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# Low stress abrasion of laser irradiated GFRP composites: an experimental and microstructural study

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The present paper reports, the mechanism of material removal during low stress abrasive wear of high weight percent glass fibre reinforced polymer (GFRP) composites. Two different geometries of glass fibre reinforcement namely woven roving (WR) and chopped strand mat (CSM) were used. Unsaturated isophthalic polyester and bisphenol based epoxy resins were used as matrix for the reinforcement. Rubber Wheel Abrasion Tester (RWAT) was used for evaluating the abrasive wear behaviour of the composites. The composite samples were irradiated using a low power He-Ne laser for different time periods, having intensity of 5 mW. The abrasive wear performance of the composites has been determined as a function of applied load, sliding distance and laser irradiation time. The microstructural features of the abraded surfaces of both the laser irradiated and unirradiated composites have been observed by using a scanning electron microscope. Unsaturated polyester based glass fibre woven roving (WR) composite had a higher wear volume as compared to the epoxy based composite. The trend reversed in the case of chopped strand mat (CSM) composites, in which epoxy-based composite showed higher wear volume. The abrasive wear volume of all the composites decreased on irradiating it with laser. These results have been discussed, based on experimental wear data and observed microstructural features of the abraded surfaces. © *2002 Kluwer Academic Publishers*

## 1. Introduction

Studies on the abrasive wear behaviour of the fibre reinforced polymer (FRP) composites more commonly glass fibre reinforced polymer (GFRP) composites, is a fancy subject of investigation for number of researchers. Contemporary research investigations are in progress for an universally acceptable theory of wear. Further the effect of various irradiation on the physico-chemical and wear properties of these composites are yet to be studied. A number of researchers have gone through the problem, to provide information on the wear data and involved mechanism for GFRP composites [1–8]. Sung and Suh [1] found that anisotropic wear behaviour is the characteristic feature of continuous FRP composite. Cirino *et al.* [2] studied the abrasive wear behaviour of continuous FRP composite and gave schematic illustrations to explain the wear phenomenon based on the SEM micrographs of the abraded surfaces. The non-linear increase in wear rate with sliding speed and applied load for woven GFRP was reported by Vishwanath *et al.* [3]. Chand and Fahim [4] used woven GFRP for two-body abrasive wear study and derived theoretical model for the specific wear rate of the composites. Apart for this many reviews in the past have summarized the relation between the abrasive wear and mechanical properties [5–8]. Out of these majority of investigations have been carried out where abrasives are fixed to a surface (two body abrasive wear). Interestingly, majority of the problems should be characterized as three-body abrasive wear, once the debris formed and trapped between the operating surfaces. Despite the importance it is not tackled adequately, only a few papers on three body abrasive wear of polymers and FRP's [9–12] are available in literature.

The studies on effect of laser irradiation on the physico-chemical, mechanical and wear behaviour of polymers and their composites have received very little attention [13–22]. Although, it is well established that laser irradiation is capable of bringing modification at the surface and subsurface regions [16–19, 22], which dominates the wear performance of the composites. A few papers are available in literature [20, 22, 23] to provide some information on the effect of laser on wear performance of the composites. In this paper, an attempt has been made to understand the three-body abrasive wear behaviour of glass fibre reinforced polymer (GFRP) composites under various external operating conditions and material parameters. These parameter includes applied load, form of glass fibre reinforcement, and types of polymer matrix. Finally, the effect of laser irradiation for different time periods on the wear behaviour of the composite has been studied and analyzed.

## 2. Materials and methods

### 2.1. Materials

E-glass fibres in form of woven roving (WR) and chopped strand mat (CSM) provided by FGP (India) Ltd., India were used as reinforcement for the preparation of composites. Unsaturated isophthalic polyester and bisphenol based epoxy resins were used for making the glass fibre reinforced polymer composites. For preparing the glass polyester composites, 1% cobalt nephthaltate as accelerator and then 1% methyl ethyl ketone peroxide (MEKP) as hardener were mixed thoroughly in the isophthalic polyester resin. The mixed resin was then applied on the known quantity of glass fibre mat by using brush and the excess resin was squeezed out by using roller. 30% Dicynodiamine as hardener is heated at 70°C and mixed in the epoxy resin. On homogeneous mixing, the resin was applied on the known amount of glass fibres as mentioned above. Then, the pressure is utilized to spread the resin uniformly in both types of the composite. The pressure of 200 psi is applied on the composites. The composite samples were kept at 120 and 160°C for polyester and epoxy respectively, during curing under the mentioned pressure for two hours [24].

The composites were designated as woven glass polyester (GWP), glass woven roving epoxy (GWE), glass chopped strand mat polyester (GCP) and glass chopped strand mat epoxy (GCE) composites. The details of the composition and some properties of the GFRP composites, used in the present study have been tabulated in Table I [24]. The experimental test samples for various tests were cut from the composite laminates.

### 2.2. Strength test

The mechanical properties of the GFRP composites were evaluated using ASTM standard test procedure. The standard test specimens were machined from the composite laminates as per the ASTM specifications. Tensile strength test [ASTM D-638] and flexural strength test [ASTM D-790] were carried out on INSTRON Testing Machine Model No. 1185. The impact strength test [ASTM D-256] was tested on lzod Impact tester, CEAST make (Italy). The details of the experimental test procedure are described elsewhere [24]. The strength values were tabulated in Table I.

