MULTI-RESPONSE OPTIMIZATION OF TRIBOLOGICAL CHARACTERISTICS OF HYBRID COMPOSITES USING DFA AND ANOVA

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Abstract: *The present article considers an experimental study of tribological performance of Aramid and palm fibers reinforced with nylon hybrid composites. Friction and wear tests for hybrid composite material were conducted by using DUCOM pin-on-disc apparatus. Experiments were carried out based on L27 Taguchi orthogonal design with three parameters, such as fiber percentage, load, and sliding distance, each at three levels. Desirability function analysis (DFA) was employed to optimize the tribological parameters for hybrid composites. From the analysis of DFA, the optimum values for minimization of coefficient of friction and specific wear rate were identified to be fiber percentage at 15 (wt. %), load at 40 N, and sliding distance at 600m. Analysis of variance (ANOVA) was employed to determine the significance of parameters on multiple performance index (composite desirability in DFA). From the results of ANOVA, the fiber weight percentage was the most influencing parameter followed by load, and sliding distance on tribological study of hybrid composites.*

Keywords: *Hybrid Composite, Tribological Properties, GRA, DFA, ANOVA.*

Nomenclature

NFCs	Natural Fiber Composites
PTFE	Polytetrafluoroethylene
AF	Aramid fiber
PF	Palm fiber
NY	Nylon
DFA	Desirability Function Analysis
A	Fiber weight Percentage (wt. %)
B	Load
C	Sliding distance
K_0	Specific wear rate
ANOVA	Analysis of Variance
DOF	Degrees of freedom
NFC	Natural Fiber Composite
d_i	Individual desirability for responses
d_G	Composite desirability

1. INTRODUCTION

The polymer composites are widely being used now-a-days in many industrial applications because of their excellent properties such as superior strength to weight ratio, non-toxicity, light weight, design flexibility, resistance to corrosion, better coefficient of friction, easy to fabricate, self-lubricating property and wear resistance (Mohan et al., 2012). The suitable production process and right combination of filler material are plays an important role in the preparation of polymer composites to achieve desirable properties (Cheung et al., 2009). Inclusion of inorganic particles into the polymers is an effective way to fabricate polymer composite materials with improved tribological properties. There are different factors that can influence the mechanical performance of natural fiber composites (NFCs), which are selection of the fiber – including type, extraction method, harvesting time, chemical treatment, aspect ratio and fiber content, selection of matrix, fiber orientation, fiber dispersion, interfacial strength, and porosity (Pickering et al., 2007).

Natural and synthetic fiber reinforced polymer composite materials are attractive and replacing conventional metals due to their excellent properties. Because of their superior advantages, they are being widely used for tribological purposes such as brakes, gears, seals, clutches, transmission belts, bearings, office automation machinery, tank track pads, artificial joints and, rollers (Mishra and Biswas, 2016). Plant-based fiber reinforced polymer composites serves an alternative reinforcement for the synthetic fibers and provide advantages like processing flexibility, abundant, highly specific stiffness, non-toxic, low cost, easy recyclability, non - irritation of skin, eyes or respiratory system, anti - corrosive etc. (Malhotra et al., 2012). Palm fiber is a natural fiber which is having moderate tensile strength and moderate flexural strength as compared to other natural fibers. Aramid fibers are belongs to a class of heat resistant and strong synthetic fibers which is having the lower density, highest strength to weight ratio, high toughness, and widely being used in aerospace and military applications (Hillermeier, 1984). It also provides good wear resistance and lower coefficients of friction. Wear condition encountered in gears and vanes, in fluids handling pumps in industries, shock loading, roll neck bearings in steel mills subject to heat, bushes and seals in mining and agricultural equipment has been intensified (Harsha and Tewari, 2002). Wear is the damage to a solid surface in the form of a continuous loss of materials due to relative motion between the contacting surfaces (Mohapatra et al., 2014). Wear occurs through various mechanisms such as abrasion, adhesion, corrosion, erosion, and fatigue. Wear is the major cause of loss of mechanical performance and wastage of material and the reduction in wear results in substantial savings (Stachowiak and Batchelor, 2013). The major expenses in many processes are the cost of replacing the worn components. Because of this more attention is given towards the reducing wear (Misra and Finnie, 1980). Abrasive wear failure alone accounts 60% of the total cost (Deo and Acharya, 2010). Three body abrasive wear is the major problem occurs in industrial and agricultural equipments, whereas in material removal operations two - body abrasion happens (Anand and Kumaresh, 2012; McGee et al., 1987).

Biswas and Satapathy (2009) developed a mathematical model for estimating erosion damage caused by solid particle impact on red mud filled glass fiber reinforced epoxy matrix composites using taguchi experimental design. They found that the filler content in the composites, the impingement angle, velocity and erodent temperature have substantial influence in determining the rate of wear from the composite surface due to property of erosion. Shalwan and Yousif (2012) revealed that the type of treatment, orientations, physical characteristics and volume fraction of the natural fibers significantly influence the tribological and mechanical behaviour of composites. Kumar et al. (2015) carried out the tribological properties of various nano clay (Cloisite 25A) loaded epoxy, with and without inclusion of E- Glass fiber using Taguchi's technique. The authors indicated that the combination of factors mostly influenced the process to attain the minimum coefficient of friction and wear. They concluded that the fiber inclusion on laminates has minimum contribution on wear and coefficient of friction when compared to without fiber laminates. Pathan et al. (2016) studied the effect of parameters such as load, sliding speed, sliding distance, and percentage of glass fiber as a filler material on multiple performance characteristics namely wear and coefficient of friction using taguchi based grey relational analysis. It was observed that load at 3 kg, sliding speed at 5.1836 m/s (900 rpm), sliding distance at 2 km, and glass fiber at 15% (wt. %) were the optimum parameters for polytetrafluoroethylene (PTFE). Kumar et al. (2016) investigated the tribological properties of composites fabricated using bio-waste horn fiber (HF) and phenol formaldehyde (PF) resin using grey relational analysis and ANOVA.

