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Sliding Wear Characteristics of Bone Powder Filled Hybrid Fiber Reinforced Epoxy Composites

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Abstract: *The aim of the research article is to study the dry sliding wear behaviour of epoxy with different wt.% of bone powder filled E-glass/jute fiber reinforced composites. Taguchi's orthogonal array (L_{27}) was used to investigate the influence of tribological parameters. The results indicated that when the filler content was increased up to 10 wt.% the specific wear rate was decreased but coefficient of friction increases. Form 10 wt.% to 15 wt.% of filler content specific wear rate was increased but coefficient of friction decreases. After the thorough analysis of control factors, optimal factor setting has been suggested for specific wear rate and coefficient of friction. Furthermore, the worn surfaces of the samples were analyzed by scanning electron microscopy (SEM) to study the wear mechanisms and to correlate them with the wear test results.*
Keywords: *hybrid composites, wear test, Taguchi's analysis, scanning electron microscopy.*

I. Introduction

Natural fibers are a renewable resource and have several advantages associated with them, such as, they impart the composite high specific stiffness and strength, a desirable fiber aspect ratio, biodegradability, they are readily available from natural sources and more importantly they have a low cost per unit volume basis [1]. These natural fibers can be used in the manufacture of fiber based polymer composites because they posses attractive physical and mechanical properties. Polymer composites have a special property of self lubrication and this made the composites suitable in tribological applications such as cams, seals, brakes, bearings etc. F. Asuke et al., [2] have studied the effect of applied load on the wear behavior of polymer matrix composites produced by using carbonized bone particles (CBp) as reinforcement. The result shows that the wear rate increased with increases in applied load and decreased with increasing in carbonized bone particles. B. Suresha et al., [3] have done experiment on dry sliding wear and two-body abrasive wear behaviour of graphite filled carbon fabric reinforced epoxy composites. The results show that for increased load and sliding velocity, higher wear loss was recorded and wear is reduced to a greater extent by addition of the graphite filler in carbon-epoxy composite which was dominated by microplowing/microcutting mechanisms instead of microcracking. B. N. Ramesh and B. Suresha [4] have studied the abrasive wear behavior of carbon fabric reinforced epoxy composites filled with functional fillers like alumina (Al_2O_3) and molybdenum disulphide (MoS_2) separately in different proportions. The experiments were planned according to Taguchi L_{18} orthogonal array. The result showed that the grit size, type of filler and filler loading were the most significant factors in controlling the specific wear rate of the C-E composite. S. Basavarajappa et al., [5] have experimentally investigated glass–epoxy composite with influence of graphite filler under varying applied load, sliding distance and sliding velocity by using a pin-on-disc apparatus. For increased applied load situation for pure glass–epoxy composite higher weight loss was recorded. As the percentage of graphite increases lower weight loss was observed in the glass–epoxy composite. Rashmi et al., [6] studied the dry sliding wear behaviour of epoxy with different wt.% of organo-modified montmorillonite (OMMT) filled nanocomposites and concluded that sliding distance was the most significant factor affecting wear rate of epoxy nanocomposites. Experimental results showed that the inclusion of 5 wt.% OMMT nanofiller increased the wear resistance of the epoxy nanocomposite. A. Rout and A. Satapathy [7] have done experiment on rice husk filled epoxy composites. Taguchi orthogonal array design and artificial neural network analysis was also carried out. The result showed that sliding velocity was the most infusing factor followed by filler content and normal load. They have concluded that rice husk filled composites improves the wear resistance. T. B. Yallew et al., [8] have fabricated woven jute fiber reinforced PP composites. The tribological behavior was analyzed by a computerized pin-on-disc wear testing machine at an dry operating condition with different working parameters of sliding speed (1–3 m/s), applied load (10–30 N) and sliding distance (1000–3000 m). The incorporation of woven jute fiber as reinforcement into PP matrix shows more than 65% reduction in specific wear rate and 45% reduction in the coefficient of friction. N. Mohan et al., [9] have fabricated with and without Tantalum Niobium Carbide (Ta/NbC) filled glass epoxy composites. These composites wear tested for dry sliding wear behavior at elevated temperatures. The result showed that as the temperature increases specific wear loss increases. Ta/NbC filled glass epoxy composites exhibited lower wear rate and higher coefficient of friction as compared with pure composite and worn surface was analyzed by scanning electron microscopy. F. Asuke et al., [10] have been studied the effects of uncarbonized (fresh) and carbonized bone particles on the microstructure and mechanical properties of polypropylene composites. The results showed that the addition of carbonized bone particles reinforcement composite has superior mechanical properties than uncarbonized bone particles composite. They have concluded that for optimum service condition and to have better mechanical properties bone particle addition should not exceed 15 wt.%. In view of the above, an attempt was made to study the effect of bone powder as a filler material in E-glass/jute fiber reinforced epoxy composites. The wear characteristics of these hybrid composites were investigated.

II. Experimental Details

2.1. Materials

In this work, 7-mil E-glass fiber as a reinforcement material was used which was supplied by Suntech Fibers Private Ltd. Woven jute fiber as a reinforcement material was used which was supplied by Jute Cottage, Bangalore. Unsaturated polyester epoxy L-12 (3202) manufactured by Atul LTD, Gujarat, India and supplied by Yuge marketing, Bangalore was used as matrix material and K-6 hardener was added to epoxy while fabricating the composite materials. Goat bones were washed and cleaned. Thin top surface layer of the bone was removed by using grinding machine and powder was prepared. An approximate density value of bone powder was 1.95 g/cc.

