Parametric optimization of Three-Body Abrasive Wear Behavior of Bidirectional and Short Kevlar Fiber Reinforced Epoxy Composites

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Abstract

In this article, the mechanical and three body abrasive wear behavior of Bidirectional and short Kevlar fiber reinforced epoxy composites at five different fiber loading (10wt%, 20wt%, 30wt%, 40wt% and 50wt%) have been evaluated. The mechanical properties i.e. tensile strength, flexural strength, inter-laminar-shear strength, and impact strength are performed to notice the behavior of mechanical properties with that of fiber loading. The loss in weight of the material during three body abrasion can be tested using DUCOM Tr-50 Dry Abrasion Tester. The steady state specific wear of the composites can be evaluated for normal load and sliding speed by keeping other parameters remains constant. The results show that the wear rate increases with the increase in the value of normal load for bidirectional as well as short fiber composites whereas, with the increase in the value of sliding velocity the specific wear rate decreases in both the cases. Wear characteristics and their significant factor settings are successfully analyzed using statistics based Taguchi experimental design and analysis of variance (ANOVA) respectively. Finally, the experimental wear rate results are compared with the theoretical one and the error lies with in the acceptable limit i.e for bidirectional Kevlar fiber composites the error values are within 8% and 5% for that of short fiber composites. The SEM micrographs studies reveal the dynamics of three-body abrasive wear and underlying micro-mechanisms that serve as determinant for wear performance of such composites.

Keywords: composites, wear, mechanical

1. Introduction

Polymer matrix composites are being accepted as an innovative substitute over traditional materials due to its enhanced mechanical properties, light weight and longer life. In fiber reinforced composites (FRC's) matrix glues the fiber together and in turn transfer forces to fiber which provide strength and flexibility to the composite material. Natural as well as artificial fibers are both offering a wide demand for FRC's and the advantage of the use of artificial fiber such as glass fiber, kevlar fiber and carbon fiber is that their dimensions are precisely measured and controlled within a close proximity to the desired once. Measured and controlled dimensions provide a basis of true comparison [1, 2]. The advantage of using synthetic fiber such as Kevlar fiber is that they have improved properties and are particularly stronger due to low surface defects. Research have been undertaken to find more innovative material over available once, due to random orientation and small length of chopped aramid fiber load is not equally transferred in all the directions whereas, in bi-directional aramid fabric the length of the fiber are long and weave in the form of matting and load can easily be transferred from one portion to another [3]. The incorporation of fibers into polymer matrices raises the composite modulie that are appropriate to make engineering composites [4]. Fibers in normal and parallel (N–P) and normal and anti-parallel (N–AP) direction with respect to sliding plane impart maximum wear resistance. Whereas, N–P was best for light loads while N–AP was best for high loading conditions. Aramid fabric revealed significant potential to improve abrasive wear performance of polyetherimide composites when the fabric was perpendicular to the abrading surface, performance of the composites was substantially better than the case when it was in the parallel orientation [5, 6]. Hence, fabric reinforcement composites enhanced the abrasive wear resistance significantly [7]. Among two body abrasion and three body abrasion, three body abrasion is widely available as in three body abrasion loose particles are present in between the work-piece and the abrasive medium. Incorporation of Kevlar pulp into epoxy contributed to improve the friction and wear behavior considerably. The optimum wear reduction was obtained when the content of Kevlar pulp increased to 40vol.-% [8]. Similarly, Larsen et al. [9] while comparing friction and wear for glass or carbon/aramid reinforced epoxy resin hybrid weave found that glass/epoxy shows overall consistent performance whereas, carbon/epoxy shows superior wear behavior only for few pv conditions.

From the brief literature cited above it is evident that very few studies have been conducted using Kevlar fiber, however to the best of authors knowledge almost no study has been done on three body abrasive wear behavior of bidirectional and short Kevlar fiber reinforced epoxy composites with certain wt.-% composition. In this study, minimum specific wear rate and comparing the properties of bidirectional and short Kevlar fiber composites have been investigated.

2. Experimental procedure

2.1 Materials and Specimen

Bi-Directional Aramid fabric (Kevlar 29) 3k – Plain weave 200 G.S.M. as shown in figure 1(a) and chopped Aramid fiber (200 G.S.M. and 4-5mm fiber length) as shown in figure 1(b) manufactured by Teijin Aramid Corporation are used as a reinforcing material. Its chemical description is poly para-phenylene terephthalamide. Fiber reinforced polymer composites of bi-directional and short kevlar fiber are separately prepared with epoxy resin chemically belonging to epoxide family used as a matrix material. Its chemical description is Bisphenol A Diglycidyl ether. The low temperature curing epoxy resin (LY556) and corresponding hardener (HY951) are mixed in the ratio of 10:1 by weight as recommended. Epoxy resin and corresponding hardener are supplied by Ciba Geigy India LTD. Kevlar fiber and epoxy resin has young's modulus of 105GPa and 3.42GPa respectively and possesses density of 1450 Kg/m^3 and 1100Kg/m^3, respectively. The bidirectional Kevlar fiber composites are prepared by simple hand lay-up technique; layers of fibers are varied in number to get the desired percentage by weight of fiber composition. Composite slab for 10wt. % fiber composition has a thickness of 5.7mm whereas the thickness obtained for 50wt. % fiber composition is 8.3mm. The increase in thickness of composite at 50wt. % fiber loading is due to the increase in the layers of fibers. For preparation of short Kevlar fiber composites, short fibers and epoxy resin are initially weighed in separate container in desired weight percentages. The weighed fibers are then mixed with epoxy resin and stirred continuously to get a uniform mixture. The mixture is then poured in a wooden mould initially provided with mould release sheets. The mixture is then labeled with the help of rollers. Apply some weights and left for solidification for 24 hours. Similar procedure is adopted for five different compositions (i.e. 10wt%, 20wt%, 30wt%, 40wt% and 50wt %) respectively After that all the composites are removed from the mould and dried in the furnace at a temperature of 50^{0}C for 15 min only to remove moisture from the composites.

2.2 Experimental details

Three body abrasive wear tests of bidirectional and short Kevlar fiber reinforced epoxy composites are carried out on DUCOM Tr-50 dry abrasion tester (ASTM G 65). DUCOM TR 50 test instrument is designed such that a flat test sample is pressed radially against a wheel with a known force. Abrasive media is introduced into the contact area between the sample and the wheel such that the wheel carries the abrasive particles between the sample and the wheel creating a scenario of three body abrasive wear (flow rate of abrasive particles is 358gms/min). The detail of the experimental procedure was reported in our previously published work [**10**]. The loss of weight of test samples indicates wear resistance and parameters selected at which three body abrasion test is being carried out are as shown in Table. 2.

The loss in volume of sample is computed in the following manner:

Loss in volume in mm^3 =

$$\frac{\left(wt.before\,test\,(g) - wt.after\,test\,(g)\right)}{Density\left(\frac{g}{cm^3}\right)} \times 1000$$

The specific wear rate (W_S) is calculated experimentally from the equation:

$$Ws = \frac{\Delta m}{\rho t F_N V_s} \qquad (1)$$

Where, Δm: mass loss in the test duration (gm), ρ : density of the composite (gm/mm^3), t : test duration (sec), V_s : sliding velocity (cm/sec), F_N : average normal load (N).

2.3 Test for mechanical properties

The variety of tests that decide the characteristic of a material included the density, hardness, tensile strength (T.S.), flexural strength (F.S.), Inter laminar shear strength (I.L.S.S.) and Impact strength (I.S.) respectively.

The theoretical density of composite material in terms of weight fraction can easily be calculated with the help of Agarwal and Broutman [11] equation. The difference in the values of theoretical and experimental density is a measure of the presence of voids and pores in the composites. The void fraction is calculated as given by:

$$\Delta v = \frac{\rho_{ct} - \rho_{exp}}{\rho_{ct}} \times 100 \qquad (2)$$

Where Δv = Void fraction, ρ_{ct} = Theoretical density and ρ_{exp} = Experimental density

Micro hardness measurement is done as per Leitz micro hardness tester. Diamond indenter with a square shaped pyramidal base (angle 136^0) between opposite faces) is used to make an impression on composite specimen. The tensile test is generally performed on rectangular shaped specimen with the narrow gauge length in the middle and broadens end tabs. During the test a uniaxial loads acting outwards from both the ends (UTM Instron 1195) [12]. The ASTM standard test method for tensile properties of fiber resin composites has the designation D 3039-76. The ASTM standard test recommends that the specimens with fiber parallel to the loading direction should be 200mm long and 11.5mm wide. A three point bend test is conducted on universal testing machine Instron 1195 to find out the flexural strength of the composite sample with span length of 30mm and a crosshead speed of 10mm/min are maintained for the loaded specimen subjected to failure. Inter laminar shear strength tests are conducted as per ASTM D 2344-84 test standards on universal testing machine Instron 1195. Span length of 50mm and cross head speed of 10mm/min is maintained [13]. Impact strength is the capability of the material to withstand a suddenly applied load and is expressed in terms of energy. These tests are being carried out on impact tester at low velocities. The tests are done as per ASTM D 256 test standards [14]. Dimensions for specimen taken for impact test are 64mm × 12.7mm × 3.2mm with a V-groove of 2.5mm depth at the centre of the specimen. The specimen is then fixed in the slot such that the groove of the specimen facing towards the striking end of the hammer. The surfaces of bidirectional as well as short Kevlar fiber are examined by scanning electron microscope (Carl Zeiss NTS GmbH, SPRA 40VP). Finally, the composite samples are mounted on stubs and photomicrographs are taken for each composition at different amplification range for analysis and study.

2.4 Experimental design

The technique of defining and investigating all possible conditions in an experiment with the minimum number of iterations involving multiple factors is known as design of experiments. This technique has been utilized widely in engineering analysis to optimize the performance characteristics with the combination of design parameters [15, 16]. Taguchi method obtains the optimal condition by reducing the number of trials (iterations) for the particular combination [17]. Here, Taguchi experimental method is planned for five parameters viz. fiber content, normal load, sliding distance, abrasive size and rotation speed as shown in Table 2 and each at five labels. The impact of five such parameters is studied using the L_{25} (5^5) orthogonal array design. The experimental observations are further transformed into signal-to-noise (S/N) ratios. The S/N ratio for minimum three body abrasion can be expressed as "lower is better", which is calculated as logarithmic transformation of loss function as shown below.