### 2.3. Low stress (three body) abrasive wear testing

Low stress abrasive wear tests on GFRP composites have been carried out on FALEX, Rubber Wheel Abrasion Test (RWAT) apparatus. Angular silica sand particles of size ranging from 200 to 300 $\mu$m were used as dry and loose abrasives. The shape of the abrasive used, were not spherical, rather they had typically sharp edges and uneven surface in the rest of the region [10]. Silica sand particles as abrasives were gravity feed between the rotating rubber wheel and vertically held static composite specimen at a rate of 265 gm/min. A chlorobutyl rubber of thickness 12.7 mm was rimmed on a 203 mm diameter wheel to form the counter surface. The wheel rotated at a speed of 280 revolutions per minute at an approximate sliding velocity of 3.34 meter $sec^{-1}$. Static load of 3, 4.5 and 6 Newton's were applied on specimen using dead load on the load arm. Weight loss measurements were done at a regular test interval (each test interval corresponding to a sliding distance of 100 meters) using an electronic balance of accuracy $1 \times 10^{-4}$ gm.

### 2.4. Laser irradiation

The samples of standard size were mounted on the specially fabricated jig for laser irradiation. He-Ne laser having lasing intensity of 5 mW as directly focused on the sample. The sample was manually moved in the straight line during irradiation. The speed of scanning was adjusted according to the laser irradiation time. In the present study, all the samples were irradiated for 4 and 6 min. and in addition to this glass woven epoxy (GWE) composite was further irradiated for 2 and 8 min. to study the effect of laser irradiation time.

### 2.5. Microstructural analysis

The microstructures of the abraded surfaces were examined by using a scanning electron microscope of JEOL, Japan make model JSM 5600. Before taking the micrographs, the samples were mounted on the sterds and coated with a thin layer of gold by using vacuum coating.

## 3. Results and discussion

The low stress abrasive wear volume of the GFRP composites measured as a function of increasing sliding distance are shown in Figs 1–3. Fig. 1 shows the low stress abrasive wear volume of both laser irradiated and unirradiated woven glass polymer GWP (GPC-9) and GWE (GEC-5) composites at an applied load of 6 N. The wear volume of unirradiated composites were on the higher side as compared to laser irradiated (6 min.) composite. The GWP composite showed higher wear volume loss as compared to GWE composite. It may be

TABLE I Constituents, composition and some properties of GFRP composites used in the present research study

| Sample name | Resin system | Glass fibre Type (wt%) | Density ($g/cm^3$) | Tensile strength (MPa) | Flexural strength (MPa) | Impact strength ($kJ/m^2$) |
|---|---|---|---|---|---|---|
| GCP | Polyester[a] | CSM (70.0) | 2.14 | 266.5 | 206.6 | 186.0 |
| GWP | Polyester[a] | WR (70.9) | 2.3 | 318.0 | 175.2 | 128.4 |
| GWE | Epoxy[b] | WR (76.0) | 2.38 | 366.0 | 316.4 | 221.4 |
| GCE | Epoxy[b] | CSM (74.7) | 2.38 | 184.1 | 239.4 | 210.3 |

[a]Unsaturated isophthalic polyester.
[b]Bisphenol based epoxy.
WR: Woven roving fabric of 360 GSM, CSM: chopped stand mat of 450 GSM.

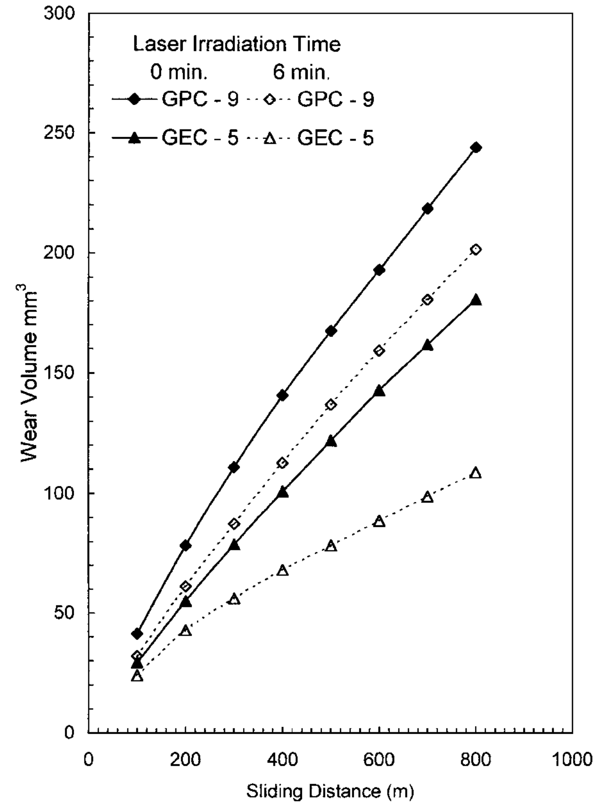



*Figure 1* Plot for variations in wear volume against sliding distance for WR composites tested at an applied load 6 N.