2.2. Fabrication of Composites

The hybrid fiber reinforced epoxy composites were prepared by keeping constant 50 wt.% of epoxy and 50 wt.% of fiber (40 wt.% of E-glass fiber and 10 wt.% of jute fiber) as shown in "Table 1". The composites filled with varying concentrations (0 wt.%, 10 wt.% and 15 wt.%) of bone powder were fabricated by using hand layup technique. Jute plies were placed in between E-glass plies and also E-glass plies were placed at extreme ends of the composites. The epoxy, hardener and fillers were mixed thoroughly in a basin and the mixture was subsequently stirred constantly. The woven E-glass and woven jute fiber was positioned manually. Mixture so made was brushed uniformly over the E-glass and jute plies. Entrapped air was removed manually with squeezes or rollers to complete the composite structure. The composites were put under load for about 24 hours for proper curing at room temperature.

Table 1: Fabricated composites with constant 40 wt. % of E-glass fiber and 10 wt. % of jute fiber

Hybrid composites	Epoxy (wt.%)	Filler material (wt.%)
GJE	50	0%
GJEB1	40	10%
GJEB2	35	15%

2.3. Specimen Preparation

The fabricated hybrid composites were taken out from the mould and then specimens of suitable dimensions were prepared from the composites for wear tests according to ASTM G99 standards. The composites were cut by using Zigzag board cutter machine. Three identical test specimens were prepared for each test.

2.4. Test of Density

The theoretical density (ρ_t) of hybrid composite material in terms of weight fractions of different constituents can be obtained from the following "equation 1" [15].

$$\rho_t = \frac{1}{\left(\frac{W_g}{\rho_g}\right)+\left(\frac{W_j}{\rho_j}\right)+\left(\frac{W_m}{\rho_m}\right)+\left(\frac{W_f}{\rho_f}\right)} \qquad (1)$$

where, W and ρ represent the weight fraction and density respectively. The suffixes g, j, m and f stands for the E- glass fiber, jute fiber, matrix (epoxy) and filler respectively.

The actual density (ρ_e) of the composite can be determined experimentally by simple water immersion technique. The volume fraction of voids (V_v) in the composites was calculated using the following "equation 2" [15].

$$V_v = \frac{(\rho_t - \rho_e)}{\rho_t} \qquad (2)$$

2.5. Dry Sliding Wear Test Apparatus

DUCOM pin on disc test apparatus was used to investigate the dry sliding wear characteristics of hybrid composite specimens as per ASTM G99 standards. The disc made of hardened EN-31 hardened ground steel to 62 HRC, surface roughness 1.6 µm Ra, 120 mm track diameter and 8 mm thick. Specimen with size of 10 mm x 10 mm x 30 mm was subjected vertically to the counter face where the contact area was constant. Wear test was carried out for the constant sliding distance of 2000 m, sliding velocities of 1.4 m/sec, 2 m/sec and 2.6 m/sec against normal loads of 20 N, 40 N, and 60 N and wear rate data reported was the average of two runs. Care was to see that the specimen was continuously cleaned with woolen cloth to avoid the entrapment of wear debris and to achieve uniform experimental procedure. After each test the disc was cleaned using acetone solution. The initial weight before run and final weight after run was measured using a precision electronic balance with an accuracy of ± 0.01 mg.

The specific wear rate (mm^3/Nm) was then expressed on 'volume loss basis as shown below "equation 3" [4].

$$K_s = \frac{\Delta m}{\rho t v F}$$
(3)

where, K_s = Specific wear rate (mm^3/Nm), Δm = Mass loss (gms), ρ = Density of specimen (g/cc), t = Test duration (sec), v = sliding velocity (m/s), F = Applied load (N).

2.6. Taguchi Experimental Design

Taguchi technique was used for analyzing the influence of control factors on performance output. The most important stage in the design of experiment lies in the selection of the control factors. In the present work, the impact of three parameters such as sliding velocity, normal load and filler content were studied using L_{27} (3^{13}) Taguchi orthogonal design. The experimental results were transformed into a signal-to-noise (S/N) ratio. The S/N ratio for minimum wear rate coming under "smaller is better" characteristic, and it was calculated as logarithmic transformation of the loss function as shown below "equation 4" [8].

$$\frac{S}{N} = -10\, log\left[\frac{1}{n}(y_1^2 + y_2^2 + \cdots y_n^2)\right] \qquad (4)$$

where 'n' indicates the repeated number of trial conditions, y_1, y_2….y_n indicates the response of the dry sliding wear characteristics respectively. For ''Lower is better" (LB) characteristic of the above S/N ratio transformation, it was suitable for minimizations of coefficient of friction and specific wear rate. The standard linear graph was used to assign the factors and interactions to various columns of the orthogonal array.

The plan of the experiments: The experiments were conducted as per the standard orthogonal array L_{27} (3^{13}). The selection of the orthogonal array was based on the condition that the degree of freedom for the orthogonal array should be greater than or equal to sum of those wear parameters.

In the present investigation L_{27} Taguchi orthogonal array was chosen, this has 27 rows and 13 columns. The wear parameters chosen were (1) sliding velocity (2) normal load and (3) filler content and their levels indicated in "Table 2". The experiments consisted of 27 tests (each row in the L_{27} orthogonal array) and were assigned with parameters. The first column in table was assigned to sliding velocity (S), second column was assigned to normal load (L), fifth column was assigned to filler content (FC) and remaining columns were assigned to their interactions. The dry sliding wear tests results were subjected to the analysis of variance.