Smaller is the better characteristic: $\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right)$ (3)

Where, n is the number of observations and y is the observed data.

The plan of experiments in the present study for both bidirectional and short Kevlar fiber are as follows: the first column is assigned to sliding velocity (A), second column to fiber loading (B), third column to normal load (C), fourth column to sliding distance (D) and fifth column to abrasive size (E) respectively. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the experimental design.

3 Results and discussion

3.1 Physical and Mechanical properties

The selected compositions of Kevlar fiber reinforced epoxy composites revealed that by the addition of fibers in the composites influences the physical and mechanical properties respectively.

3.1.1 Effect of fiber loading on void content of bi-directional/ short Kevlar fiber-epoxy composites

It may be observed from Table 1, that the experimental and theoretical observed density is not similar. The values of experimentally observed densities are somewhat less than that of theoretical densities. The difference is a measure of pores and voids in the composite and it usually varies from 0.794% to 2.702% for bidirectional Kevlar fiber and from 0.483% to 3.26% for short Kevlar fiber, which is approximately negligible in comparison to the weight of the composite. Thomason et al. [18] and Lee and Jang [19] reported that when the fiber content is more than the required optimal quantity automatically the physical and mechanical properties of composites reduced.

3.1.2 Effect of fiber loading on hardness of bi-directional / short Kevlar fiber -epoxy composites

Figure1 shows the comparison in the properties of hardness for bidirectional as well as short Kevlar fiber reinforced epoxy composites. For bidirectional composites hardness increases with the increase in fiber loading but slightly decreases for 20wt.% and 40wt.% fiber loading whereas for short fiber composites hardness increases with the increase in fiber loading up to 30wt.% fiber loading and then suddenly drops. The decrease in hardness is due to the presence of pores and voids which can be clearly verified with the help of Table 1. The void fraction values are more where the hardness values are less whereas the void fraction values are less where the hardness values are more.

3.1.3 Effect of fiber loading on tensile strength of bi-directional / short Kevlar fiber -epoxy composites

Figure 2 shows the effect of fiber loading on the tensile strength of composites. The tensile strength increases with the increase in fiber loading of the composite except that at 20wt% bidirectional Kevlar fiber composition. This decrease may be due to improper bonding in between the matrix (epoxy) and the layer of Kevlar fiber and hence shear stress induced between the layers of the composite. Whereas, in short Kevlar fiber composites tensile strength decreases at 50wt.-% fiber loading this decrease may be attributed to the fact that at higher fiber loading due to the decrease in the percentage of epoxy resins the bonding between the epoxy and the fiber decreases. Similar observations were noticed by Youjiang et al. [20] for mechanical properties of fiber glass and Kevlar woven fabric reinforced epoxy composites. While comparing between bidirectional and short fiber composites in bidirectional composites due to uniform weave and spacing in between the fibers the loads can effectively be transferred and resulting in the increase in tensile strength than that of short Kevlar reinforced composites.

3.1.4 Effect of fiber loading on flexural strength and inter-laminar-shear-strength of bi-directional/ short Kevlar fiber -epoxy composites

Figure 3 shows the effect of fiber loading on the flexural strength of the composites. Flexural strength increases with the increase in fiber composition of the composites (bidirectional and chopped). However, for short Kevlar fiber at 50wt.-%, the flexural strength decreases, this decrease may be due to the weak fiber to fiber interaction and dispersion problem. Asri and Khalil [21] also reported that the reduction in flexural strength of the thermoplastic composites may be due to the low interaction and poor dispersion of fiber in the matrix. While comparing the values, flexural strength for chopped fiber composites are more than that of bidirectional composites i.e. bonding between bidirectional fiber and epoxy is less in comparison to that of short Kevlar fiber reinforced composites. Inter-laminar shear strength (ILSS) is useful to test for composites where the chances for failure of lamina in layered composite is more to initiate when subjected to shearing stresses. Fig.4 shows the effect of fiber loading on Inter laminar shear strength (I.L.S.S.) of the composites. I.L.S.S. value increases with the increase in fiber loading of the composites, however for short fiber after 40wt.-% fiber loading the I.L.S.S. value decreases due to the presence of higher percentage of pores and voids in the composite (Table 1). Gerard [22] and Hancox and Wells [23] also noticed similar observations in the increase of I.L.S.S. values with the increase in fiber loading. While comparing the graphs of bidirectional and short fiber reinforced epoxy composites the Inter laminar shear strength values are more for bidirectional fiber reinforced composites in comparison to that of chopped composites (Fig.4). This may be due to the fact that bidirectional composite consist of fiber layers and strength can effectively be transferred, from one end to another in case of bidirectional composites than that for chopped fiber reinforced composites. Also above 30wt. % fiber composition I.L.S.S. values remain constant.

3.1.5 Effect of fiber loading on impact strength of bi-directional / short Kevlar fiber-epoxy composites

Figure 5 shows the effect of fiber loading on the impact strength of bidirectional and short Kevlar fiber reinforced epoxy composites. Impact strength increases with the increase in fiber loading in the epoxy matrix up to some extent (40wt.-%) and further decreases. However, at higher fiber loading the fiber to matrix bonding reduces and hence at 50wt.-% fiber loading impact strength is less in case of both bidirectional and short Kevlar fiber composites.

3.2 Steady state specific wear

3.2.1 Effect of sliding velocity on specific wear rate for bi-directional composites

The term steady state is used to describe a situation where some, but not all, the variables of a system are constant. Variables refer to the terms sliding velocity, fiber loading, normal load, sliding distance and abrasive size. Here, our approach is to find the effect of sliding velocity on specific wear rate of bidirectional Kevlar fiber reinforced epoxy composites keeping other variables as constant (At constant normal load: 40N, sliding distance: 60m and abrasive size: 375 µm). As specific wear rate decreases with the increase in sliding velocity up to 120cm/sec but further increases for 144cm/sec sliding velocity for all the compositions (Fig. 6a). The decrease may be attributed to the fact that as the speed increases contact time between the rubber wheel and the specimen automatically decreases and hence less wear occurs. But at exceptionally higher speeds such as 144cm/sec rubber wheel is not in direct contact with the specimen at all the times and specimen jumps of the wheel and in contact with the specimen only at few points. Due to the higher normal pressure at the particular point of contact the amount of material removal is more and hence specific wear rate increases.

3.2.2 Effect of normal load on specific wear rate for bidirectional composites

Number of experiments is carried out to notice the effect of normal load on specific wear rate of bidirectional Kevlar fiber reinforced epoxy composites. Normal load vary in a steps of 20N from a minimum of 20N to the maximum of 100N for 10wt%, 20wt%, 30wt%, 40wt% and 50wt% fiber reinforcements. Fig.6b shows the effect of normal load on specific wear rate of the composites. Specific wear rate increases with the increase in normal load on the specimen. This increase may be attributed to the fact that as the normal load increases more surface is in contact with the rubber wheel and abrasive particles. Abrasive particles penetrate inside the surface of the specimen and hence weight loss and specific wear rate increases.

3.2.3 Effect of sliding velocity on specific wear rate of short Kevlar fiber composites

Steady state specific wear tests are conducted to notice the effects of sliding velocity on specific wear rate of short Kevlar fiber reinforced composites and also to study the comparative evaluation between long and short fiber reinforcement. Fig.7a shows the effect of change in specific wear rate with the change in sliding velocity for all the composites. This is due to the fact that the surface area of contact is same for all sliding velocities whereas the duration of contact reduces as the sliding velocity increases. Also the specific wear rate is minimum for 10wt% fiber loading and maximum for 50wt% fiber loading (Fig.7a) i.e. as the fiber reinforcement increases the specific wear rate increases.

3.2.4 Effect of Normal Load on specific wear rate of short Kevlar fiber composites

Figure 7b shows the effect of Normal load (N) on the specific wear rate of short Kevlar fiber reinforced epoxy composites keeping other parameters remained constant i.e. sliding velocity: 72cm/sec, sliding distance: 60m and abrasive size: 375 µm respectively. Specific wear rate increases with the increase in normal load of the composites for 30wt % and 50wt% fiber reinforcement until 80N normal load whereas for 100N normal load the specific wear rate decreases. For 10wt%, 20wt% and 40wt% fiber reinforcement the specific wear rate increases up to 60N normal load, decreases for 40wt% fiber loading and then further increases for 50wt%. It is clear from the above discussion that specific wear rate increases up to some extent with the increase in normal load and then remains almost constant due to reduction in the amount of matrix material (epoxy) resulting in weaker bonding interface between the fiber and matrix material at higher fiber loading.

3.3 Analysis of experimental results by Taguchi experimental design

Taguchi experimental design approach is applied to find out S/N ratio of all the bidirectional and short Kevlar fiber reinforced epoxy composites. Table 3 shows the S/N ratio of specific wear rate of the bidirectional and short Kevlar fiber reinforced composites. The overall mean for the S/N ratio for 25 different iterations was found to be 26.933 db for bi-directional Kevlar fiber reinforced epoxy based composites and 31.971 db for the short Kevlar fiber reinforced epoxy based ones. The analysis was made using the popular software used for design of experiment applications known as MINITAB 15. The minimum specific wear rate for bidirectional Kevlar fiber reinforced composites is observed from Fig. 8a. Similarly, for chopped fiber composites minimum specific wear rate combination is presented in Fig. 8b as $A_1B_1C_5D_1E_5$. Since the specific wear rate values for short fiber composites are less in comparison to that of bidirectional composites therefore short Kevlar fiber reinforced epoxy composites is better choice.