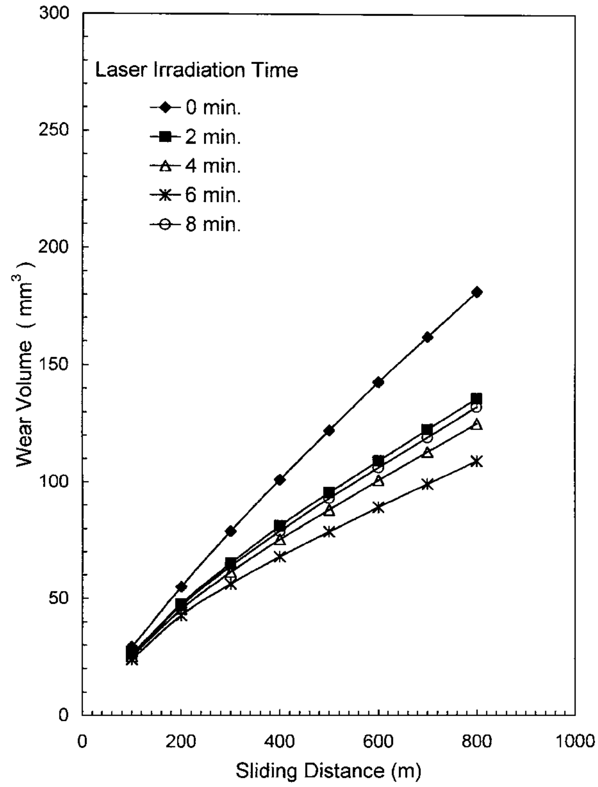



*Figure 3* Plot for variations in wear volume against sliding distance for GWE composites tested at an applied load of 6 N and irradiated for different time.

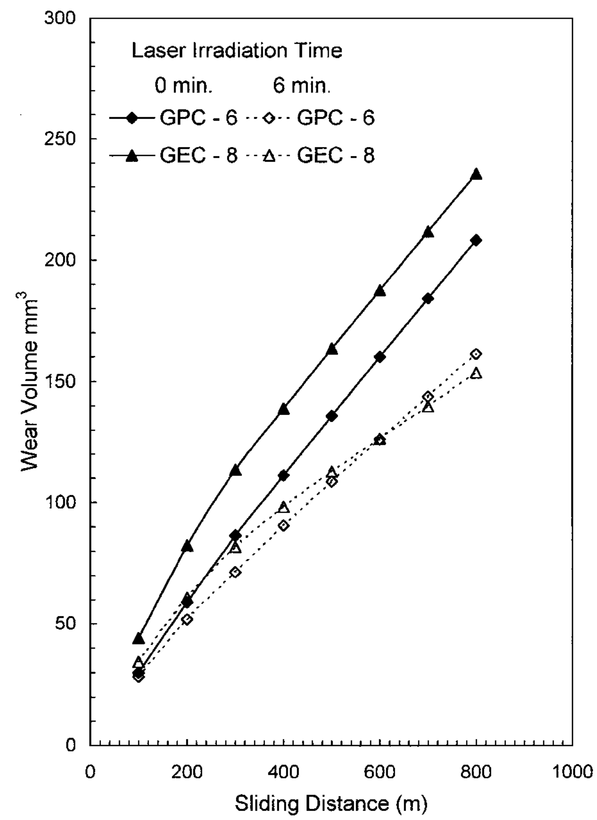



*Figure 2* Plot for variations in wear volume against sliding distance for CSM composites tested at an applied load of 6 N.

attributed to the fact that epoxide group forms strong bond with the glass fibres, besides having superior mechanical properties as compared to its counterpart polyester. Secondly, the epoxy resin shows small percentage of shrinkage (1–2%) on curing. On contrary, the polyester resin is characterized by high shrinkage (upto 8%) [25] during the process of curing, which decreases the adhesion between the glass fibre and the matrix as reflected from the tensile strength values shown in Table I.

Fig. 2 shows the three body abrasive wear volume of chopped strand mat GCP (GPC-6) and GCE (GEC-8) composites as a function of increasing sliding distance at an applied load of 6 N for both unirradiated and 6 min. laser irradiated composites. The GCE (GEC-8) composite showed higher wear volume for both unirradiated and laser irradiated composites as compared to its counterpart polyester based composite. This unique behaviour of CSM-polymer composite is quite interesting because it is well established and reported that the epoxy based composite have better mechanical properties than polyester based composite, but the abrasive wear data, which doesn't follow the above trend. It may be attributed to the fact that in CSM the chopped fibres are coated with binders. These binders are polyester based or shows good compatibility with the polyester resin. Hence, the quality of adhesion with polyester is superior as compared to epoxy resin in this case. The consequences of low adhesion is thus reflects from the abrasive wear data plotted in Fig. 2.

Fig. 3 shows the abrasive wear volume of GWE composite as a function of increasing sliding distance, at an applied load of 6 N, when irradiated for different laser irradiation time. It has been reported [12], that the low stress abrasive wear volume of the glass fibre reinforced polymer composite doesn't increases linearly with increasing sliding distance. Similar trend was observed

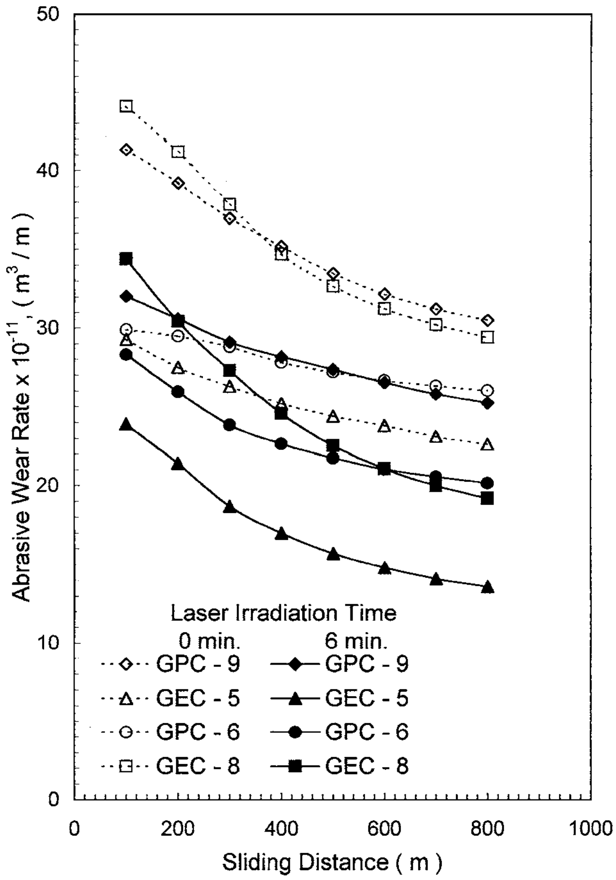



*Figure 4* Plot for variations in wear volume against sliding distance for laser irradiated WR epoxy composites for different irradiation time.

for the wear volume laser irradiated composites too. The significant decrease in abrasive wear volume with laser irradiation was observed. The least wear volume was observed for the composite irradiated for 6 min. On further increasing the laser irradiation time to 8 min. the wear volume of the composite increased as compared to 4 min. and 6 min. laser irradiation.