Table 2: Levels of variables used in the experiments

Control factor	Symbols	Level I	Level II	Level III	Units
Sliding velocity	A	1.4	2	2.6	m/s
Normal load	B	20	40	60	N
Filler content	C	0	10	15	%

III. Results and Discussion

3.1. Density

In the present research work, the theoretical and experimental densities of hybrid composites along with the corresponding volume fraction of voids are presented in "Table 3". It was found that the composite density values calculated theoretically from weight fractions were not equal to the experimentally measured values. It was evident that the density values for hybrid composites increase with the addition of filler content. It was further observed that with the incorporation of fillers, the void fractions in these composites also increase. Similar observation has been reported earlier for hybrid composites filled with different filler content.

Table 3: Theoretical and experimental densities of hybrid composites

Hybrid composites	Theoretical density in gm/cc	Experimental density in gm/cc	Volume fraction of voids in %
GJE	1.6183	1.5621	3.47
GJEB1	1.6919	1.6255	3.92
GJEB2	1.7312	1.6120	6.88

3.2. Wear Properties

The experimental data for specific wear rate and coefficient of friction of bone powder filled hybrid composites reported in the "Table 4". The overall mean for the S/N ratio of the specific wear rate and the coefficient of friction are found to be 91.995 db and 7.105 db respectively.

Table 4: Experimental design using L_{27} array for bone powder filled hybrid composites

S. No	Sliding Velocity (S) in m/s	Normal Load (L) in N	Filler content (FC) in %	Specific Wear Rate (W) in mm^3/Nm	S/N Ratio (db)	Coefficient of Friction (μ)	S/N Ratio (db)
1	1.4	20	GJE	8.01E-05	81.93	0.396	8.046
2	1.4	20	GJEB1	1.58E-05	96.05	0.593	4.539
3	1.4	20	GJEB2	1.58E-05	96.02	0.195	14.199
4	1.4	40	GJE	7.20E-05	82.85	0.427	7.391
5	1.4	40	GJEB1	7.88E-06	102.07	0.528	5.547
6	1.4	40	GJEB2	5.53E-05	85.14	0.37	8.636
7	1.4	60	GJE	4.27E-05	87.39	0.48	6.375
8	1.4	60	GJEB1	1.58E-05	96.05	0.636	3.931
9	1.4	60	GJEB2	2.11E-05	93.52	0.414	7.660
10	2	20	GJE	7.99E-05	81.95	0.369	8.659
11	2	20	GJEB1	1.57E-05	96.07	0.612	4.265
12	2	20	GJEB2	6.31E-05	84.00	0.507	5.900
13	2	40	GJE	3.99E-05	87.97	0.452	6.897
14	2	40	GJEB1	1.57E-05	96.07	0.675	3.414
15	2	40	GJEB2	1.58E-05	96.04	0.398	8.002
16	2	60	GJE	3.73E-05	88.57	0.293	10.663
17	2	60	GJEB1	1.05E-05	99.60	0.467	6.614
18	2	60	GJEB2	1.58E-05	96.04	0.352	9.069
19	2.6	20	GJE	6.41E-05	83.86	0.366	8.730
20	2.6	20	GJEB1	4.73E-05	86.50	0.689	3.236
21	2.6	20	GJEB2	3.17E-05	89.99	0.37	8.636
22	2.6	40	GJE	4.81E-05	86.36	0.437	7.190
23	2.6	40	GJEB1	7.89E-06	102.06	0.617	4.194
24	2.6	40	GJEB2	7.91E-06	102.03	0.339	9.396
25	2.6	60	GJE	2.67E-05	91.46	0.479	6.393
26	2.6	60	GJEB1	3.68E-05	88.68	0.637	3.917
27	2.6	60	GJEB2	5.28E-06	105.55	0.304	10.343

Table 5: Response table for specific wear rate of bone powder filled hybrid composites

Level	A	B	C
1	91.23	88.49	85.82
2	91.81	93.4	95.91
3	92.95	94.1	94.26
Delta	1.72	5.61	10.09
Rank	3	2	1

Table 6: ANOVA table for specific wear rate of bone powder filled hybrid composites

Source	DF	Seq SS	Adj SS	Adj MS	Test F	P (%)
A	2	1.50	1.498	0.75	0.38	1.05
B	2	23.89	23.89	11.95	6.13	16.67
C	2	63.41	63.41	31.71	16.26	44.25
A*B	4	13.02	13.02	3.26	1.67	9.09
A*C	4	15.06	15.06	3.77	1.93	10.51
B*C	4	10.84	10.84	2.71	1.39	7.57
Residual Error	8	15.57	15.57	1.95		10.87
Total	26	143.29				100.00

DF - degree of freedom, Seq SS - sequential sum of squares, Adj. SS - extra sum of squares, Seq MS - sequential mean squares, F - F-test and P - percent contribution

