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Effect of Abrasive Types on the Three-body Abrasive Wear Behaviour of Glass-Vinyl Ester and Carbon-Vinyl Ester Composites

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Woven fabric reinforced polymer composites are attracting the attention of material scientists in recent years in view of enhancement in physical and mechanical properties as well as ease in processing. Though woven fabric type and lay out of composite is known to control the properties, the information on the tribo-performance of the woven fabric reinforced vinyl ester composites in the literature is scanty. Hence, the present investigation focuses on the vinyl ester based composite reinforced with glass fibers in one case and carbon fibers in the other case. They were made by vacuum assisted resin transfer moulding process. Further, the samples were characterized for three-body abrasive wear behaviour using dry sand rubber wheel abrasion tester with two different abrasives (silica sand and quartz). The wear data revealed that the C-V composite showed lower abrasion loss compared to G-V composite. The scanning electron microscopic pictures depicting the worn surface features supported the wear data.

Keywords: *woven fabric reinforced vinyl ester composites; abrasives; three-body abrasive wear; scanning electron microscopy*

1.0 INTRODUCTION

Polymers based composites are getting replaced in place of conventional engineering materials because of specific advantages such as ease of processing, self lubrication, high specific strength and stiffness. These are used for many engineering applications including power industries [1-2]. The fiber reinforcements in a polymer matrix, known as FRPCs, make them unique from the point of improved performance. The common reinforcements generally used are glass, carbon (graphite), aramid (Kevlar) fibers. E-glass fibers give beneficial mechanical properties at reasonable cost. Carbon or graphite fibers are widely known for their best performance as reinforcements in polymer composites. The purpose of the matrix material in FRPCs is to bind the fibers together. Also, the matrix resin material gives the FRP materials the ability to transfer the load as well as between the fibers. The most common matrix materials are epoxy, polyamide, vinyl ester, polyester, polypropylene, and poly ether ether ketone (PEEK).

Abrasive wear is defined as the hard asperities of the surface which moves across a softer surface under load, penetrates and removes material from the softer surface, leaving grooves [3]. Abrasive wear is classified as two-body, three-body and combination thereof. Two-body abrasive wear occurs when a rough/hard surface or abrasive media slides across another surface resulting in remove of material. The three-body abrasive wear takes place when the particles are

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loosely held and move relative to another, and possibly rotate, during sliding across the wearing surface. Most of the three-body abrasive wear problems are encountered in chute liners in thermal power plants, mining and earth moving equipment, while two-body abrasion occurs primarily in material handling operations. In most of the abrasive wear experiments the particles are harder than the wearing surface.

A three-body abrasion is generally considered more practical, but it appears to have received less attention than a two-body problem. The information available regarding the three-body abrasive wear of thermoset polymer composites, especially the woven fabric reinforced composite [4, 5, 6] is rather limited and in most of the studies, silica sand has been used as a abrasive. In the last few years, number of studies on polymer composites subjected to abrasive wear have been reported [7-11]. Budinski [7] investigated abrasion resistance of different types of polymers. It is reported that polyurethane showed better abrasion resistance over other materials. Evans *et al.* [8] also studied different types of polymers, and the data revealed that the low density polyethylene (LDPE) showed the lowest abrasion loss against rough mild steel but a higher wear rate in abrasion with coarse corundum paper. Cenna et al. [9] studied abrasion resistance of three types of vinyl ester resin systems, i.e. un-reinforced, reinforced with glass fibers and reinforced with particles of ultra-high molecular weight polyethylene (UHMWPE). They reported that UHMWPE reinforcement enhanced the wear resistance against both coal and mineral ignimbrite abrasives. Cirino *et al.* [10, 12] investigated the sliding and abrasive wear behaviour of PEEK polymer with different types of continuous fibers and it was reported that the wear rate showed a decreasing trend with increase in the fiber content.