Fig. 4 shows the wear rates of the composites as a function of increasing sliding distance. GCE (GEC-8) composite showed maximum wear rate followed by GWP (GPC-9) composite both in the case of unirradiated and 6 min. laser irradiated composites. The wear rates of unirradiated composites were on the higher side and it decreases with increasing sliding distance for all the composites. The decrease in wear rate due to laser irradiation is higher for epoxy based composites as compared to polyester based composites. The histogram for specific wear resistance of the composites is shown in Fig. 5. The graph reveals that the specific wear resistance of GWE (GEC-5) composite during three body abrasive wear can be significantly improved by irradiating it with laser. GWP (GPC-9) composite on the other hand showed least improvement in specific wear resistance after laser irradiation. Similarly, GCP (GPC-6) composite too showed a marginal improvement in specific wear resistance. The composite irradiated for 6 min. Showed maximum improvement in specific wear resistance, which decreased with further increase in the laser irradiation time.

Figs 6–9 shows the photomicrographs of abraded surface of the composites. These photomicrographs

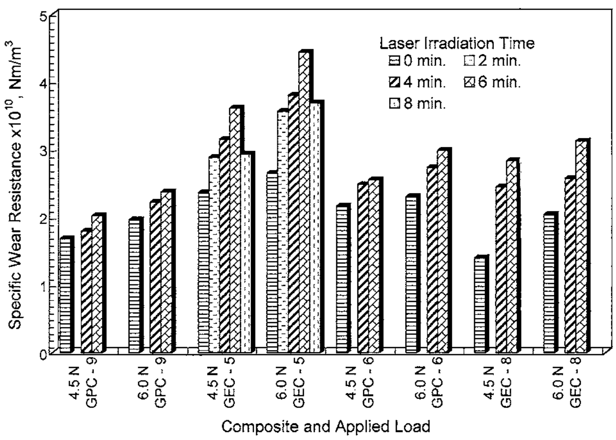



*Figure 5* Histogram comparing specific wear resistance of composites after constant sliding distance of 800 m.

were taken after 800 meters of sliding distance, when tested at an applied load of 6 N. Fig. 6a and b shows the micrograph of abraded surface of unirradiated GWP (GPC-9) and GWE (GEC-5) composites respectively. The overall matrix wear leading to fractured fibres were the significant features. The weak interfacial bonding leading to naked fibres were also observed at both the abraded surface. It was also observed that the brittle fracture of matrix and fibre dominates the fracture induced abrasive wear process. Fig. 7a and b shows the micrographs of abraded surface of unirradiated chopped strand mat GCP (GPC-6) and GCE (GEC-8) composites respectively. Severe matrix wear along with fractured fibres dominates the surface features of the abraded surface. The weak interfacial bonding leading to debonding and fibre fragmentation were other prominent features. A lots of loose debris and severely damaged fibres are also visible apart from various other microstructural features, which are tabulated in Table II.

Fig. 8a shows the micrograph of 2 min. laser irradiated GWE composite. Significant microstructural features observed in the SEM micrographs are listed in Table III. The damage in the local region can be seen with evidences of fibre cutting, interfacial debonding, and fibre removal. Small sized loose debris can be seen in the micrograph. Fig. 8b shows the magnified view of abraded surface. The photomicrograph clearly shows the consequence of cutting action by the sharp edge of abrasive particle over the composite surface. This is the unique feature observed in the photomicrograph, which otherwise was dominated by brittle fracture induced wear process. 4 min. laser irradiated GWE (GEC-5) (Fig. 8c) composite shows marginal improvement in the interfacial bonding. The absence of overall fibre fracture is also observed. In Fig. 8d (6 min. laser irradiated) composite, the size of local damaged region is reduced considerably with few fibre damages. The improvement in the interfacial bonding is the significant feature of the micrograph.