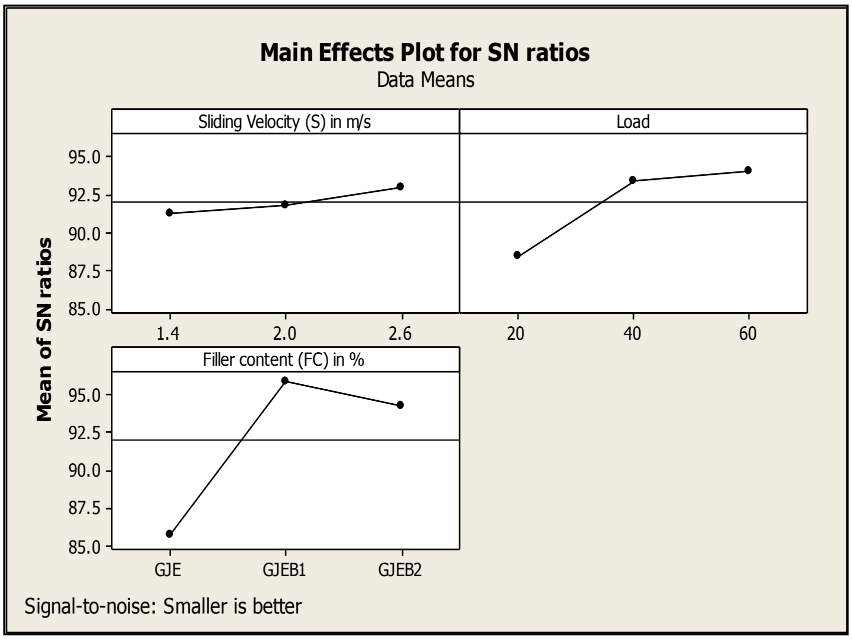


Figure 1: Effect of control factors on specific wear rate of hybrid composites

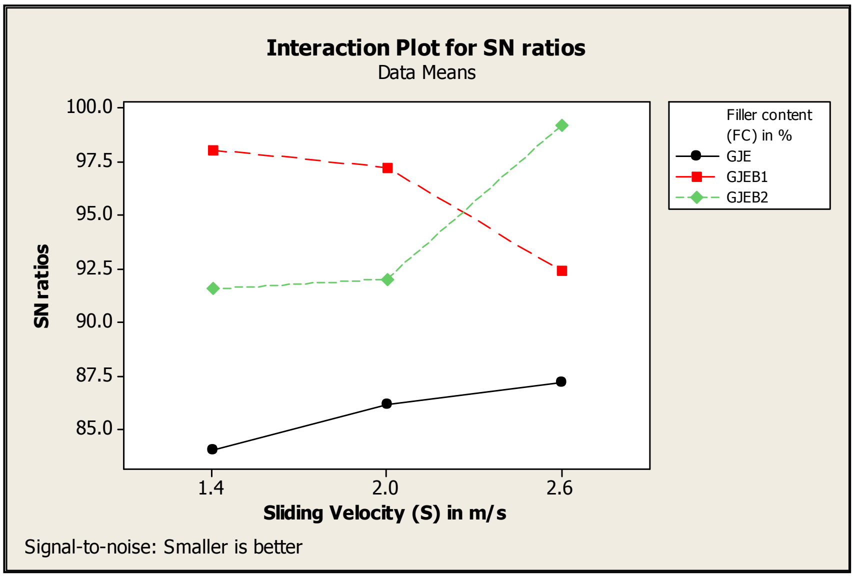


Figure 2: Interaction graph between sliding velocity and filler content for specific wear rate

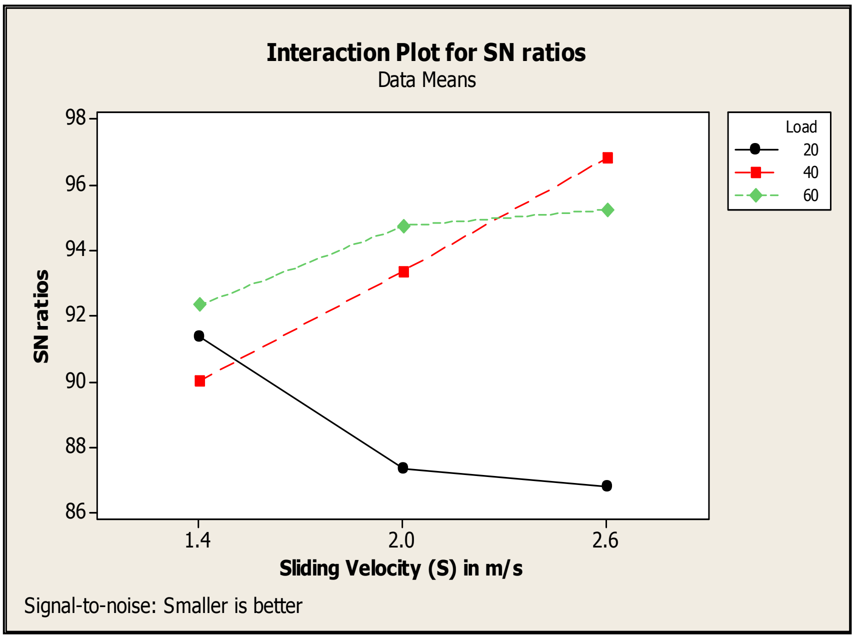


Figure 3: Interaction graph between sliding velocity and normal load for specific wear rate

