modulus, E (GPa)</td>
<td>8.34</td>
<td>10.9</td>
<td>11.55</td>
<td>12.01</td>
</tr>
<tr>
<td>Elongation, e (mm)</td>
<td>7.1</td>
<td>6.2</td>
<td>6.0</td>
<td>5.7</td>
</tr>
</tbody>
</table>

**B. Abrasive wear volume and specific wear rate**

Fig. 1(a & b) shows the wear volume as a function of abrading distance for unfilled G-E and SiC filled G-E composites at different loads. Fig. 2 is histogram showing specific wear rate (Ko) of unfilled G-E and SiC filled G-E composites at different loads.

The wear data reveal that the wear volume tends to increase near linearly with increasing abrading distance and strongly depends on the applied load for all the composites tested. It was observed that the wear performance is improved for G-E composite due to inclusion of SiC filler. The variations in the specific wear rate with abrading distance at 23 and 36N loads are shown in Fig. 2, respectively. The specific wear rate decreases with increasing abrading distance but increases with increase in applied load. The results revealed higher abrading nature of G-E composite compared to particulate filled G-E specimen. The phenomenon of decrease in specific wear rate is due to the nature of microparticles used.

**Figure 2:** Specific wear rate comparison of G-E with SiC at (a) 23 N and (b) 36 N.

Thus, in the initial stage of abrasion, abrasive is in contact with matrix and has less hardness compared to that of angular silica sand. At that particular instance, the ratio of Ha (hardness of abrasive particles) to Hs (hardness of the surface) is much more than unity, resulting in severe matrix damage and the rate of material removal is very high. Similarly, when glass fibers are in contact with abrasive particles bi-directional fibers provide better resistance to the process of abrasion. It is seen that the specific wear rate for all the samples is high at lower abrading distance and low for higher abrading distance. This is attributed to the fact that at lower abrading distance low modulus matrix was exposed and at higher abrading distance high modulus fiber was exposed to abrasion. These exposed fibers, because of their high hardness values, provide better
resistance against the abrasion and in turn, abrasive particles have to work more to facilitate failure in the fibers (i.e., much higher amount of energy is required to facilitate fiber failure). Higher wear volume was noticed for G-E composites compared to particulate filled G-E composites. This is because the hard ceramic particles have high specific modulus compared to glass fiber and possesses higher hardness. The SiC filler in G-E had better wear resistance as compared to unfilled G-E composites. Lancaster [20] studied the abrasive wear behaviour of 13 polymers reinforced with 30% short carbon fibers and reported that abrasive wear had decreased for 7 of the polymers tested and had deteriorated for the remaining 6 polymers. Thus, in the present work also, similar observations were found which are in agreement with the findings reported in the literature [20].

C. Analysis of abrasive wear by Taguchi technique

The experiments were conducted as per the standard orthogonal array. The selection of the orthogonal array was based on the condition that the degree of freedom for the orthogonal array should be greater than or equal to sum of those wear parameters. In present investigation L₀ orthogonal array was chosen. The wear parameters chosen were speed, load, material and abrading distance. The experiment consists of 9 tests and was assigned as shown in Table 3. The experimental results are analyzed using Taguchi method and the significant parameters affecting wear have been identified as shown in Table 4.

### TABLE 3: STANDARD ORTHOGONAL L₀ ARRAY WITH OUTPUT RESULTS.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Speed</th>
<th>Load</th>
<th>Material</th>
<th>Abrading Distance</th>
<th>Weight loss</th>
<th>S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(rpm)</td>
<td>(N)</td>
<td></td>
<td>(m)</td>
<td>(gms)</td>
<td>(db)</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>12</td>
<td>1</td>
<td>250</td>
<td>0.0282</td>
<td>30.9950</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>24</td>
<td>2</td>
<td>500</td>
<td>0.2099</td>
<td>13.9404</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>36</td>
<td>3</td>
<td>750</td>
<td>0.4562</td>
<td>6.8169</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>12</td>
<td>2</td>
<td>750</td>
<td>0.0811</td>
<td>21.8196</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>24</td>
<td>3</td>
<td>250</td>
<td>0.1477</td>
<td>16.6124</td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>36</td>
<td>1</td>
<td>500</td>
<td>0.2467</td>
<td>12.1566</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>12</td>
<td>3</td>
<td>500</td>
<td>0.0816</td>
<td>21.7662</td>
</tr>
<tr>
<td>8</td>
<td>200</td>
<td>24</td>
<td>1</td>
<td>750</td>
<td>0.3308</td>
<td>9.6087</td>
</tr>
<tr>
<td>9</td>
<td>200</td>
<td>36</td>
<td>2</td>
<td>250</td>
<td>0.2741</td>
<td>11.2418</td>
</tr>
</tbody>
</table>