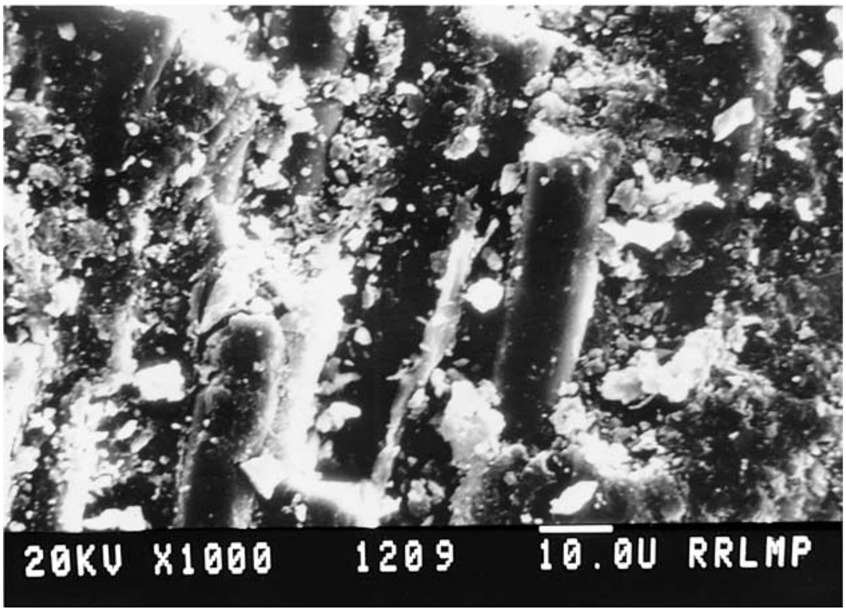
Fig. 9a shows the consequence of 4 min. laser irradiation on abrasive wear performance of GCE (GEC-8) composite. Matrix wear leading to exposed fibres are the significant features of the micrograph. When compared with the micrograph of unirradiated GCE (GEC-8) composite, it is found that abraded surface of

TABLE II List of microstructural features observed from the photomicrograph of abraded surface of GFRP composite

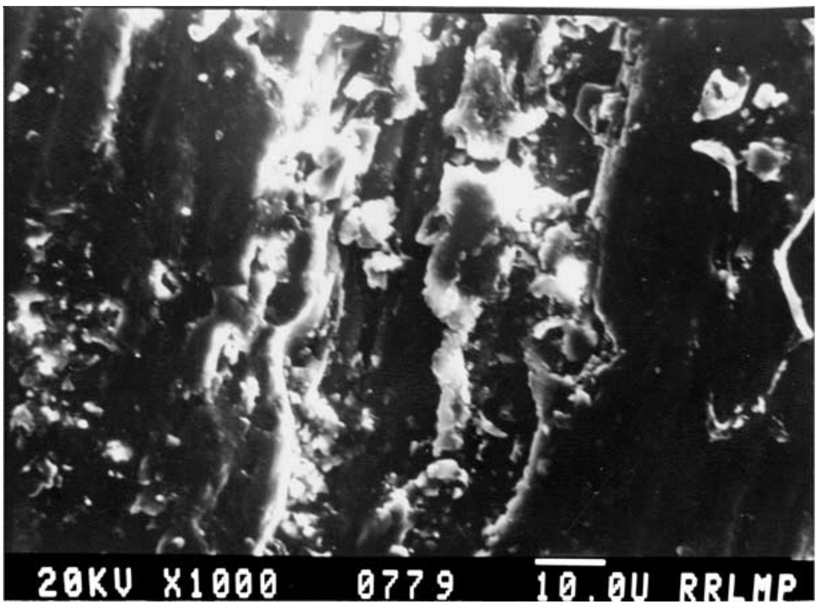
| GWP | GWE | GCP | GCE |
|---|---|---|---|
| Over all matrix wear | Matrix wear | Matrix wear | Severe matrix wear |
| A few fibre fractures | Fibre fracture and cutting | Few fractured fibres | Large number of fractured fibres |
| Very weak interface leading to debonding | Interfacial debonding | Weak interface leading to debonding | Very weak interface leading to debonding |
| No evidence of fibre pull-out | Fibre pull outs and fibre removal | Fibre pull-outs and fibre fragmentation | Fibre pull outs and fibre disalignment |
| No severe fibre fragmentation | Deep groove formation due to fibre pull out | Severe damage to fibre and matrix at local region | Fibre wear and removal |
| Abrasive wear process is dominated by brittle fracture | Abrasive wear process is dominated by brittle fracture | Abrasive wear process is dominated by brittle fracture | Severe fibre damage in local region |
| Formation of loose debris | Formation of loose debris | Formation of loose debris | Formation of loose debris |

irradiated composite shows improved interfacial characteristics. Fig. 9b shows further improvement in the interfacial adhesion between the fibre and the matrix. The fibres were found to be well covered with the epoxy resin as compared to unirradiated or 4 min. laser irradiated composite.

On analyzing the abraded surface using scanning electron microscope (SEM) different forms of surface




(a)




(b)

*Figure 6* SEM photomicrograph of abraded surface of unirradiated woven roving composite, tested using particles of size ranging 200–300 $\mu$m and at an applied load of 6 N: (a) GWP composite and (b) GWE composite.

TABLE III List of microstructural features observed from the photomicrograph of abraded surface of GWE composite irradiated for different time periods

| 0 minute | 2 minute | 4 minute | 6 minute |
|---|---|---|---|
| Complete matrix failure and its removal | Partial matrix failure and its removal | Localized matrix failure and its removal | Mild matrix removal |
| A large number of naked fibres | A few naked fibres | Mostly fibres have coating of resin with few naked fibres | Mostly fibre are coated with resin, almost no naked fibres |
| Very low interfacial bonding | Improved interfacial bonding | Good interfacial bonding | Very good interfacial bonding |
| Fibres are fractured leading to its fragmentation | Fibre cutting due to abrasive action of the abrasive particles | Highly brittle failure of matrix | Localized failure of fibre/matrix |
| Fibre pullout is evident | Fibre fracture and removal | No indication of fibre fracture | |
| Loose debris of big and small sizes | Increased brittleness of matrix | A lot of small sized loose debris | Debris formation in localized region |

appeared as mentioned above, which is helpful for further analysis of involved wear mechanism. The composites characterized by high weight fraction of fibre show more pronounced brittle fracture of glass fibre and resin matrix, with increased fibre-matrix debonding at the interfaces. This debonding lead to the removal of matrix between fibres, which allows fibres to fracture and its removal, depending on the adhesion between