Vinyl ester resins are stronger than polyester resins and cheaper than epoxy resins. Vinyl ester resin utilizes a polyester resin type of cross-linking molecules in the bonding process. Vinyl ester is a hybrid form of polyester resin which has been toughened with epoxy molecules within the main molecular structure. Vinyl ester resins offer better resistance to moisture absorption than polyester resins. No reports could be cited in the literature in respect of three body wear behaviour of glass-vinyl ester (G-V) and carbon-vinyl ester (C-V) composites.

In view of the above, the present research work focuses on the three-body abrasive wear characteristics of C-V and G-V composites. Further, an attempt has been made to understand the role of different fabric reinforcement in vinyl ester matrix composites and their wear behaviour with silica sand and quartz as abrasives. Scanning electron microscopy (SEM) has been used to examine the worn surfaces to arrive at the micro-structural features.

2.0 EXPERIMENTAL DETAILS

2.1 Materials

In this investigation, E-glass (FGI-1854)/carbon (T700) fabric as reinforcements and vinyl ester as the matrix were chosen. The woven roving (2-D-Rovcloth) was identified as one of the fabrics. Rovcloth 1854 consists of single end glass rovings with Fiber Glass Industries' (FGI) Super 317 sizing for ease of handling, fast wet out, and compatibility with a number of resins including vinyl ester. The aeral weight was 610 g/m^2 and the construction was unbalanced with 59% of the fibers in the warp direction and the remaining 41% of the fibers in the fill direction.

The carbon stitch bonded fabric designated as LT650-C10-R2VE was supplied by the Devold AMT AS, Sweden. This was an equi-biaxial fabric produced using Toray's Torayca T700 12k carbon fiber tow with a vinyl ester compatible sizing. The areal weight of the fabric was 634 g/m^2. Both the directional fibers were stitched with polyester knitting thread. Toray's Torayca T700 12k carbon fiber was selected because of its higher strength.

The matrices used were Dow Chemical's Derakane 510A-40 and 411-350, a brominated vinyl ester, formulated for the vacuum assisted resin transfer molding (VARTM) process. The bromination imparts a fire-resistant property to the composite. It has a higher fracture strain than the typical polyesters, and hence this may give rise to superior mechanical properties, impact resistance etc. The vinyl ester with a viscosity of 350 cps is ideal for the VARTM process. Derakane 510A-40 has a specific gravity of 1.23; tensile modulus and strength of about 3.4 GPa and 73 MPa respectively; and heat distortion temperature of 225° F.

2.2 Panel fabrication

The composite panels of size 600 x 900 x 2.5 mm^3 were fabricated by the VARTM process produced elsewhere. To achieve 2.5 mm nominal thickness, six plies of FGI-1854 Rovcloth fabrics or four plies of LT650-C10-R2VE fabrics were used. All the fabrics were cut and stacked in the 0° (warp) direction with the warp face down. The pre-forms were protected from dirt, grease and other contaminants that may prevent layer bonding during consolidation. The panels were cured at 25.6° C for 72 h and later post cured at 71.1° C for about 20 h. The volume fraction of glass and carbon fiber is 60% and 58%, respectively. The post cured panels were inspected visually for surface defects and tap tested for delaminations. All panels were found to be free from surface defects and delaminations.

2.3 Three body wear

The dry sand/ rubber wheel abrasion tester (ASTM G-65 guidelines) was used to conduct the three-body abrasive wear experiments [13]. The sample was cleaned (dry) and its initial weight was determined in a high precision digital balance (0.1 mg accuracy, Mettler Toledo) before it was mounted in the sample holder. In the present study silica sand and quartz were used as abrasives. The tests were conducted at a rotational speed of 200 rpm. The rate of feeding the abrasive was 255 ± 5 g/min.