3.4 Surface morphology

Scanning electron micrographs are taken for bidirectional as well as short Kevlar fiber reinforced epoxy composites for all the compositions of composition. Fig.9 shows the worn surface of bidirectional Kevlar fiber reinforced epoxy composites at different operating conditions. Fig.9a shows that at lower sliding velocity the fibers are slightly dislocated from its position due to the removal of epoxy resin and part of epoxy accumulated during fabrication. It is also observed that fibers are either fractured or removed at lower sliding velocity (48cm/sec) (See Table 3, Expt. No. 1, Column 7). Due to lower sliding velocity the contact time between abrasive sand particles and the specimen is more resulting in more and more number of particles embedded inside the surface of the specimen and hence more wear rate noticed. However, with the increase in sliding velocity, the matrix material are removed and entire load is carried out by the fibers as shown in Fig. 9b (See Table 3, Expt. No. 6, Column 7). It is clearly observed that slightly removal of fibers from the surface of composites for 10wt.-% bidirectional Kevlar fiber reinforced epoxy composites, but shear and brittle fracture occurs, due to shear deformation induced in fibers body. Similarly, under lower sliding velocity i.e. 48cm/sec for 20wt.-% fiber loading as compared with 10wt.-% fiber loading the wear rate is too minimum as shown in Fig. 9c (See Table 3, Expt. No. 2, Column 7). This may be due to the increase in fiber layer from 10wt.-% to 20wt.-% and proper mixing of resin materials with the Kevlar fiber. However, with increase in sliding velocity from 48cm/sec to 72 cm/sec, with change in weight percentage of fiber loading (20wt.-%) the specific wear rate increases drastically irrespective of the other controlling factors as shown in Fig. 9d (See Table 3, Expt. No. 7, Column 7). At higher particle size, medium fiber loading and normal load with minimum sliding velocity, more and more particles get embedded on the surface of the specimen, resulting in higher wear rate (Fig.9e). Fig. 9e shows that the breakage of fibers is due to more amount of material removed and weaker interface between the fibers and the matrix (See Table 3, Expt. No. 3, Column 7). However, in Fig. 9f under similar weight percentages of fiber loading (30wt.-%) at maximum sliding velocity and abrasive particle size but with medium normal load and sliding distance the wear rate becomes minimum as compared with

Fig. 9e (See Table 3, Expt. No. 23, Column 7). This may be due to in bidirectional fiber reinforced composites at higher sliding velocity the initial matrix layer removed and then fiber mat is exposed to abrasive medium and since due to continuous abrading action of the layer of fiber against rubber wheel the abrasive particles breakage of fiber took place. Similarly, for 40wt.-% of bidirectional Kevlar fiber reinforced epoxy composites under low sliding velocity the wear rate is comparatively minimum among other three sets of composites (See Table 3, Expt. No. 4, Column 7) as shown in Fig. 9g. This may be due to higher loads the frictional force developed at the interface of rubber wheel and the specimen is more but at lower sliding velocity. After continuous rubbing of the rubber wheel the matrix initially removed and along the sliding direction the fibers are broken but along perpendicular directions of the rubber wheel the fibers structure are remained unchanged. It may be due to that reason the wear rate becomes minimum. However, at higher sliding velocity both the directions the bidirectional Kevlar fiber are broken and the wear rate increases as shown in Fig. 9h (See Table 3, Expt. No. 24, Column 7). This may results in higher amount of wear and breaking of part or end of fibers. Fig. 9i and Fig. 9j show the micrograph of 50wt.-% Kevlar fiber reinforced composites at minimum and maximum sliding velocities respectively. In both the cases the matrix removal remains same and the bidirectional Kevlar fiber clearly visible. However, in 50wt.-% fiber loading both in minimum and maximum velocity the wear rate becomes minimum among rest of the compositions (See Table 3, Expt. No. 5, Column 7 and See Table 3, Expt. No. 25, Column 7) respectively.

Similarly, the three body abrasive wear behavior of short Kevlar fiber reinforced epoxy composites micrographs are presented in Fig.10 under controlled conditions. Fig.10a shows the abrasive wear behavior of short fiber reinforced composites at lower sliding velocity (See Table 3, Expt. No. 1, Column 9). In Fig. 10a at lower sliding velocity the matrix materials are removed from the composite surface and the abrasive particles are mixed with the short Kevlar fibers. Hence, the wear rate of the composite becomes less among other fiber reinforcements at low sliding velocity. However, with the increase in sliding velocity under similar fiber loading the wear rate increases gradually as shown in Fig. 10b (See Table 3, Expt. No. 21, Column 9). As Lamy and Burtin [24] conducted scratching tests to observe the abrasive wear behavior of surface damage of the composite materials. According to them, the amount of energy loss during scratching is greater than the energy dissipated during grooving, and parallel to the fibres direction. Similarly, under lower sliding velocity i.e 48cm/sec for 20wt.-% short Kevlar fiber reinforcement the wear rate of the composite is increased as shown in Fig. 10c (See Table 3, Expt. No. 2, Column 9). This may be due to the increase in short random fiber loading the binding force between fiber and resin become reduced. Therefore, wear rate mainly depends up on the upper surface of the composite materials instead of other layers. However, with increase in sliding velocity from 48cm/sec to 72 cm/sec, with the same weight percentage of fiber loading (20wt.-%) the specific wear rate increases marginally irrespective of the other controlling factors as shown in Fig. 10d (See Table 3, Expt. No. 7, Column 9). At higher particle size, medium fiber loading and normal load with minimum sliding velocity, the wear rate decreases (Fig. 10e) as compared with the Fig. 10d (See Table 3, Expt. No. 3, Column 9). Abraded ends shows that huge amount of matrix material has been removed from the composite surface during the process as the load acting normal to the surface of the specimen is more. However, Fig. 10f under similar weight percentages of short fiber loading (30wt.-%) at maximum sliding velocity and abrasive particle size but with medium normal load and sliding distance the wear rate becomes minimum as compared with Fig. 10e (See Table 3, Expt. No. 23, Column 9). Similarly, for 40wt.-% of short Kevlar fiber reinforced epoxy composites under low sliding velocity the wear rate is comparatively maximum between 10wt.-%, 20wt.-% and 30wt.-% fiber loading respectively (See Table 3, Expt. No. 4, Column 9) as shown in Fig. 9g. Similar observations have also reported by Cirino et al. [25, 26], that at higher normal load the abrasive wear rate increases. This may be due to energy barrier created at the interface of the composite surface. Therefore, at lower loads, the energy generated by abrasive particles is not sufficient enough to break the surface energy barrier and at higher loads, particles gain energy from the high speed rubber wheel and hence high wear loss was observed [25, 26]. However, at higher sliding velocity short Kevlar fiber are broken and the wear rate decreases at medium normal load, which is in agreement with Cirino et al. [25, 26] as shown in Fig. 9h (See Table 3, Expt. No. 24, Column 9).

Similarly, for 50wt.-% short Kevlar fiber reinforced composites at minimum and maximum sliding velocities (Fig. 10i and Fig. 10j), the wear rate is maximum at lower sliding velocity (See Table 3, Expt. No. 5, Column 9) and minimum at higher sliding velocity (See Table 3, Expt. No. 25, Column 9) respectively. The higher wear rate exhibit possibly because of fibers is subjected to torsional loading in addition to shear by abrasive particles (Fig. 10). The mechanism is resulted in due to the higher energy gain of the abrasive particles from the high-speed rubber wheel and the crack propagation through the fiber and the interfacial debonding are also observed. As results in more and more amount of matrix material removed and fibers being removed in the form of wear material.

3.5 ANOVA and the effects of factors

In order to find out statistical significance of various factors like sliding velocity, fiber loading, normal load, sliding distance and abrasive size on specific wear rater of the bi-directional and short Kevlar fiber reinforced epoxy composites, analysis of variance (ANOVA) is performed based on Taguchi experimental results. Table 4 and Table 5 show the results of the ANOVA with the specific wear rate of bi-directional and short Kevlar fiber epoxy based composites taken in this investigation. This analysis is undertaken for a level of confidence of significance of 5 %. The last column of the table indicates that the main effects are highly significant (all have very small p-values) (Table 4, Column 7).

From Table 4, it can be observed for bidirectional (long) Kevlar fiber-epoxy based composites that fiber loading ($p = 0.003$), sliding velocity ($p=0.150$), abrasive size ($p = 0.243$), and normal load ($p=0.343$) have great influence on specific wear rate. However, sliding distance ($p = 0.354$) shows less significant contribution on specific wear rate of the composites.

Similarly, from Table 5, it can be observed for the short Kevlar fiber reinforced epoxy composites the fiber loading ($p = 0.040$), normal load ($p = 0.444$), abrasive size ($p = 0.535$) and sliding distance ($p = 0.836$) have major influence on specific wear rate. The remaining factor is less significant effect on the specific wear rate of the composites. Therefore, from this analysis it is clear that short Kevlar fiber reinforced epoxy composites are more suitable for abrasive wear environment as compared to that of bi-directional Kevlar-epoxy composites. Whereas, for structural application point of view bi-directional Kevlar fiber reinforced epoxy composites show better mechanical properties than short Kevlar fiber reinforced epoxy composites.

3.6 Calculations of theoretical results and comparison with experimental results

Steady state three body abrasive wear and Taguchi's design of experiments is being carried out for different percentages of fiber and epoxy resin. L_{25} array is being selected to test for optimum factor combinations and specific wear rate. The experimental values are then compared with that of the theoretical once [**27**] and error percentage is calculated. Therefore, the theoretical specific wear rate of the composites is calculated by using Eq. 4 for three-body abrasive wear rate as:

$$Ws_{th} = \frac{\mu \times F \times L}{H \times \varepsilon} \qquad (4)$$

The developed theoretical predictive results of specific wear rate (Ws_{th}) of bidirectional (long)/ short Kevlar fiber reinforced epoxy composites are calculated using Eq. 4. From the Eq. 4, it is evident that specific wear rate is directly proportional to coefficient of friction (μ), percentage of fiber reinforcement (F) and length of fiber (L) whereas inversely proportional to hardness of the composite (H) and percentage length for elongation to break (ε) of fiber. Here length of fiber (L) for long Kevlar fiber is 20cm as the composite are prepared for 20 cm length × 20cm width whereas, the elongation to break selected is 3.6% of the length of fiber as per the specifications given by supplier (Teijin Aramid Corporation, India) whereas the length of short Kevlar fiber is 5mm and elongation to break is 3.6% of the length of the fiber. Coefficient of friction (μ) is the ratio of frictional force to the normal load. The values of frictional force, normal load and hardness are given in Table 6. These theoretical values are compared with the values obtained from experimental results conducted under similar operating conditions. Table 7 presents a comparison between experimental results and theoretical results. The errors in experimental results are compared with theoretical results for bi-directional and short Kevlar fiber reinforced epoxy composites. The error lies in the between 0.09%-7.58% for bidirectional Kevlar fiber (Table 7) and 0.27-4.95% for short Kevlar fiber reinforced epoxy composites (Table 7).

4. Conclusions

Comparative study carried out on bidirectional and short Kevlar fiber reinforced epoxy composites to notice the effect of three body abrasion (based on several factors) on the specific wear rate of composites. Based on the above observations, following points may be concluded as under.