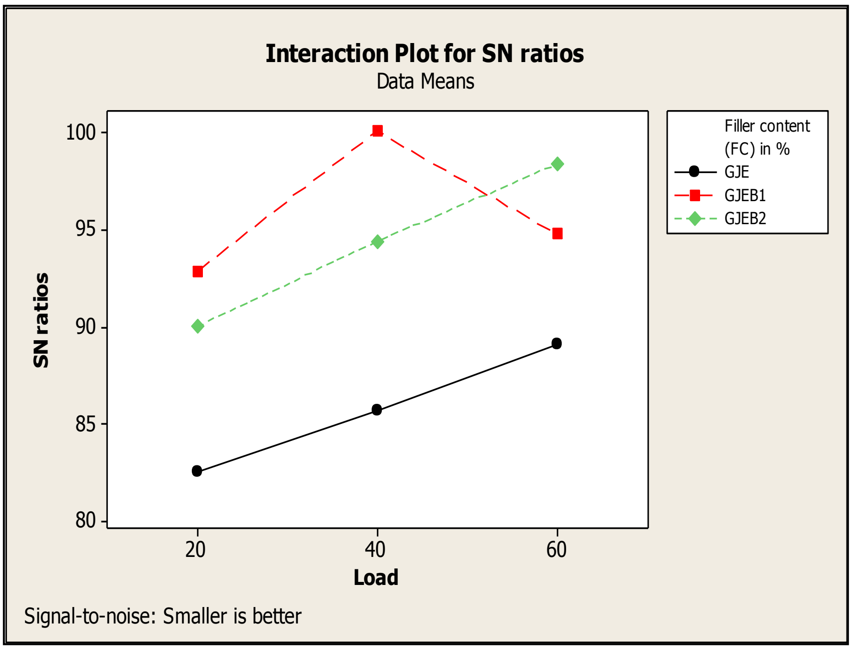


Figure 4: Interaction graph between normal load and filler content for specific wear rate

3.2.1 ANOVA and Effects of Factors on Specific Wear Rate

From the ANOVA "Table 6" it was observed that the filler content (C) factor (P = 44.25%), normal load (B) factor (P = 16.67%) and interaction (AxC) between sliding velocity x filler content (P = 10.51%) have great influence on the specific wear rate and hence theses are physically and statistically highly significant. However interaction (AxB) between sliding velocity x normal load (P = 9.09%), (BxC) interaction between normal load x filler content (P = 7.57%) and sliding velocity (A) factor (P = 1.10%) have lesser effect on specific wear rate as error value (P = 10.87) was higher side hence less significant. From the analysis of ANOVA and response "Table 5" of the S/N ratio for specific wear rate, it was observed that the filler content has major impact on specific wear rate followed by normal load and sliding velocity.

The influence of each control factor (sliding velocity, normal load and filler content) on the specific wear rate was analysed with a main effects plot as shown in "Fig. 1" and an interaction plot as shown in "Figs. 2 to 4". From the analysis of ANOVA and response "Table 5" of the S/N ratio for specific wear rate, it was observed that the filler content (C) has major impact on the specific wear rate followed by the normal load (B) and sliding velocity (A). It means that for bone powder filled hybrid composites with the increases of the filler content, sliding velocity and normal load the specific wear rate decreases i.e., good wear resistance. It was also observed that the filler content plays adverse effect, when the filler content was increased from 0 wt.% to 10 wt.% the specific wear rate was decreased and for 10 wt.% to 15 wt.% it further increases. Analysis of these results leads to the conclusion that optimal values of the parameters for minimizing the wear rate when the sliding velocity and normal load were at level 3 and the filler content was at level 2.

Table 7: Response table for COF of bone powder filled hybrid composites

Level	A	B	C
1	7.369	7.357	7.816
2	7.054	6.741	4.406
3	6.893	7.218	9.093
Delta	0.477	0.616	4.687
Rank	3	2	1

Table 8: ANOVA table for COF of bone powder filled hybrid composites

Source	DF	Seq SS	Adj SS	Adj MS	Test F	P (%)
A	2	0.00900	0.00900	0.00450	1.52718	2.07
B	2	0.00022	0.00022	0.00011	0.03733	0.05
C	2	0.30110	0.30110	0.15055	51.09278	69.33
A*B	4	0.05480	0.05480	0.01370	4.64943	12.62
A*C	4	0.02850	0.02850	0.00713	2.41804	6.56
B*C	4	0.01711	0.01711	0.00428	1.45167	3.94
Residual Error	8	0.02357	0.02357	0.00295		5.43
Total	26	0.43430				100.00

DF - degree of freedom, Seq SS - sequential sum of squares, Adj. SS - extra sum of squares, Seq MS - sequential mean squares, F - F-test and P - percent contribution