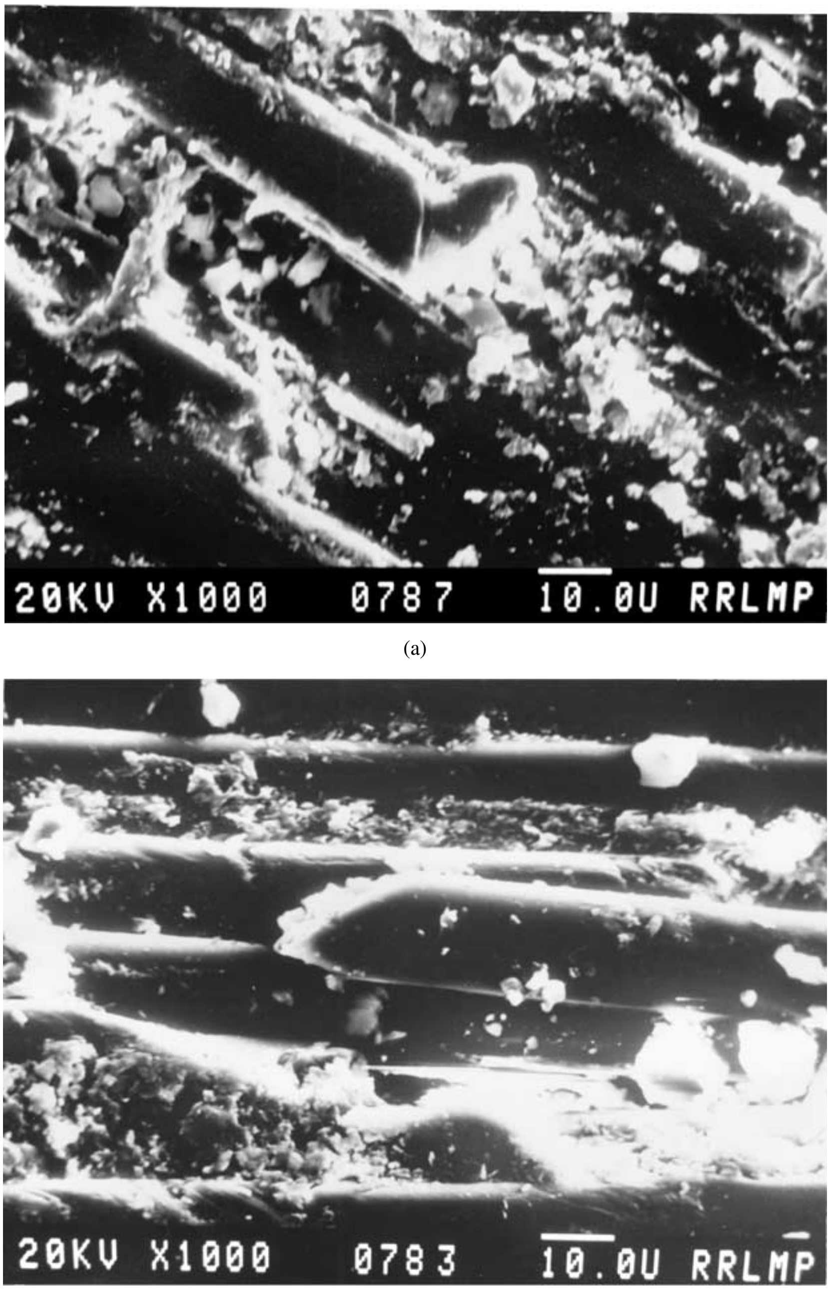
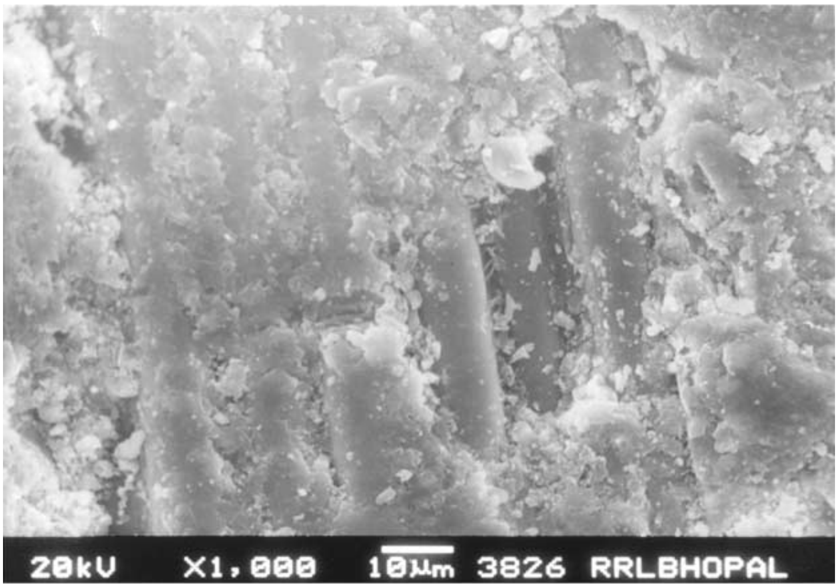
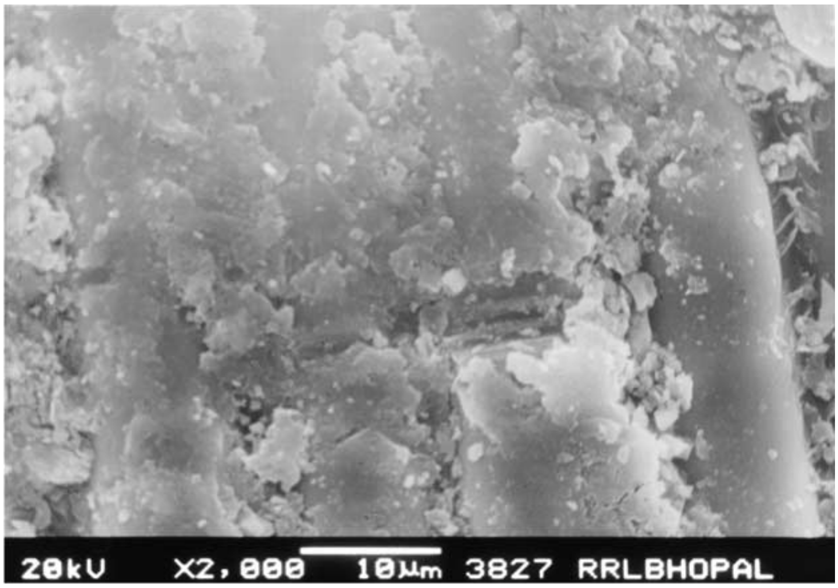