1. Specific wear rate changes with the change in sliding velocity and normal load of the composites. With the increase in sliding velocity specific wear rate decreases whereas specific wear rate increases with the increase in normal load for both bidirectional and short Kevlar fiber reinforced composites.
2. Taguchi design of experiments is used to calculate minimum specific wear rate for the given set of five factors each having five variables. The minimum specific wear rate for bidirectional Kevlar fiber reinforced composites is for $A_{III}B_{I}C_{II}D_{II}E_{IV}$ whereas for chopped fiber minimum specific wear rate is for $A_{III}B_{I}C_{II}D_{III}E_{IV}$. Since the specific wear rate values for short fiber composites are less in comparison to that of bidirectional composites therefore short Kevlar fiber reinforced epoxy composites is better choice (where A,B,C,D and E denotes the control factors and I,II,III,IV and V denotes the corresponding levels in the text).

3. Theoretical values of specific wear rate are calculated based on the given wear model and further compared it with experimental specific wear rate values. The errors values for bi-directional Kevlar fiber reinforced epoxy composites lies in the range 0-8%. Whereas, for short Kevlar fiber reinforced epoxy composites error lies is in the range of 0-5%.
4. Mechanical properties such as tensile strength, flexural strength, Inter laminar shear strength, impact strength and hardness increases with the increase in fiber loading from 10wt% to 50wt% except for few points where decrease may be noticed, this may be due to improper boding between the fiber and the resin and due to the presence of pores and voids. Also mechanical properties values for bidirectional KFRE composites are more than that for short KFRE composites except that for hardness and impact strength where vice-versa happens.
5. Future study can be extended to new fiber/ matrix combinations and the resulting experimental findings can be further analyzed similarly.

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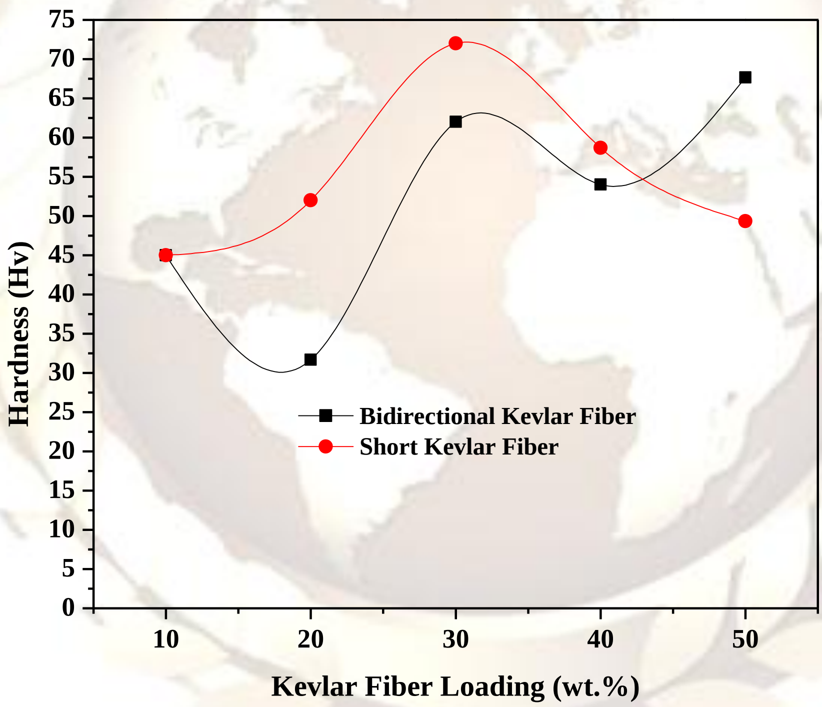


Fig. 1 Effect of fiber loading on hardness of Kevlar fiber reinforced epoxy composites

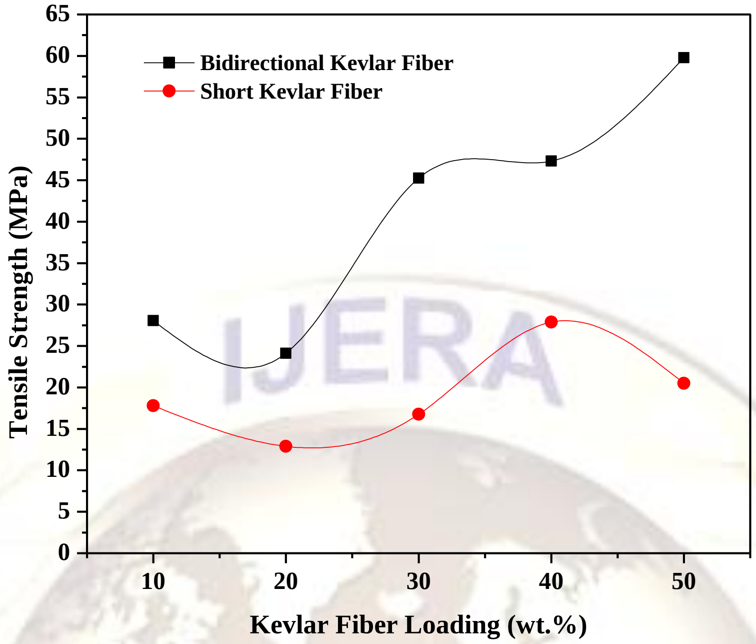


Fig. 2 Effect of fiber loading on tensile strength of Kevlar fiber reinforced epoxy composites

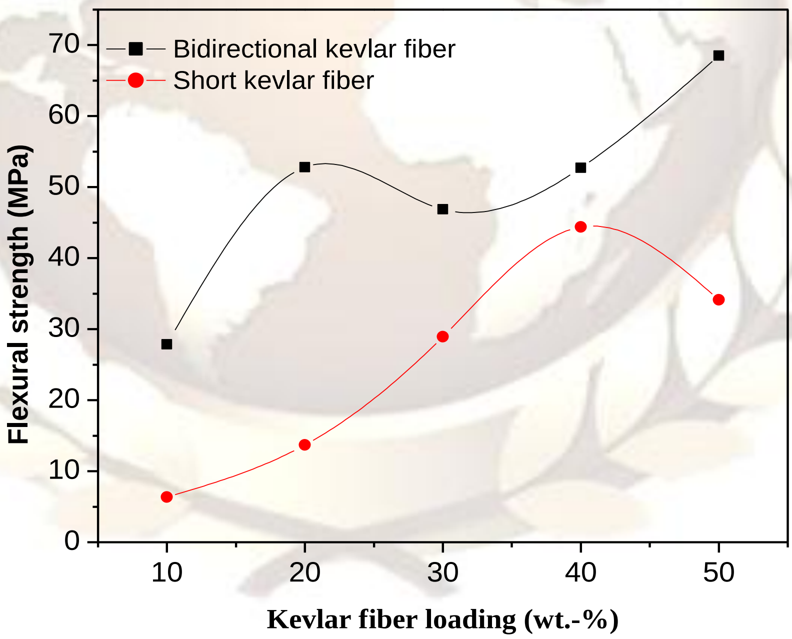


Fig. 3 Effect of fiber loading on flexural strength of Kevlar fiber reinforced epoxy composites

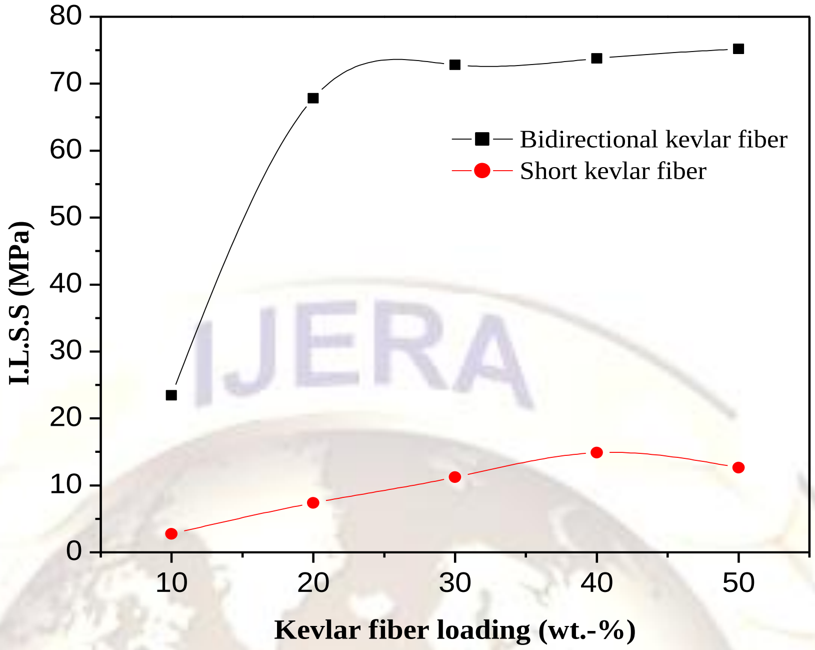


Fig. 4 Effect of fiber loading on inter-laminar shear strength of Kevlar fiber reinforced epoxy composites

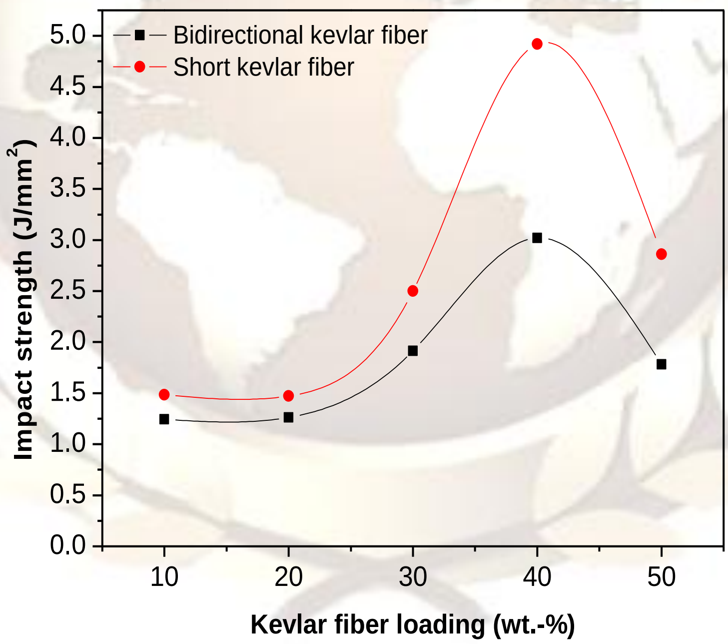


Fig. 5 Effect of fiber loading on impact strength of Kevlar fiber reinforced epoxy composites