The abrasives were introduced between the test sample and rotating rubber wheel made of chlorobutyl rubber (hardness: Durometer A 58-62). The test sample was pressed against the rotating wheel at a specified force by means of a lever arm while a controlled flow of abrasives abrades the test surface. The rotation of the abrasive wheel was such that its contacting face moves in the direction of the sand flow. The pivot axis of the lever arm lies within a plane, which is approximately tangential to the rubber wheel surface and normal to the horizontal diameter along which the load is applied. At the end of the test, the sample was removed, thoroughly cleaned and again weighed (final weight). The difference in the weight of the sample before and after the test was noted. Further, three tests were performed for one category of samples and the average value was reported. The experiments were carried out at a normal load of 22 N. Further, the abrading distances were varied in steps of 270 m from 270 m – 1080 m. For the second longer duration test; say 540 m distance, the abrasion tests were carried out on the very same wear track where first (i.e., 270 m) shorter runs were involved. Densities of the polymer composites were determined using the same high precision digital balance using Archimedes principle. The wear loss was then converted into wear volume loss using the measured density data. The specific wear rate (K_s in m^3/Nm) was calculated from the equation;

$$K_S = \frac{\Delta V}{L \times d} \quad (1)$$

Where, 'ΔV' is the volume loss in m^3, 'L' is the load in Newton and 'd' is the sliding distance in meters.

2.4 SEM study

After wear test, the worn surfaces were examined using SEM (JSM 840A model and JEOL make). Prior to the examination, a thin gold film was deposited on the worn surface.