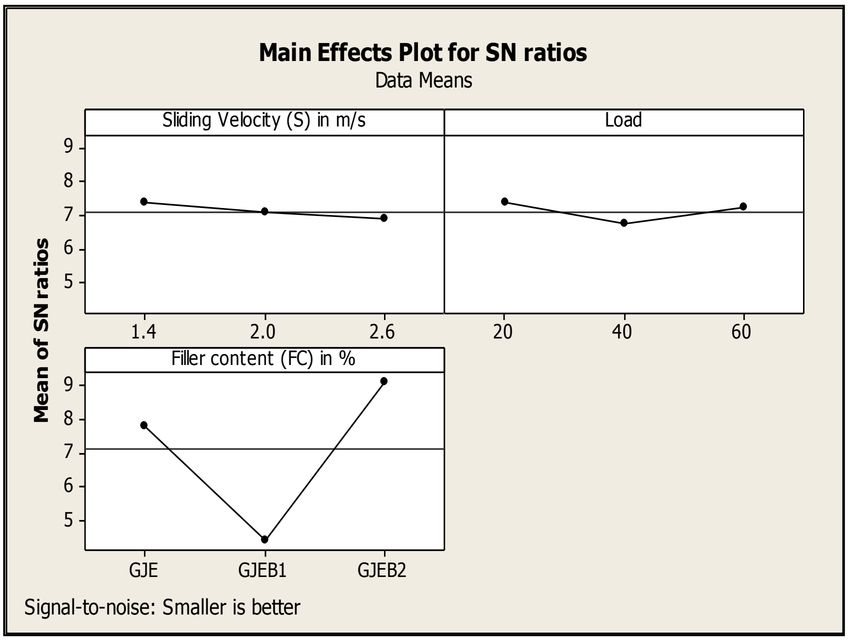


Figure 5: Effect of control factors on COF hybrid composites

3.2.2 ANOVA and Effects of Factors on Coefficient Of Friction

ANOVA "Table 8" for the coefficient of friction that the filler content (C) factor (P = 69.33%), interaction between sliding velocity x normal load (AxB) and the interactions between sliding velocity x filler content (AxC) have significant influence on the coefficient of friction. However interaction of normal load x filler content (P = 3.94%), sliding velocity (P = 2.07%) and normal load (B) factor (P = 0.05%) do not have a significant effect (both physically and statistical) on coefficient of friction as their values are quite smaller than error (P = 5.43%) so they are neglected. From the analysis of ANOVA and response "Table 7" of the S/N ratio of coefficient of friction, it was observed that the control parameter filler content (C) has major impact on coefficient of friction followed by normal load and sliding velocity.

The influence of each control factor on the coefficient of friction was analyzed with a main effects plot as shown in "Fig. 5" and an interaction plot as shown in "Figs. 6 to 8". From the analysis of ANOVA and response "Table 7" of the S/N ratio for coefficient of friction, it was observed that the control factor filler content (C) has major impact on the coefficient of friction. It means that for bone powder filled hybrid composites, with the increases of the filler content from 0 wt.% to 10 wt.% coefficient of friction increases and from 10 wt.% to 15 wt.% coefficient of friction decreases. The same trend was observed for normal load. With the increase of sliding velocity coefficient of friction decreases. Analysis of these results leads to the conclusion that optimal values of the parameters for minimizing the wear rate when the sliding velocity and normal load were at level 1 and the filler content was at level 3.

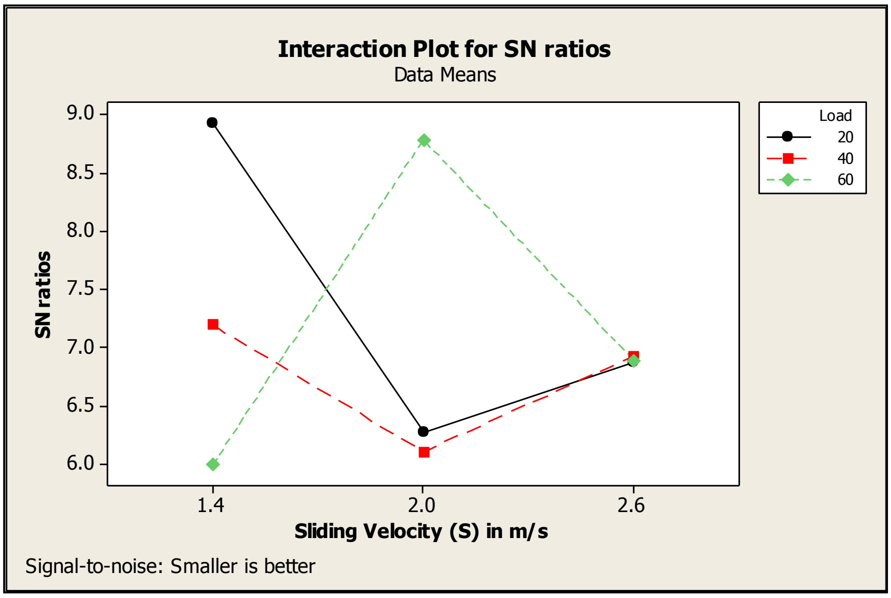


Figure 6: Interaction graph between sliding velocity and normal load for coefficient of friction

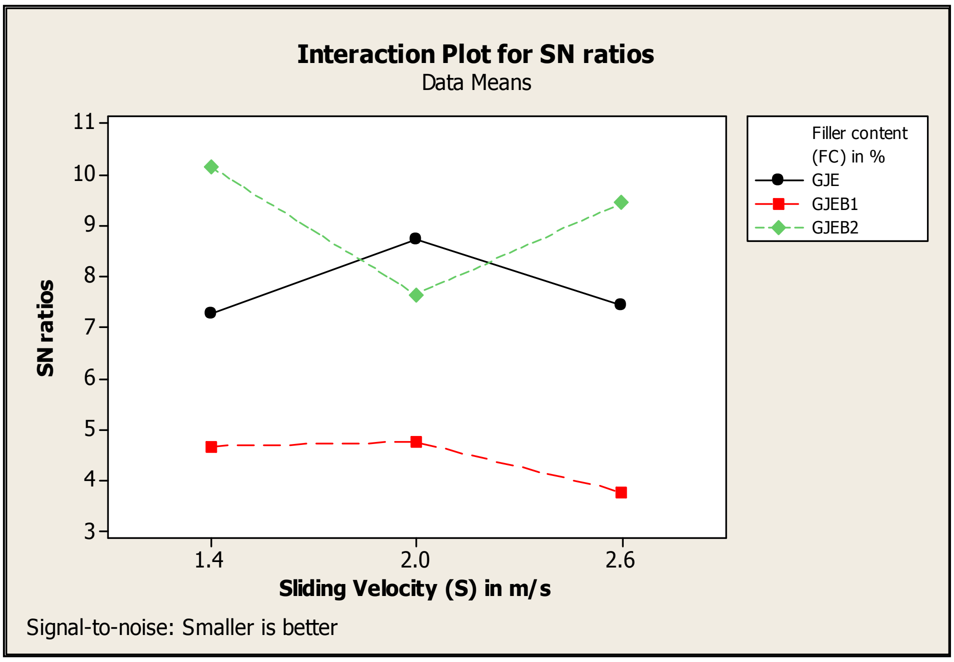


Figure 7: Interaction graph between sliding velocity and filler content for coefficient of friction