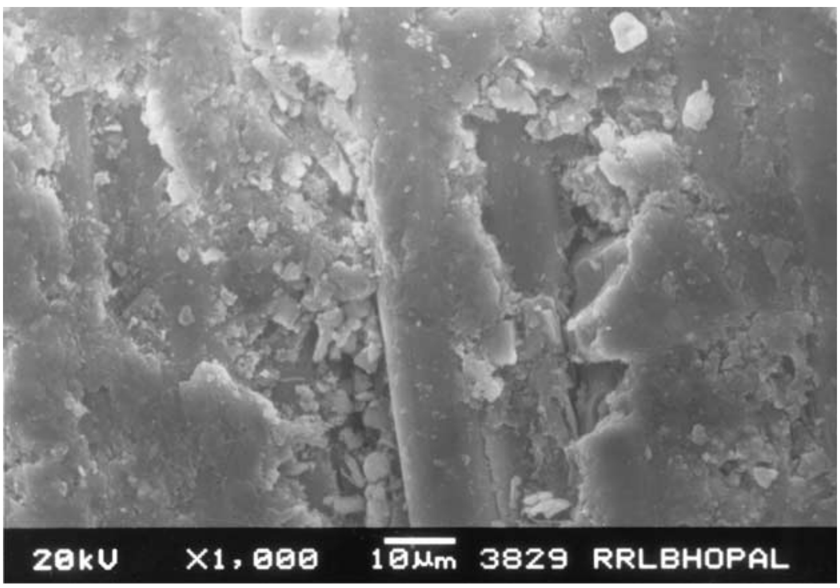

*Figure 7* SEM photomicrograph of abraded surface of unirradiated chopped strand mat composite, tested using particles of size ranging 200–300 $\mu$m and at an applied load of 6 N: (a) GCP composite and (b) GCE composite.




(a)

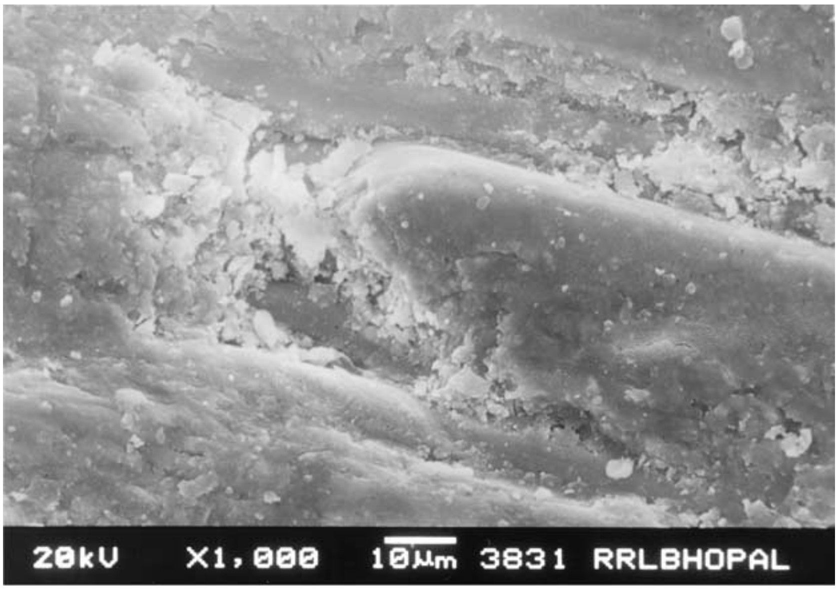



(b)




(c)

*Figure 8* SEM photomicrograph of abraded surface of laser irradiated GWE (GEC-5) composite: (a) irradiated for 2 min., (b) irradiated for 2 min. (magnified view), (c) irradiated for 4 min. and (d) irradiated for 6 min. (*Continued*.)