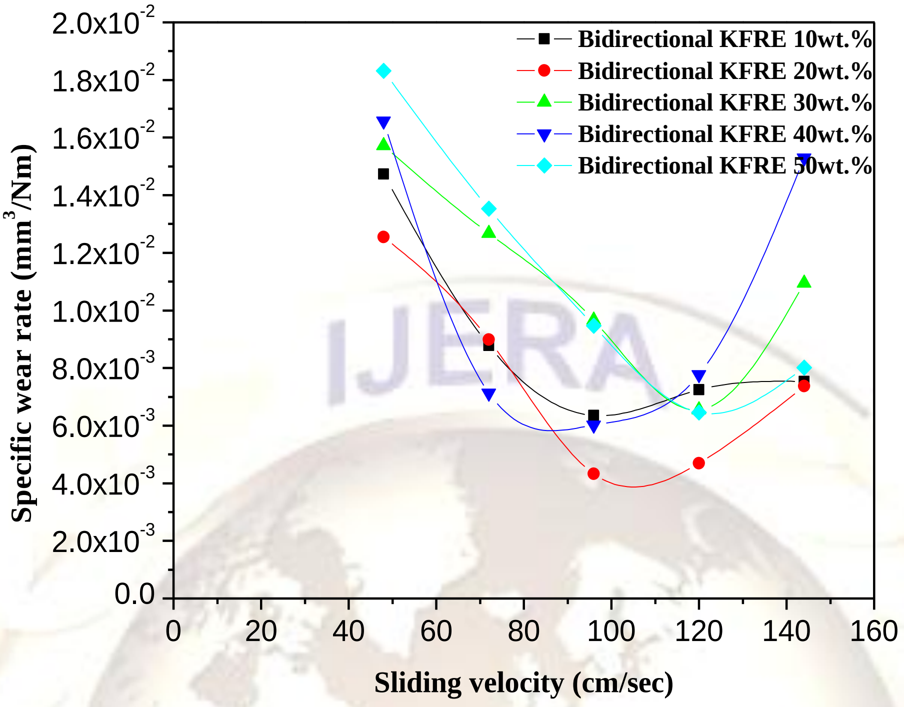


Fig. 6a Effect of sliding velocity on specific wear rate of the bi-directional Kevlar fiber reinforced epoxy (KFRE) composites (At constant normal load: 40N, sliding distance: 60m and abrasive size: 375μm)

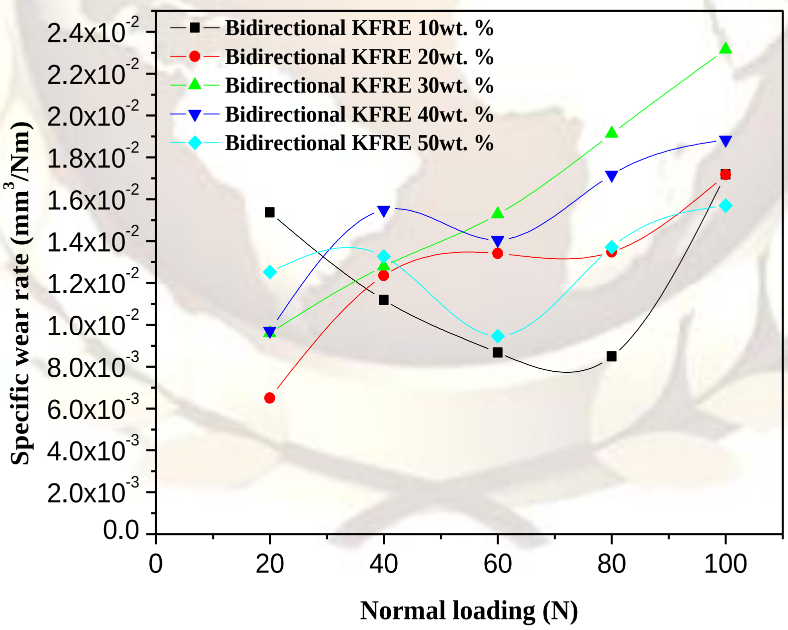


Fig. 6b Effect of normal load on specific wear rate of the bi-directional Kevlar fiber reinforced epoxy (KFRE) composites (At constant sliding velocity: 72cm/sec, sliding distance: 60m and abrasive size: 375 μm)

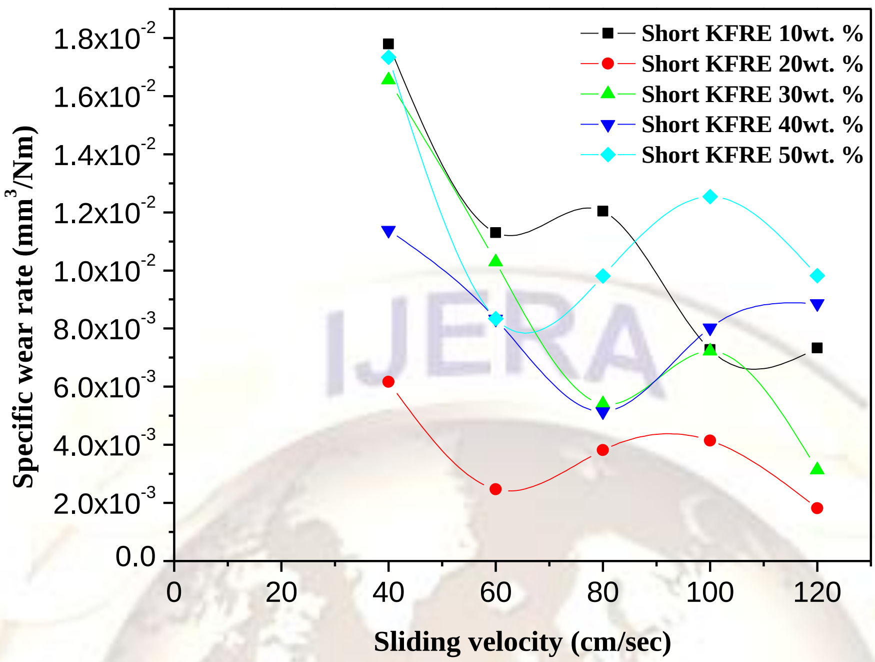


Fig. 7a Effect of sliding velocity on specific wear rate of the short Kevlar fiber reinforced epoxy (KFRE) composites (At constant normal load: 40N, sliding distance: 60m and abrasive size: 375 µm)

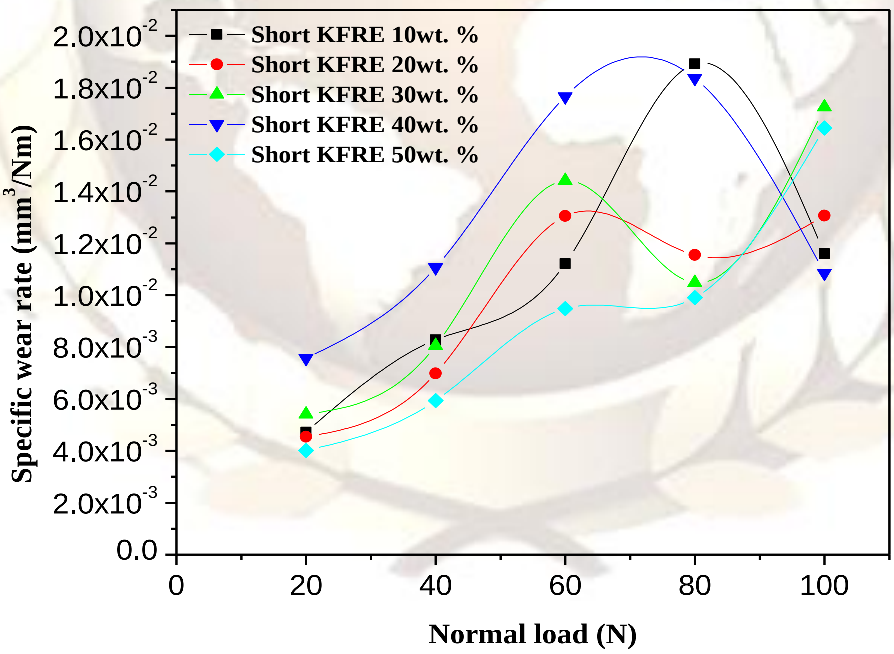


Fig. 7b Effect of normal load on specific wear rate of the short Kevlar fiber reinforced epoxy (KFRE) composites (At constant sliding velocity: 72cm/sec, sliding distance: 60m and abrasive size: 375 µm)

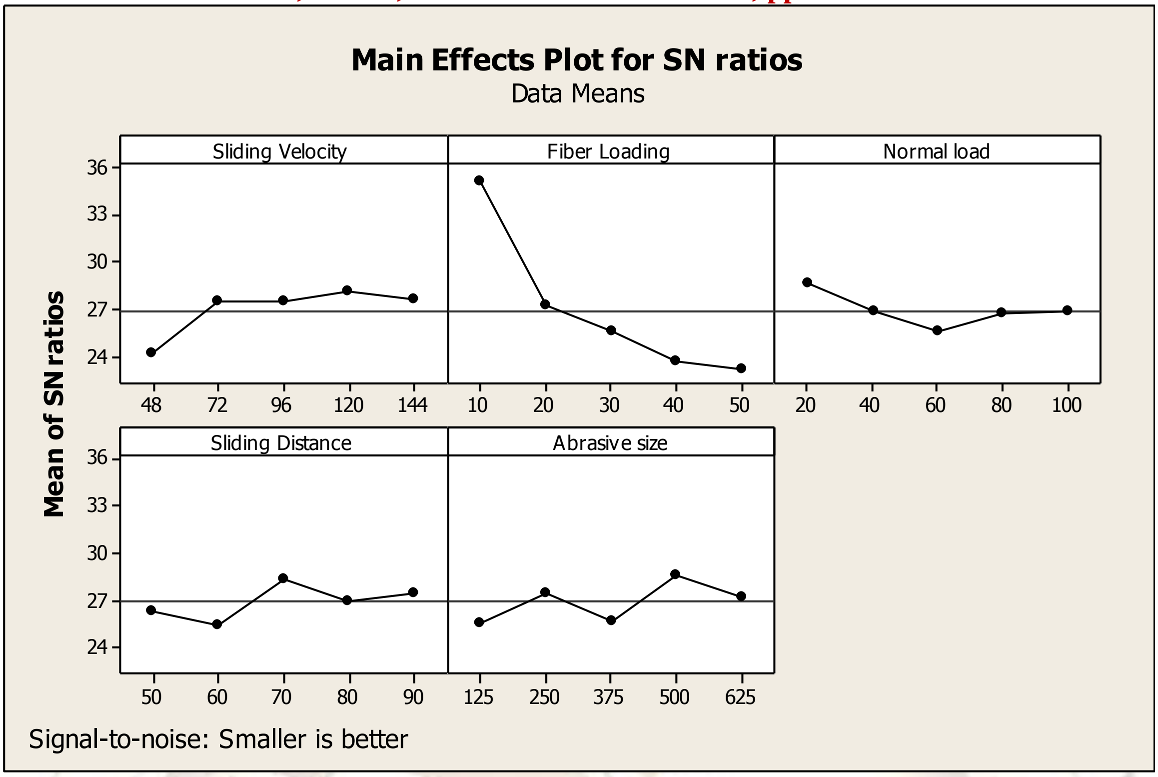


Fig. 8a Effect of control factors on signal-to-noise ratio of bi-directional Kevlar fiber reinforced epoxy composite