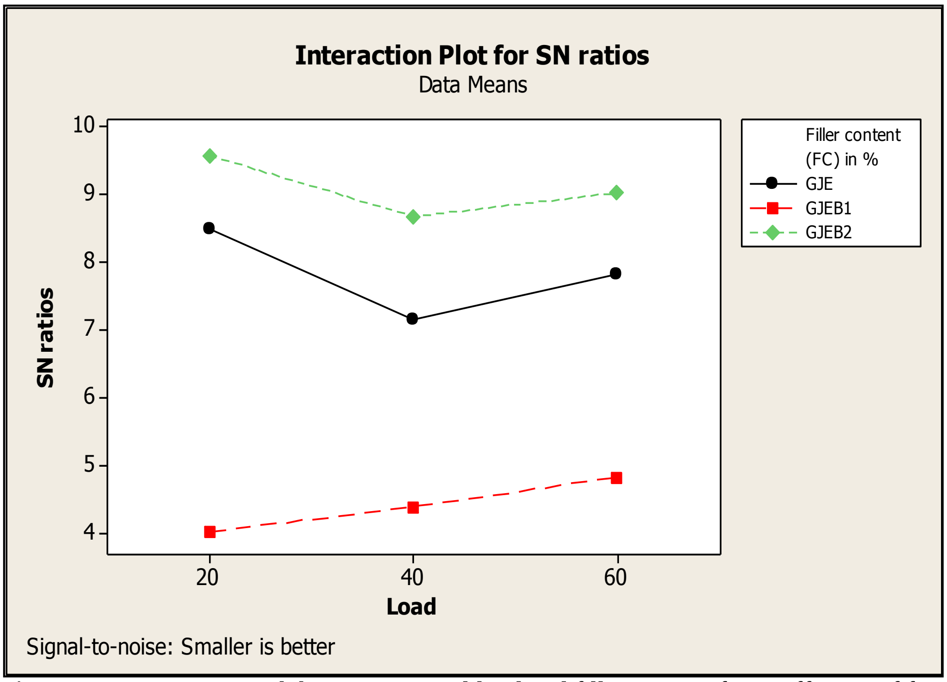
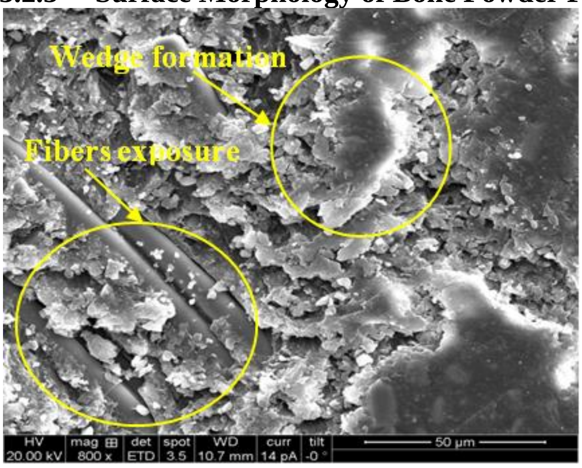
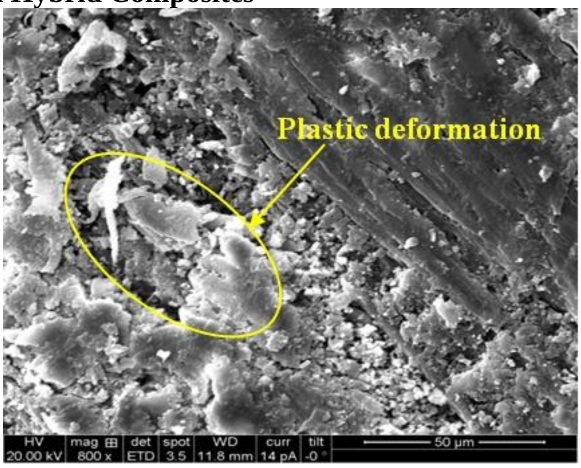


Figure 8: Interaction graph between normal load and filler content for coefficient of friction

3.2.3 Surface Morphology of Bone Powder Filled Hybrid Composites



(a)



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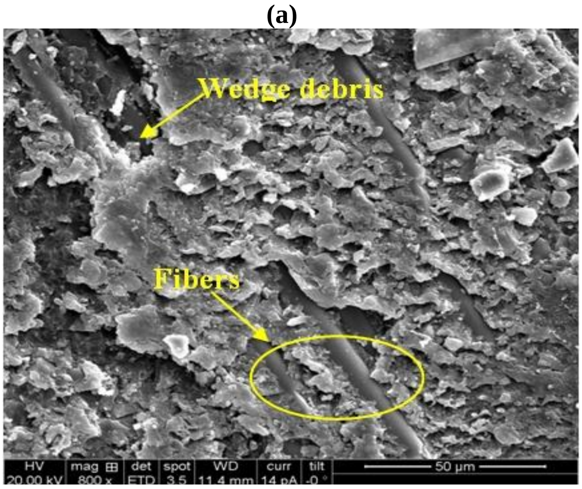