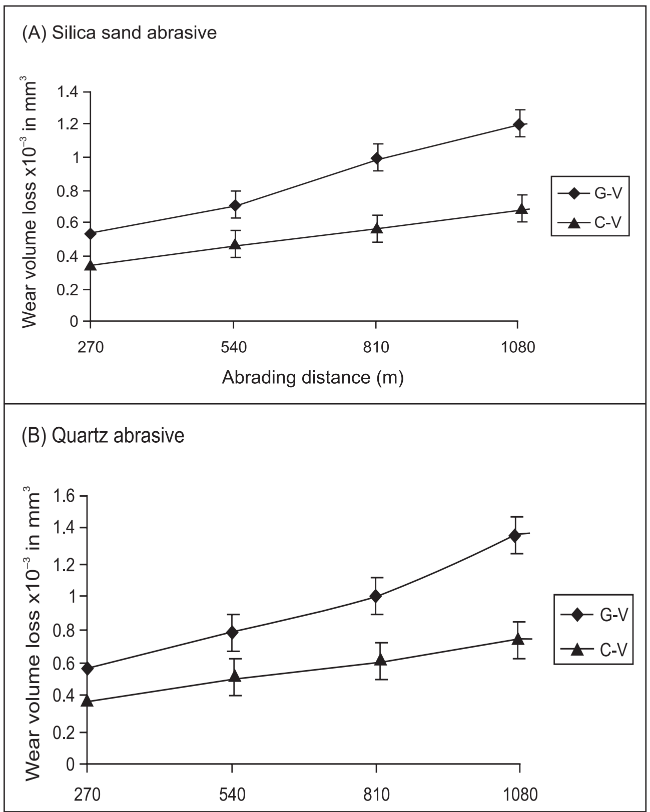
3.0 RESULTS AND DISCUSSION

3.1 Abrasive wear volume and specific wear rate

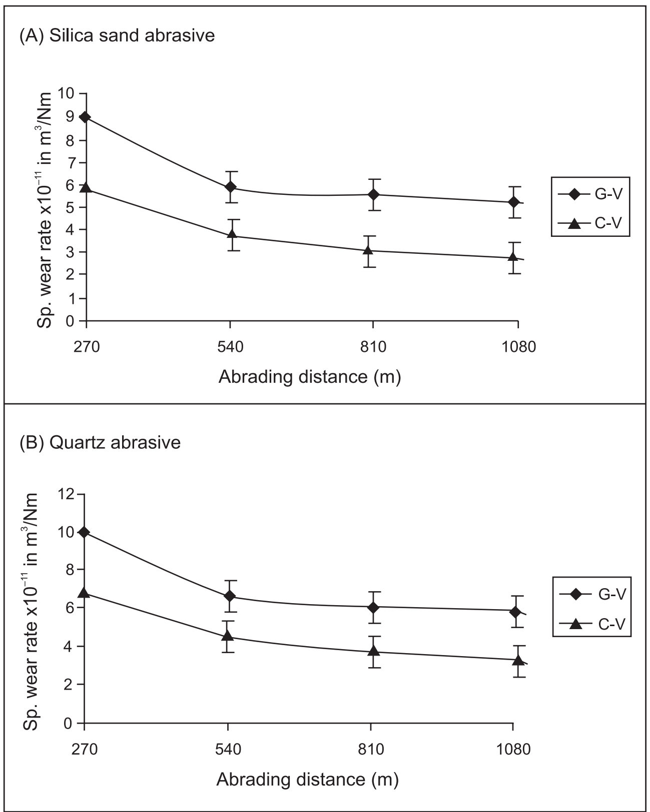
The abrasive wear volume loss data as a function of abrading distance for two different abrasives for C-V and C-V composites are shown in Figs. 1A and 1B, respectively. The wear data reveal that the wear volume loss increases linearly with increasing abrading distance. It is also seen that it is a function of the type of abrasive employed. With quartz as abrasive, the wear volume loss is higher for all the abrading distances adopted compared that of silica sand as abrasive both for C-V and G-V composites. This is because of the fact that quartz is harder and higher in particle size (250-300 μm) compared to silica sand (200-250 μm) abrasive. It is observed that the wear volume loss of C-V composite is much less than that of G-V composite irrespective of the type of abrasive used (Figs. 1A and B). The fibers (warp fibers) in C-V system which are parallel to the abrading direction might have acted as a barrier in breaking the transverse fibers (weft fibers) by virtue of the fact that it is interwoven with the warp fibers. Further, the data C-V composite gets a support because of better tensile strength and higher hardness of the carbon fibers.

Fig. 1 shows wear volume loss as a function of abrading distance at 22 N load of G-V and C-V composites with (A) silica sand as abrasive and (B) quartz as abrasive.

The variation in the specific wear rate with abrading distance at 22 N for different abrasives is shown in Figs. 2A and 2B, respectively. The specific wear rate decreases with increasing abrading distance and depends on the type of abrasive media. Like in the above case, the results revealed higher abrading nature of G-V composite compared to C-V composite with the use of different abrasives. Also, higher specific wear rate was noticed for G-V composite



FIGS. 1 WEAR VOLUME LOSS AS A FUNCTION OF ABRADING DISTANCE AT 22 N LOAD OF G-V AND C-V COMPOSITES WITH (A) SILICA SAND AS ABRASIVE AND (B) QUARTZ AS ABRASIVE



FIGS. 2 SPECIFIC WEAR RATE AS A FUNCTION OF ABRADING DISTANCE AT 22 N LOAD OF G-V AND C-V COMPOSITES WITH (A) SILICA SAND ABRASIVE AND (B) QUARTZ ABRASIVE

compared to C-V composite. Thus, in the initial stage of abrasion, abrasive is in contact with matrix which has less hardness compared to that of angular silica sand resulting in severe matrix damage and higher rate of material removal. Similarly, when glass/carbon fibers are in contact with abrasive particles bi-directional fibers provide better resistance to the process of abrasion. This is because the carbon fiber has high specific strength compared to glass fiber and possesses self lubricating property. These two characteristic properties of carbon fiber enhance the wear characteristics of the composite. The influence of quartz abrasive on the wear rate is more pronounced than that of the use of silica sand. Lancaster [14] studied the abrasive wear behaviour of various thermo plastic polymers reinforced with 30% short carbon fibers and reported that the abrasive wear loss for some of them showed decrease in trend and for the remaining samples, the abrasion loss exhibited an increase. The reason for such trends when reasoned may finally be attributed to the type and the nature of the reinforcements used as well the placement of the fibers.