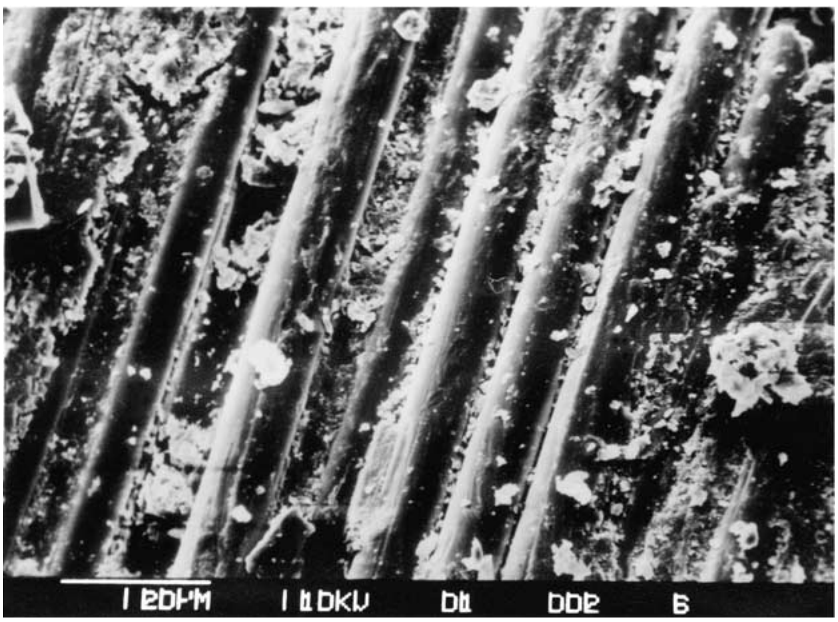

(d)

*Figure 8* (*Continued.*)

fibre reinforcement and resin matrix. This process of removal reveals that the composite, which has weak interfacial bonding, will contribute to the increase of wear volume during process of wear as is observed in case of GCE composite.

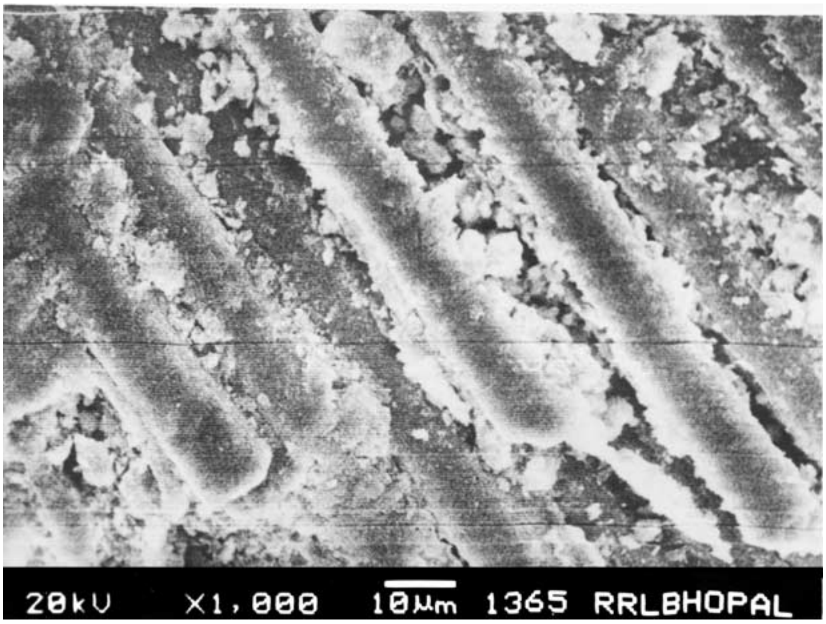
In low stress abrasive wear, abrasive particle has the freedom of movement and follows different movement patterns, when come in contact with composite and rubber wheel. One of such motion is the rolling of abrasives over the composite surface, which produces high frictional force, resulting in fatigue deformation on the surface, and hence crack initiation is started. The crack propagates in a fibre through the matrix, if the fibre-matrix is properly bonded. Due to high fibre weight fraction in the composite, fibre are bonded by thin layer of matrix, hence resulting in weak adhesion. The presence of flaw or contamination in the composite influences the strength and hence the failure of the composite under external loading. In case of pre-existing flaw in the composite, a lower energy is required to initiate a crack. Under certain condition, it is regarded as an intrinsic material property called as fracture toughness, which may be used to quantify the resistance of GFRP composite materials to fracture under loading conditions.

The laser irradiation is a powerful tool for producing high temperature in the localized region, leading to the curing and crosslinking of chains. The improvement in the bonding and crosslinking increases the inhomogenity at the local region. Further, the increase



(a)

*Figure 9* SEM photomicrograph of abraded surface of laser irradiated GCE (GEC-8) composite: (a) irradiated for 4 min. and (b) irradiated for 6 min. (*Continued.*)




(b)

*Figure 9* (*Continued.*)

in crosslinking density increases the brittleness of the localized region. On the same time when laser beam is focussed on previously cured/crosslinked region, the process of chain scission may take place. The chain scission due to laser will take place provided the energy absorbed by the local region is sufficiently more then the activation energy of the weakest bond/chain in the local region. The dependence of wear resistance of material on the microstructural properties of the surface and any reduction in the surface homogeneity enhances the wear behaviour of that particular material. It has been reported that these localized regions are responsible for the increase in wear resistance of the composite. The increase in defect concentration in the local region increases the stress concentration leading to an increase in the fracture toughness of that region.

## 4. Conclusions

An experimental study on the low stress abrasive wear behaviour of both unirradiated and laser irradiated glass fibre (chopped strand mat and woven roving) reinforced polymer (isophthalic polyester and epoxy) composites at various applied loads and laser irradiation time reveals following characteristics:

1. Abrasive wear of the GFRP composites strongly depends on the materials parameters such as type of geometry and type of resin matrix used in the composite.
2. The adhesion between fibre and matrix plays critical role in the abrasive wear performance of these composites.
3. Laser irradiation improved the abrasive wear performance of all the composites. The maximum resistance is observed for 6 min. laser irradiation.
4. The matrix failure, microcutting/micro fracture of glass fibres, interfacial debonding, fibre wear and brittle fractures dominates the overall abrasive wear behaviour of the GFRP composites.

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