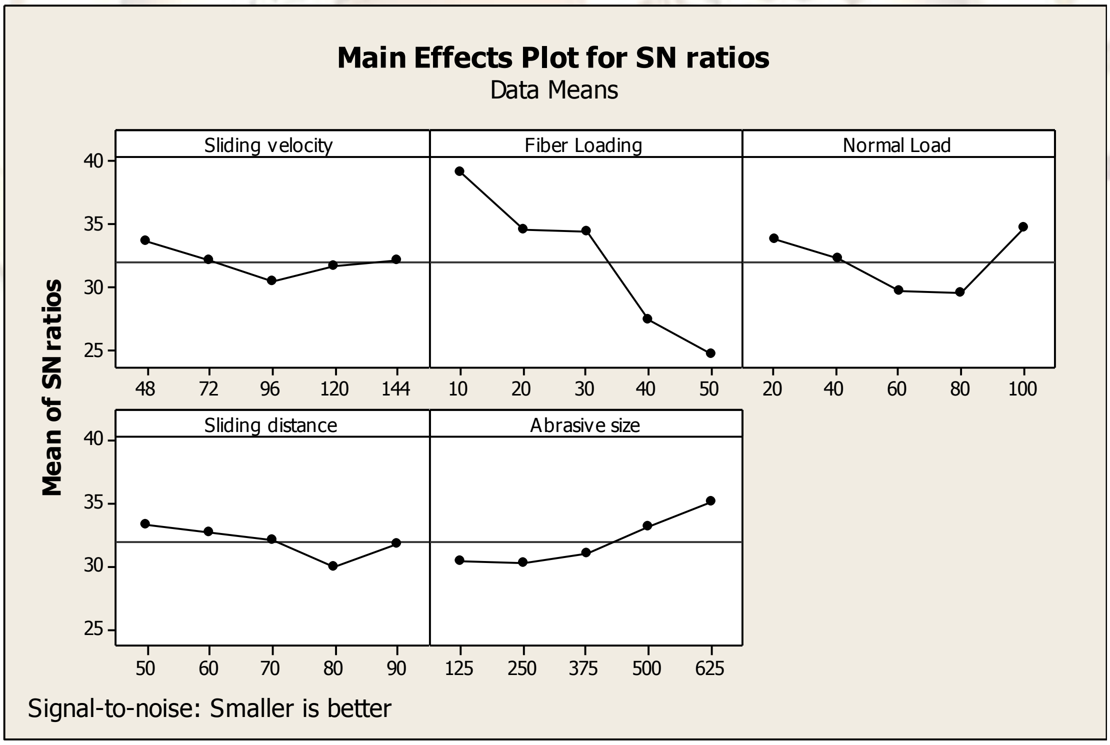
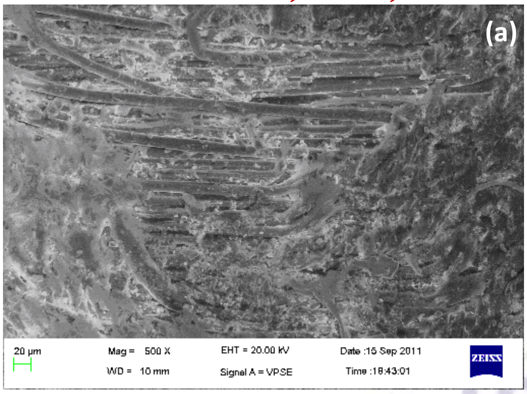
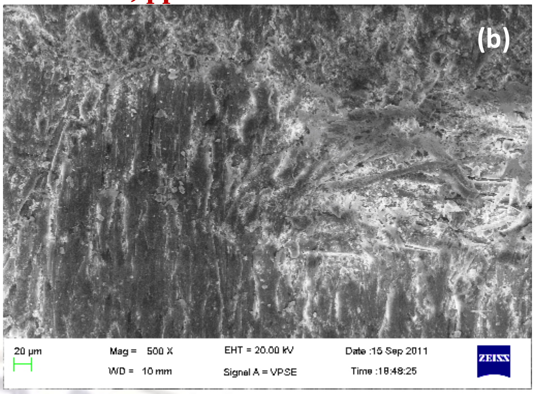


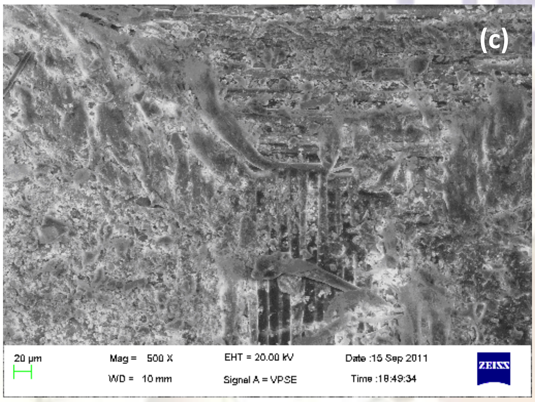
Fig. 8b Effect of control factors on signal-to-noise ratio of short Kevlar fiber reinforced epoxy composite