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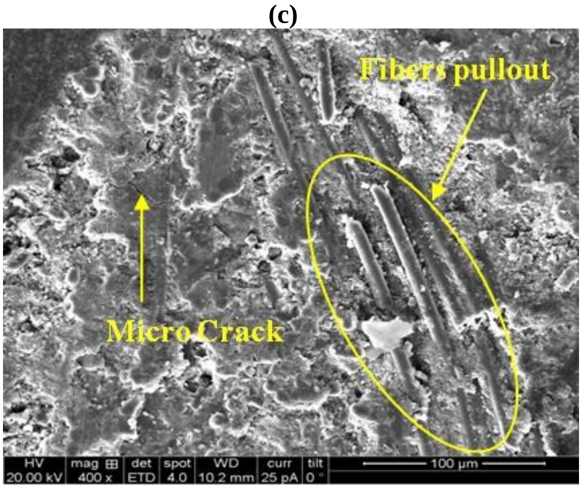

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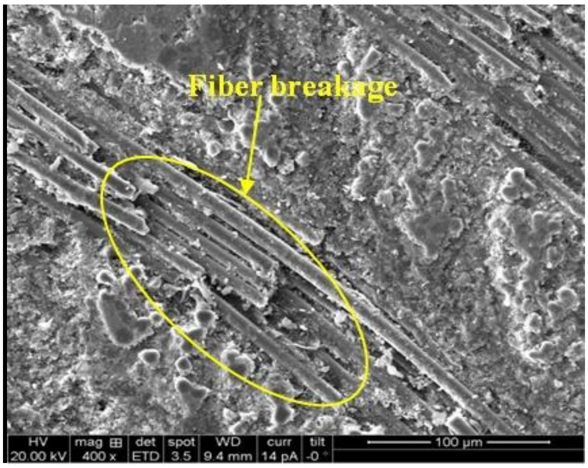

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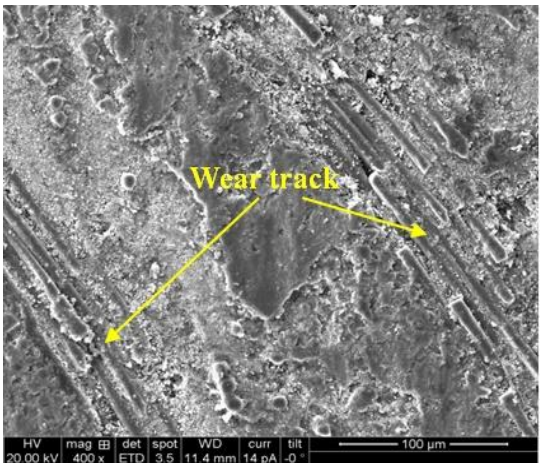

(f)

Figure 9: SEM pictures of composites for bone powder filled hybrid composites

When compared with sliding velocity and normal load the effect of filler content on specific wear rate was more as seen from main effect plot as shown in "Fig. 1". For analysis different filler content hybrid composite samples with all samples tested for 20N normal load were selected. "Figs. 9(a) to 9(c)" shows the SEM pictures of composites for different filler content (0, 10 and 15 wt.%) of bone powder filled hybrid composites. The micrograph in "Fig. 9(a)" shows the wedge formation, fiber exposure and plastic deformation of matrix which results maximum wear. The SEM picture as shown in "Fig. 9(b)" illustrates only a few fibers exposure when compared with "Fig. 9(a)" and less deformation of the matrix which indicates less wear. "Fig. 9(c)" shows more plastic deformation of the matrix which slightly increases the wear rate when compared with "Fig. 9(b)".

Similarly, coefficient of friction was affected by filler content as seen from main effect plot ("Fig. 5"), So SEM images were selected for different filler content of hybrid composites. "Figs. 9(d) to 9(e)" shows the SEM pictures for different filler content (0 wt.%, 10 wt.% and 15 wt.%) of bone powder filled hybrid composites. The worn surface of the "Figs. 9(d) and 9(f)" shows the wear track, minor crack and only few fibers exposed from the matrix which has less coefficient of friction. The SEM picture for "Fig. 9(e)" sample shows the wear track on the surface, breakage of fibers and more number of fibers exposed which increased the coefficient of friction due to the rubbing action of the fibers with the disc surface.

IV. Conclusions

The experimental investigation on dry sliding wear behaviour of bone powder filled epoxy composites leads to the following conclusions:

- Successful fabrication of bone powder filled E-glass/jute fiber reinforced epoxy composite has been done by the hand lay-up technique.
- Dry sliding wear response of these hybrid composites under different loads, filler content and sliding velocities can be successfully analyzed using Taguchi's experimental design method. Taguchi's method provides a simple, systematic and efficient methodology for the optimization of the control factors. While filler content emerges as the most significant factor affecting wear rate of bone power filled epoxy hybrid composites, other factors like load and sliding velocity have less influence on specific wear rate.
- The SEM micrographs of the specimen revels wear track, exposure of fibers due to wear of the matrix, debris formation, fiber breakage, plastic deformation of matrix and fiber matrix debonding.

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