### TABLE 4: SIGNIFICANT PARAMETERS AFFECTING WEAR.

<table>
<thead>
<tr>
<th>Level</th>
<th>Speed</th>
<th>Load</th>
<th>Material</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.25</td>
<td>24.86</td>
<td>17.59</td>
<td>19.62</td>
</tr>
<tr>
<td>2</td>
<td>16.86</td>
<td>13.39</td>
<td>15.67</td>
<td>15.95</td>
</tr>
<tr>
<td>3</td>
<td>14.21</td>
<td>10.07</td>
<td>15.07</td>
<td>12.75</td>
</tr>
<tr>
<td>Delta</td>
<td>3.05</td>
<td>14.79</td>
<td>2.52</td>
<td>6.87</td>
</tr>
<tr>
<td>Rank</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Analysis was made using minitab-16 software in order to find statistical significance of various factors like speed, load, material and abrading distance on wear loss analysis of variance performed on the experimental data. From Taguchi wear response(fig. 3) it is evident that load plays a significant role followed by distance, and speed and material plays least role. From the main effects plot for SN ratio, speed 100 rpm, load 12 N, material 1(5SiC-G-E) and distance 250 m gives minimum wear loss.

### D. Worn surface morphology

SEM micrographs of the worn surfaces are shown in Figs. 4 & 5. The worn surfaces of G-E composite samples abraded under high load, lower and higher abrading distance conditions are shown in Figs. 4 (a and b). These composite micrographs indicate that there is severe damage on the worn surface. The epoxy matrix and glass fibers are damaged more severely than that of the particulate filled G-E composite samples (Fig. 5a & 8b). The matrix is distorted and damaged by ploughing and cutting action by sharp abrasive particles. Further, it is seen that the fiber fracture process leads to more fiber breakage and some fiber removal due to the ploughing and cutting action.

Figure 3: Main effect plot for Signal to Noise ratio.

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Figure 4: SEM micrographs of abraded G-E composite at 36 N: (a) 1000 m and (b) 250 m abraded distance.

This result indicates poor adhesion of the matrix to the fibers as several clean fibers appear on the abraded surface. The higher wear rate in G-E composite may be attributed to lower matrix ductility and poorer fiber–matrix adhesion. The abraded surface shows evidence of debonding at each fiber–matrix interface is not sufficient to result in the removal of fiber. The fracture of fiber is due to abrasion and transverse bending by sharp abrasive particles, resulting in fragments of fibers torn from the matrix (Fig. 4(a)). Once again, the micrograph shows poor adhesion between fiber and matrix.

Figure 5: SEM micrographs of abraded 10 wt.% of SiC-G-E composite at 36 N: (a) 1000 m and (b) 250 m abraded distance.

It is evident from the SEM micrographs (comparing Fig. 4a & b with Fig. 5a & b) that the 10 % SiC filled G-E is showing lesser degree of worn surface features compared to unfilled G-E sample at 36 N load applications. In the case of samples subjected to 36 N load, one can see less number of broken fibers with less debris formation in the SiC filled G-E sample (Fig. 5a), whereas in the unfilled G-E sample (Fig. 4a), de-bonding of the fiber with cleavage type of fracture is seen. Now, coming to the samples subjected to higher abrading distance (1000 m), masking of fibers are noticed in the SiC filled sample (Fig. 5a). On the other hand, the SEM features of unfilled G-E sample (Fig. 4a) show large number of broken fibers with lot of distortion in the matrix and also higher degree of debris formation.

IV. CONCLUSIONS

From abrasive wear studies of unfilled G-E and SiC filled G-E composites the following conclusions can be drawn:

- Specific wear rate increased with applied load at lower abrading distance and decreased with increasing abrading distance. SiC filled G-E composite showed better abrasion resistance as compared to that of unfilled G-E composites.
- Glass fibers in epoxy matrix were broken into small pieces and removed easily whereas the particulate fillers in G-E showed less wear out. This result revealed better interfacial adhesion between glass fibers and epoxy with fillers as compared to the adhesion between glass fibers and epoxy.
- The wear volume was less in the composite material with 10% SiC filler as compared to that of unfilled G-E. Higher specific wear resistance (50%) was noticed for SiC-G-E composite than G-E composite, due to high strength and hardness of SiC filler.
- Taguchi result indicates that load plays a significant role followed by abrading distance, material and speed. From the main effects plot for SN ratio, speed 100 rpm, load 12N, material 1(5SiC-G-E) and distance 250 m gives minimum wear loss.
- SEM microphotographs revealed that the glass fibers were detrimental to abrasive wear than carbon fibers in epoxy thermosetting composites. During wear process the important SEM features observed fiber fracture, tearing of matrix, cracking wear mechanism etc.
References

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