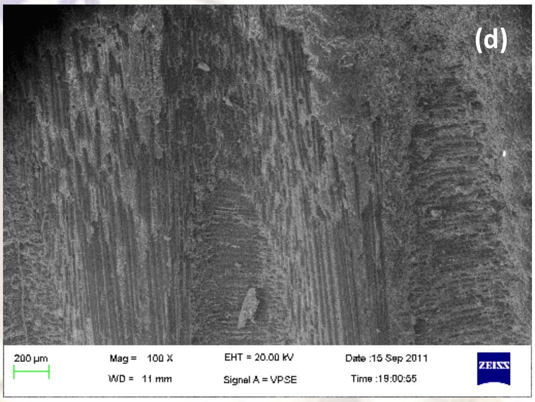
10wt.-% Bi-directional Kevlar fiber



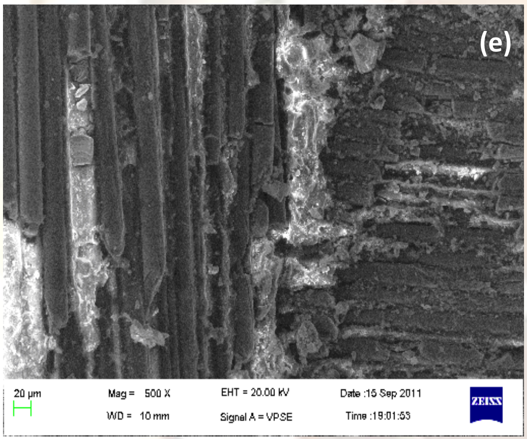
10wt.-% Bi-directional Kevlar fiber



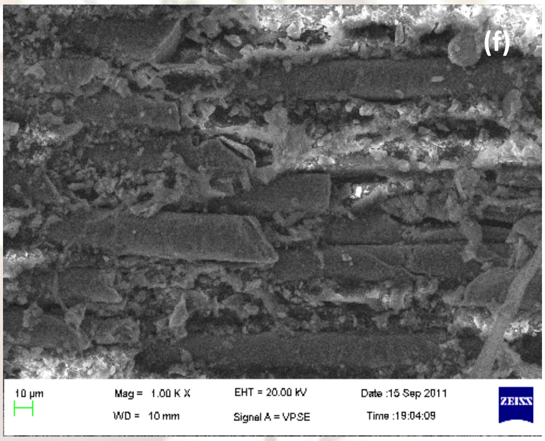
20wt.-% Bi-directional Kevlar fiber



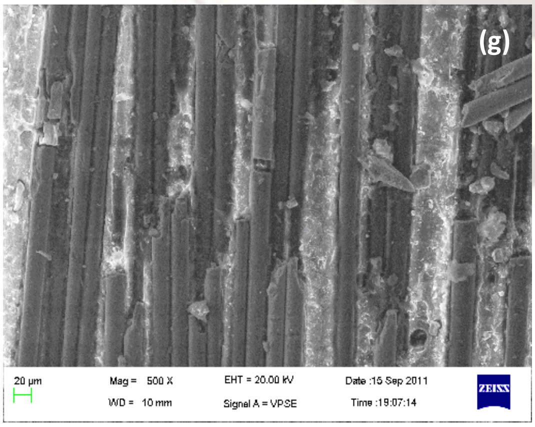
20wt.-% Bi-directional Kevlar fiber



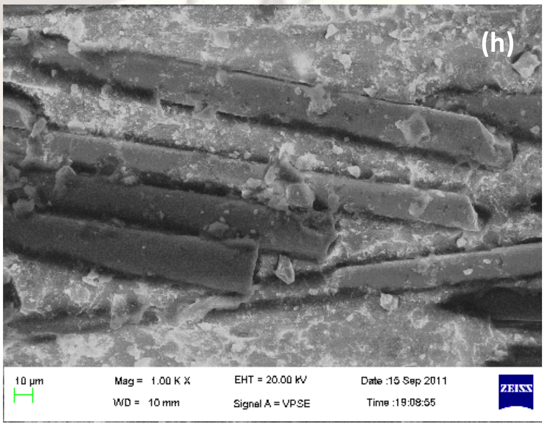
30wt.-% Bi-directional Kevlar fiber



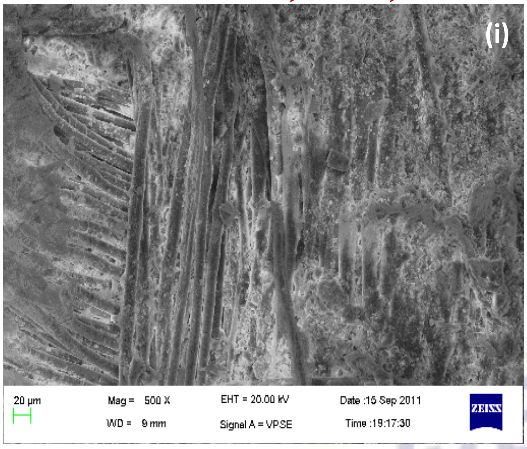
30wt.-% Bi-directional Kevlar fiber



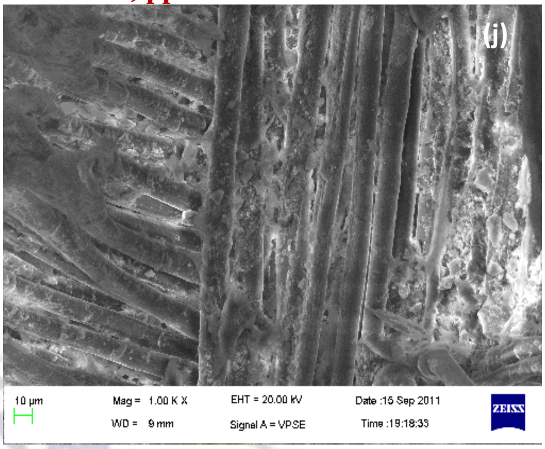
40wt.-% Bi-directional Kevlar fiber



40wt.-% Bi-directional Kevlar fiber

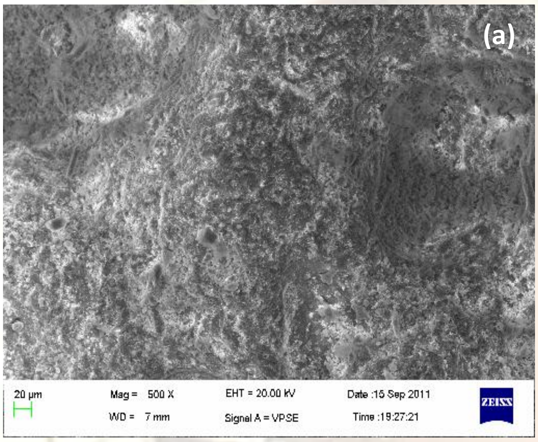


50wt.-% Bi-directional Kevlar fiber

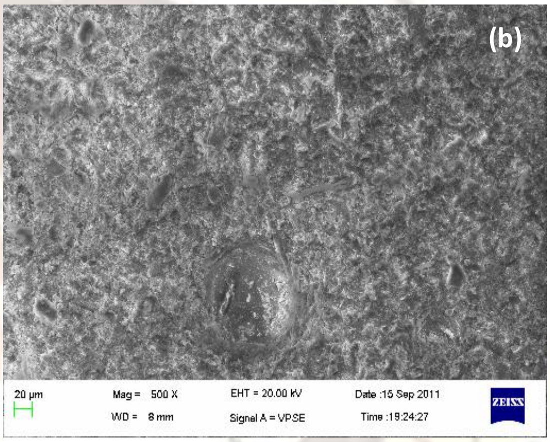


50wt.-% Bi-directional Kevlar fiber

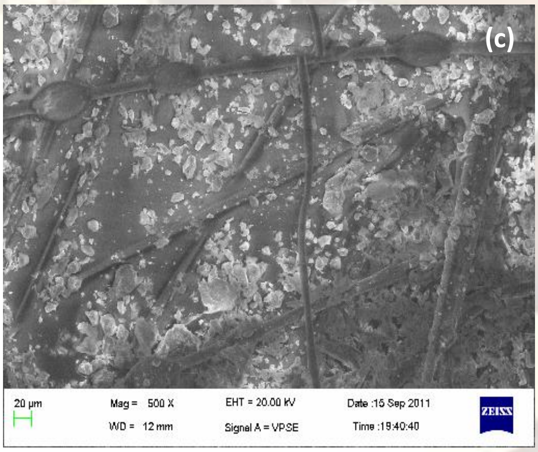
Fig. 9 SEM micrographs of bidirectional Kevlar fiber reinforced epoxy composites



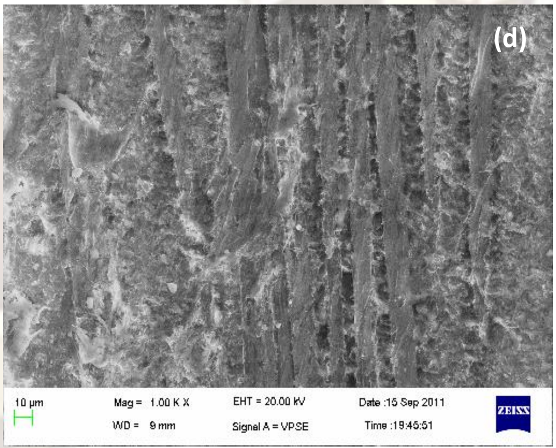
10wt.-% short Kevlar fiber



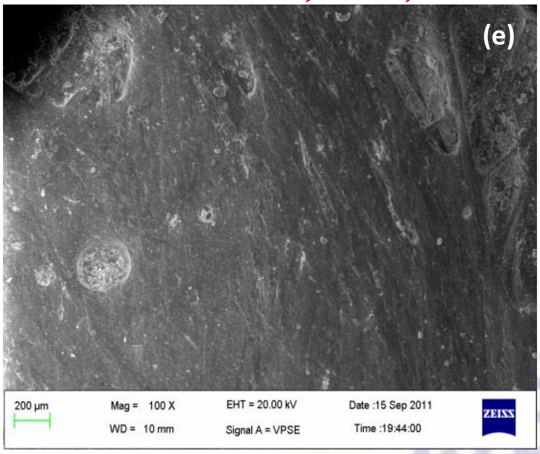
10wt.-% short Kevlar fiber



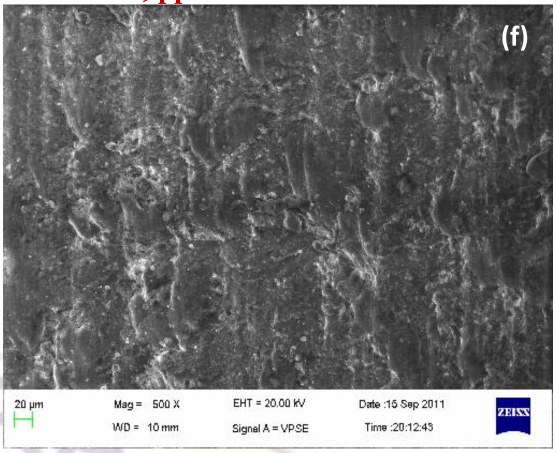
20wt.-% short Kevlar fiber



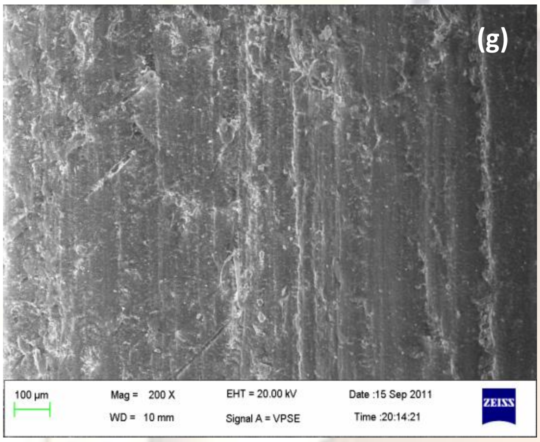
20wt.-% short Kevlar fiber



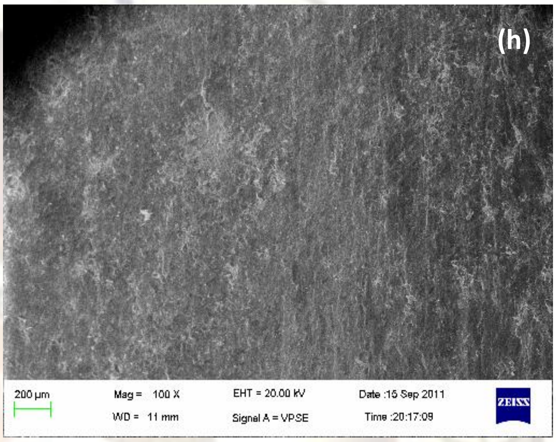
30wt.-% short Kevlar fiber



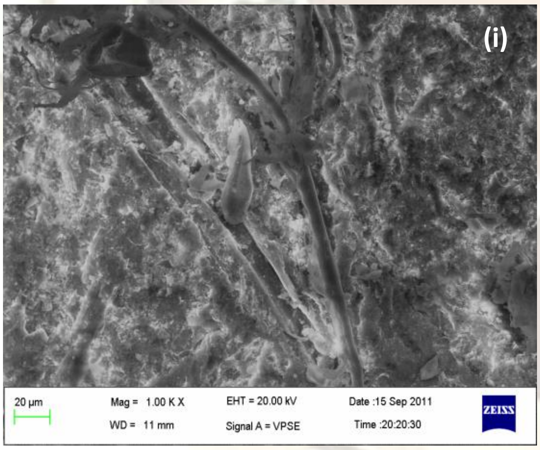
30wt.-% short Kevlar fiber



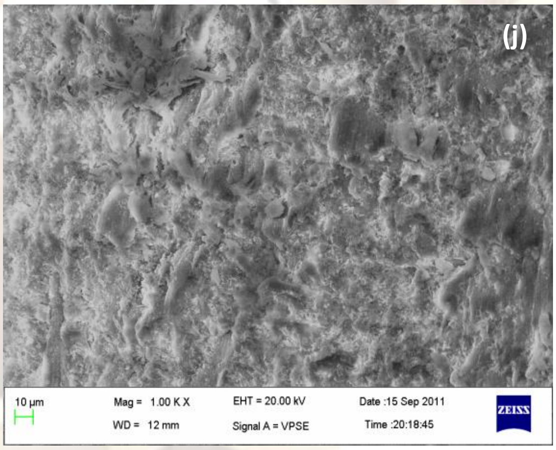
40wt.-% short Kevlar fiber



40wt.-% short Kevlar fiber



50wt.-% short Kevlar fiber



50wt.-% short Kevlar fiber

Fig.10 SEM micrographs showing surface details of short Kevlar fiber reinforced epoxy composites