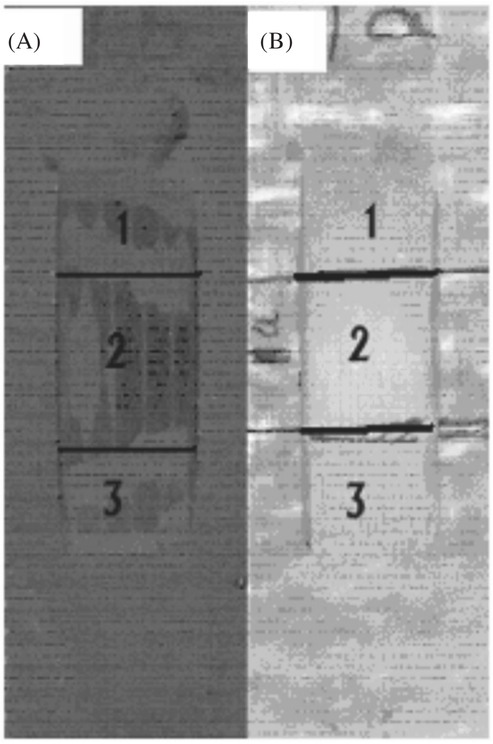


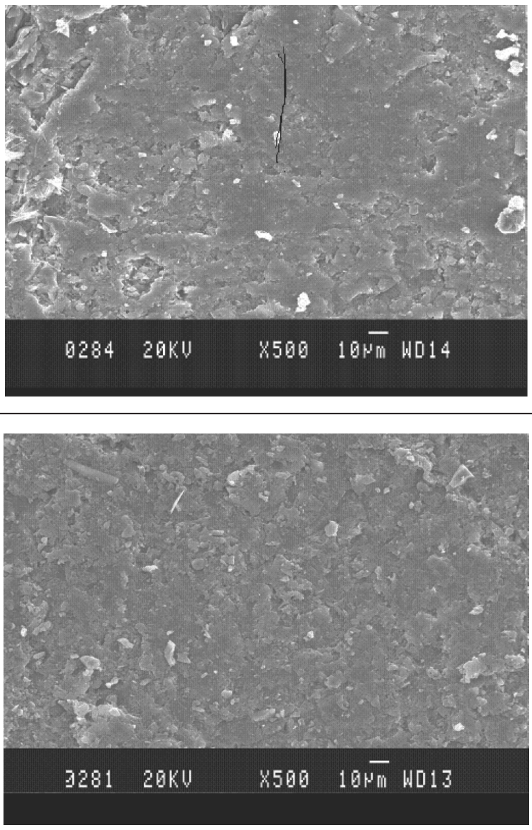
FIG. 3 A TYPICAL WEAR SCAR OF (A) C-V AND (B) G-V COMPOSITES

The published information [15] on the C-E system shows that wear volume loss of graphite filled C-E is much lower compared to C-E system for different loads employed and for both the sources, the wear volume loss increases with increase in abrading distance. In the present work also, a similar trend in respect of wear volume loss vs. abrading distance has been observed for silica sand and quartz as abrasive particles, which is in line with the published work [15]. Regarding the specific wear rate (K_s) vs. abrading distance, it is seen that K_s decreases with the increase in abrading distance, for the vinyl ester based glass reinforced composites thus getting credence from the reported work [16].