Table 1 Comparison between Experimental density and Theoretical density

S.No	Composite composition	Theoretical Density (ρct) g/cm3	Expt. Density (ρex) g/cm3	Void Fraction (Δv)= $[\frac{\rho ct - \rho ex}{\rho ct}]$x100
BKFE-1	Epoxy + 10% Kevlar Fiber (B)	1.222	1.2123	0.7937
BKFE -2	Epoxy + 20% Kevlar Fiber (B)	1.258	1.224	2.702
BKFE -3	Epoxy + 30% Kevlar Fiber (B)	1.289	1.2743	1.14
BKFE -4	Epoxy + 40% Kevlar Fiber (B)	1.322	1.289	2.49
BKFE -5	Epoxy + 50% Kevlar Fiber (B)	1.357	1.3357	1.569
SKFE -1	Epoxy + 10% Kevlar Fiber (C)	1.221	1.2067	1.17
SKFE -2	Epoxy + 20% Kevlar Fiber (C)	1.243	1.237	0.483
SKFE -3	Epoxy + 30% Kevlar Fiber (C)	1.265	1.249	1.25
SKFE -4	Epoxy + 40% Kevlar Fiber (C)	1.288	1.246	3.26
SKFE -5	Epoxy + 50% Kevlar Fiber (C)	1.313	1.2823	2.338

Note: BKFE: Bidirectional Kevlar Fiber Epoxy Composite, SKFE: Short Kevlar Fiber Epoxy Composite

Table 2 Levels of the variables used in the experiment

Control factors	Levels					
	I	II	III	IV	V	Units
Sliding velocity (A)	48	72	96	120	144	cm/sec
Fiber loading (B)	10	20	30	40	50	wt.%
Normal load (C)	20	40	60	80	100	N
Sliding distance (D)	50	60	70	80	90	M
Abrasive size (E)	125	250	375	500	625	µm

Table 3 Experimental design using L_{25} orthogonal array

Expt. No.	Sliding velocity (A) (cm/sec)	Fiber loading (B) (wt.%)	Normal load (C) (N)	Sliding distance (D) (m)	Abrasive Size (E) (µm)	Ws (L) $\frac{mm^3}{Nm}$	S/N Ratio (db)	Ws (S) $\frac{mm^3}{Nm}$	S/N Ratio (db)
1	48	10	20	50	125	0.030972	31.7099	0.009299	40.6313
2	48	20	40	60	250	0.007712	23.3867	0.019745	36.0571
3	48	30	60	70	375	0.006518	22.3247	0.018955	31.0089
4	48	40	80	80	500	0.038124	21.0981	0.026290	24.9914
5	48	50	100	90	625	0.034169	22.0289	0.035191	35.4469
6	72	10	40	70	500	0.025287	39.7542	0.007252	44.0796
7	72	20	60	80	625	0.028126	26.3524	0.022109	31.7310
8	72	30	80	90	125	0.016925	24.8939	0.018851	30.7968
9	72	40	100	50	250	0.017227	24.8480	0.014790	27.7889
10	72	50	20	60	375	0.025741	21.3362	0.001448	25.7726
11	96	10	60	90	250	0.016738	34.0939	0.003079	32.7357
12	96	20	80	50	375	0.016657	26.6217	0.019223	34.3236
13	96	30	100	60	500	0.029185	25.9885	0.013496	35.6524
14	96	40	20	70	625	0.011738	27.5894	0.007335	31.2656
15	96	50	40	80	125	0.019289	22.9640	0.009239	17.7721
16	120	10	80	60	625	0.032708	35.5415	0.019205	38.3803
17	120	20	100	70	125	0.014745	26.9851	0.013486	35.1462
18	120	30	20	80	250	0.008462	30.1554	0.002654	35.5696
19	120	40	40	90	375	0.014868	23.7594	0.003368	24.3839
20	120	50	60	50	500	0.033802	23.9033	0.016211	25.0036
21	144	10	100	80	375	0.023717	34.5553	0.010591	39.5013
22	144	20	20	90	500	0.021366	32.6283	0.007361	35.7238
23	144	30	40	50	625	0.018772	24.6166	0.013539	38.7566
24	144	40	60	60	125	0.019241	20.9887	0.006875	27.9860
25	144	50	80	70	250	0.014995	25.1935	0.005372	18.7580

Table 4 ANOVA table for specific wear rate (Bi-directional Kevlar Fiber)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	4	51.123	51.123	12.781	3.09	0.150
B	4	473.015	473.015	118.254	28.60	0.003
C	4	25.499	25.499	6.375	1.54	0.343
D	4	24.640	24.640	6.160	1.49	0.354
E	4	34.920	34.920	8.730	2.11	0.243
Error	4	16.538	16.538	4.135		
Total	24	625.735				

DF: Degree of freedom, Seq SS: Sequential sum of square, Adj SS: Adjacent sum of square
Adj MS: Adjacent sum of mean square, F: Variance, P:Test statistics

Table 5 ANOVA table for specific wear rate (Short Kevlar Fiber)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	4	27.40	27.40	6.85	0.28	0.875
B	4	699.78	699.78	174.94	7.26	0.040
C	4	112.03	112.03	28.01	1.16	0.444
D	4	33.36	33.36	8.34	0.35	0.836
E	4	87.78	87.78	21.94	0.91	0.535
Error	4	96.33	96.33	24.08		
Total	24	1056.68				

DF: Degree of freedom, Seq SS: Sequential sum of square, Adj SS: Adjacent sum of square
Adj MS: Adjacent sum of mean square, F: Variance, P:Test statistics

Table 6 Calculation of theoretical specific wear rate (Ws_{th}) of Kevlar fiber reinforced epoxy composites

Expt. No.	Fiber loading (wt.%)	Friction Force(F) (Long fiber)	Friction Force(F) (Short fiber)	Hardness (Long fiber)	Hardness (Short fiber)	Normal load (N)	Ws_{th} (Long fiber)	Ws_{th} (Short fiber)
1	10	9	3	45.00	44.00	20	0.02777	0.00946
2	20	15	6	31.67	52.00	40	0.06578	0.01615
3	30	32	14	62.00	72.00	60	0.07168	0.02699
4	40	35	25	54.00	58.67	80	0.09002	0.05918
5	50	39	5	67.67	39.33	100	0.08004	0.01766
6	10	7	4	45.00	44.00	40	0.01080	0.00631
7	20	16	15	31.67	52.00	60	0.04677	0.02672
8	30	34	19	62.00	72.00	80	0.05713	0.02749
9	40	30	22	54.00	58.67	100	0.06172	0.04165
10	50	9	3	67.67	39.33	20	0.09277	0.05297
11	10	19	21	45.00	44.00	60	0.01955	0.02229
12	20	20	15	31.67	52.00	80	0.04385	0.02009
13	30	38	15	62.00	72.00	100	0.05108	0.01735
14	40	4	3	54.00	58.67	20	0.04115	0.02839
15	50	15	15	67.67	39.33	40	0.07697	0.13243
16	10	22	16	45.00	44.00	80	0.01697	0.01262
17	20	24	16	31.67	52.00	100	0.04210	0.01708
18	30	5	3	62.00	72.00	20	0.03360	0.01735
19	40	13	13	54.00	58.67	40	0.06686	0.06154
20	50	20	13	67.67	39.33	60	0.06841	0.0586
21	10	39	16	45.00	44.00	100	0.01805	0.0101
22	20	3	3	31.67	52.00	20	0.02406	0.0160
23	30	18	4	62.00	72.00	40	0.06048	0.0115
24	40	26	13	54.00	58.67	60	0.08916	0.0410
25	50	23	25	67.67	39.33	80	0.05901	0.1127

Note: Ws_{th} : theoretical specific wear rate

Table 7 Comparison of theoretical (Ws_{th}) and experimental specific wear rate (Ws_{exp}) of Kevlar fiber reinforced epoxy composites

Expt. No.	Fiber loading (wt.%)	Ws_{th} (Long fiber)	Ws_{exp} (Long fiber)	Error (Long fiber)	Ws_{th} (short fiber)	Ws_{exp} (short fiber)	Error (short fiber)
1	10	0.02777	0.025972	6.47	0.00946	0.009299	1.80
2	20	0.06578	0.067712	2.93	0.01615	0.019745	2.51
3	30	0.07168	0.076518	6.74	0.02699	0.018955	4.31
4	40	0.09002	0.088124	2.11	0.05918	0.026290	4.88
5	50	0.08004	0.079169	1.09	0.01766	0.035191	4.35
6	10	0.01080	0.010287	4.77	0.00631	0.007252	0.98
7	20	0.04677	0.048126	2.89	0.02672	0.022109	3.03
8	30	0.05713	0.056925	0.36	0.02749	0.018851	4.95
9	40	0.06172	0.057227	7.27	0.04165	0.014790	2.06
10	50	0.09277	0.085741	7.57	0.05297	0.001448	2.87
11	10	0.01955	0.019738	0.96	0.02229	0.003079	3.54
12	20	0.04385	0.046657	6.40	0.02009	0.019223	4.32
13	30	0.05108	0.050185	1.75	0.01735	0.013496	4.92
14	40	0.04115	0.041738	1.42	0.02839	0.007335	3.72
15	50	0.07697	0.071089	7.64	0.13243	0.009239	2.41
16	10	0.01697	0.016708	1.54	0.01262	0.019205	4.52
17	20	0.04210	0.044745	6.28	0.01708	0.013486	2.37
18	30	0.03360	0.031062	7.55	0.01735	0.002654	4.02
19	40	0.06686	0.064868	2.97	0.06154	0.003368	1.90
20	50	0.06841	0.063802	6.73	0.0586	0.016211	4.07
21	10	0.01805	0.018717	3.69	0.0101	0.010591	4.75
22	20	0.02406	0.023366	2.88	0.0160	0.007361	2.13
23	30	0.06048	0.058772	2.82	0.0115	0.013539	0.28
24	40	0.08916	0.089241	0.09	0.0410	0.006875	2.81
25	50	0.05901	0.054995	6.81	0.1127	0.005372	2.37

Note: Ws_{exp} : experimental specific wear rate