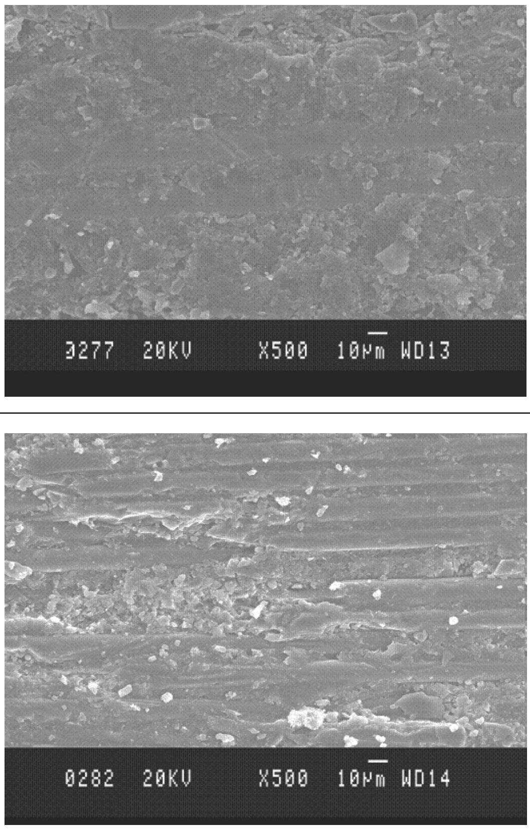
3.2 Microscopic observations

A typical wear scar of C-V and G-V composite specimen is shown in Figs. 3A and 3B. Three different zones namely entrance (marked as 1), mid (marked as 2) and exit (marked as 3) are seen under three-body abrasive wear conditions. At the entrance and exit zones, where the pressure applied to the abrasive is lowest, the damage morphologies were consistent with particle rolling.

To correlate the wear data with the microstructure, SEM pictures shown in Figs. 4 A and B and Figs. 5 A and B abraded for 270 m and 1080 m using silica sand as abrasive at a load of 22 N pertaining to C-V and G-V composites, respectively are considered for discussion. Figs. 4 A and B display the worn surfaces of C-V samples abraded using silica sand abrasives under extreme abrading distance conditions. The abraded surface of C-V composite (Fig. 4A) is relatively smooth with less evidence of fiber fragmentation (Fig. 4A) as compared to G-V composite (Fig. 5A). Also, there appears to be a good adhesion between the fiber and the matrix at the interface (Fig. 4B). Fig. 5(A) shows that fibers apparently are not well bonded to the matrix material. Further, it shows the presence of transverse fibers in



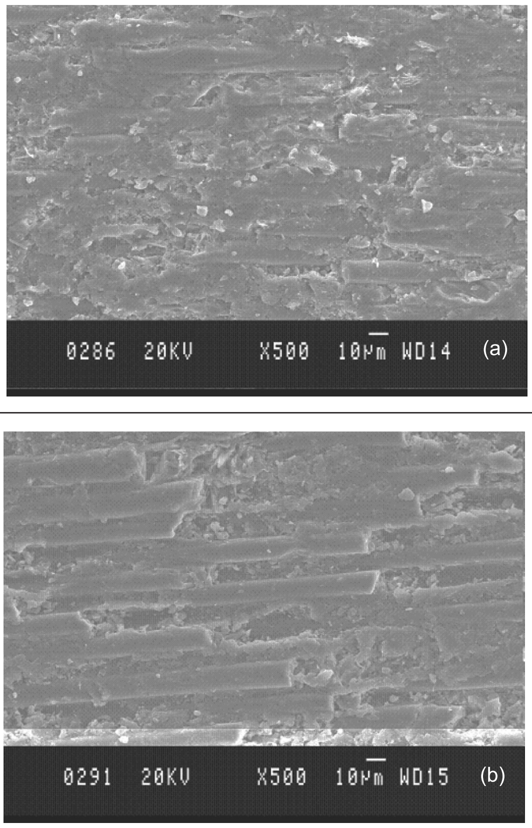
FIGS. 4 WORN SURFACE FEATURE OF C-V COMPOSITE UNDER SILICA SAND ABRASIVE; (A) 270 M, AND (B) 1080 M



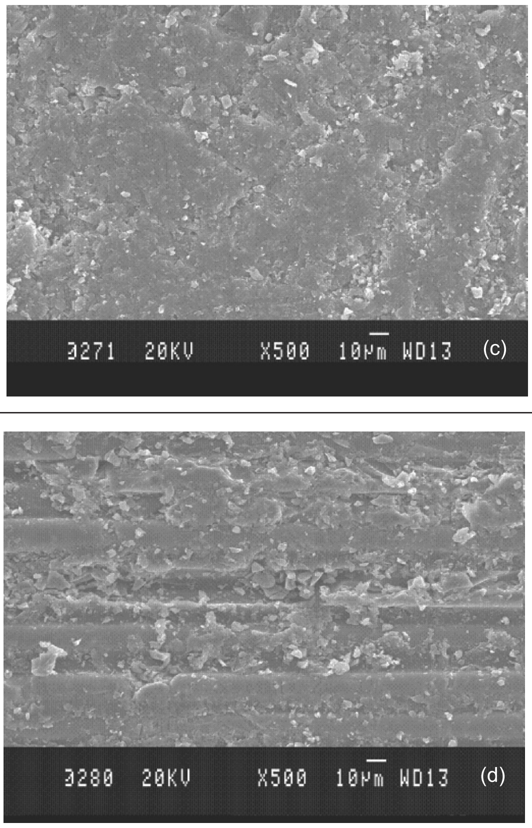
FIGS. 4 WORN SURFACE FEATURE OF C-V COMPOSITE UNDER QUARTZ ABRASIVE; (C) 270 M, AND (D) 1080 M

broken condition with matrix debris concentrated at isolated regions for 270 m run sample, while the 1080 m run sample are dominated by more number of broken fibers (Fig. 5B). There is an evidence of higher matrix removal and deep furrows in the direction of abrasion in G-V composite due to the ploughing action of sharp abrasive particles (Fig. 5B) compared to C-V composite (Fig. 4B). Further, matrix debris formation and few broken fibers (Fig. 5B) due to the cutting action of the abrasives are noticed in G-V composite subjected to 1080 m run. Whereas, there appears less matrix formation in C-V composite (Fig. 4B) subjected to the same abrading distance.

Figs. 4 C and D and Figs. 5 C and D show the worn surfaces of C-V and G-V composite, respectively, abraded using quartz as abrasive at a load of 22 N for 270 and 1080 m distance run. In these cases, the wear tracks seem to be very sharp. Higher matrix wear, fiber breakage and removal of fibers due to stress created by the hard quartz particles can be seen from Figs. 4(C) and (D). In the case of G-V composites shown in Figs. 5c and d, the influence of quartz abrasive on the slide wear is more than that is seen in C-V composites (Figs. 4 C and D). The G-V composite at lower abrading distance run exhibits less debris formation. Overall the surface topography of G-V composite at higher abrading distance shows more of fiber pulverization resulting in fiber breakage and less fiber-matrix de-bonding and masking of fibers at some regions. Thus, the wear data get very good support following the examination and interpretation of the SEM features. In both the types of samples, one striking feature observed on the surfaces is the cleavage type of fracture in the direction normal to the abrading direction (sand flow direction in all cases of the SEM micrographs are from right to left) for the 1080 m run. However, cracks on the matrix, fiber/matrix debonding and fiber breakages are less noticed in C-V composite compared to G-V composite.



FIGS. 5 WORN SURFACE FEATURE OF G-V COMPOSITE UNDER SILICA SAND ABRASIVE; (A) 270 M, AND (B) 1080 M



FIGS. 5 WORN SURFACE OF G-V COMPOSITE UNDER QUARTZ ABRASIVE; (C) 270 M, AND (D) 1080 M

It is summarized that the use of C-V composite is desirable for the tribological applications in view of lower abrasion loss obtained due to the less debris formation and fiber breakage. Also, it is seen that the bonding between the fiber and the vinyl ester matrix seems to be favorable as the fibers not getting dislodged.

CONCLUSIONS

The present investigation reveals the following:

- The abrasive type and the abrading distance are the factors influencing the specific wear rate.
- The G-V composites show higher wear volume loss with increase in abrading distance when compared to C-V composites.
- Among the two fibers employed, carbon fiber in vinyl ester matrix shows lower abrasion loss with respect to the abrading distance as well as the type of abrasive employed.
- SEM features of the G-V composite display more fiber pulverization, more fiber breakage and less fiber-matrix de-bonding compared to C-V composite.
- The C-V composite seems to be a promising material for the applications involving scratching abrasion irrespective of the abrading distance employed and the type of abrasive used.

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