From the past work done and literature survey, it was found that the abrasive wear studies of hybrid polymer composite are an interest of many authors. In the present work the hybrid composites were made of nylon (NY)/ aramid fiber (AF) / palm fiber (PF). The present paper throws a light on the effect of fiber percentage (wt. %), load, and sliding distance on multiple responses using desirability function approach with an aim to minimize coefficient of friction and specific wear rate. ANOVA technique has been employed to identify the substantial parameters affecting the multiple response characteristic for tribological study of hybrid composites.

2. MATERIALS AND METHODS

2.1 Materials

Fabrication of NY/AF/PF Hybrid Composite NY sheets, PF and AF were pre heated at 80°C for 2 hours to remove the moisture. In this composite material Nylon was the matrix material and aramid and palm fibers were used as the reinforcing materials. AF and PF were chapped into approximately 3mm length. Compression moulding method was used to produce the hybrid laminates, the die having dimension 150 x 150 x 9 mm^3 was used. The PF and AF were placed between the gaps of two successive NY layers. The die was compressed at the pressure of 150 bars at a temperature of 230°C for 10 minutes. It was air cooled for 24 hours. The different percentages of aramid and palm fibers were reinforced with Nylon and are shown in the Table 1.

Table 1: Different Percentages of Aramid and Palm Fibers

S. No	Aramid Fiber Percentage (wt. %)	Palm Fiber Percentage (wt. %)	Total Percentage (wt. %)
1	0	0	0
2	2.5	2.5	5
3	5	5	10
4	7.5	7.5	15

2.2 Experimental Setup

The wear and friction tests for Aramid and Palm fiber reinforced with Nylon composite material were conducted by using DUCOM Pin-On-Disc Tribotester as shown in the Figure 1, and its specifications are given in Table 2 according to G99-05 standard in dry sliding conditions at room temperature. The dimensions of the samples were 8 x 8 x 4 mm^3. The material specimens were glued to the metal pin. The samples were weighted before and after the experiments by using electronic balance with

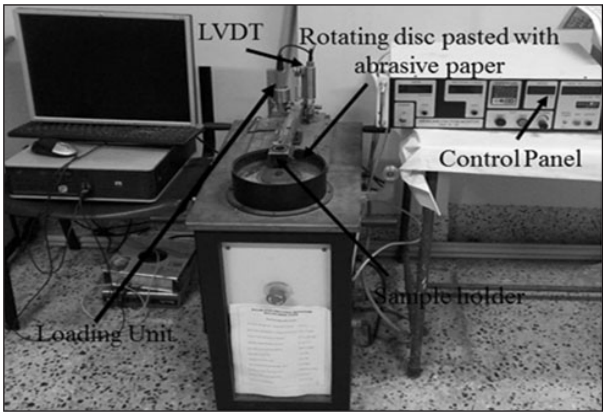

Fig 1. Schematic Diagram of Pin-on-disc Tribotester

Table 2: Pin-on-disc Tribotester Specifications

Pin Size (Diagonal/Diameter (mm))	3 to 12
Disc Size (Diameter× Thickness (mm))	165×8
Wear Track Diameter (Mean)	50 to 100 mm
Sliding Speed Range (m/sec)	0.5 to 10
Disc Rotation Speed (rpm)	200 to 2000
Normal Load (N)	5 to 200
Tangential Force (N)	0 to 200
Wear Measurement Range (µm)	0 to 2000
Exclusive Pin Heating (ºC)	Ambient to 400
Preset Timer(Hr/Min/Sec)	99/59/59
Power (V/A/Ph/Hz)	230/15/1/50

an accuracy of 0.0001 g. Specific wear rate was calculated by using Eq. (1),

$$K_0 = (w_1 - w_2) / (\rho \times S_d \times L) \quad (1)$$

Where, w_1 and w_2 are the weight of the sample before and after the abrasion test in g, ρ is the density of the material, K_0 is the specific wear rate in mm^3/N-m, S_d is the sliding distance in m, and L is the load in N.

2.3 Experimental Design

The process parameters considered for tribological test were fiber percentage (wt.%), load (N) and sliding distance (m) and the output responses were coefficient of friction (µ) and specific wear rate (mm^3/N-m). The identified parameters and their levels chosen are summarized in Table 3. The computation of degrees of freedom (DOF) is essential for selecting appropriate orthogonal array for conducting experimentation. Generally, the selected orthogonal array should serve the DOF greater than or equal to those for the process parameters. According to this an L_{16}orthogonal array in taguchi design was chosen for experimentation because it has 15 DOF, which is more than the 9 DOF in the process parameters. As per this design 16 experiments were conducted against 320 grit size of abrasive paper at constant sliding velocity of 0.523 m/s and which are presented in Table 4.

Table 3. Process Parameters and their Levels

Variable	Process Parameters	Levels			
		1	2	3	4
A	Fiber Percentage (wt. %)	0	5	10	15
B	Load (N)	10	20	30	40
C	Sliding distance (m)	150	300	450	600

Table 4: Experimental Design using L_{16} Orthogonal Array and Responses

Exp. Run	A	B	C	Coefficient of friction (μ)	Specific wear rate (mm^3/N-m)
1	1	1	1	0.74	0.1257
2	1	2	2	0.71	0.0745
3	1	3	3	0.68	0.0421
4	1	4	4	0.62	0.0340
5	2	1	2	0.69	0.0689
6	2	2	1	0.62	0.0520
7	2	3	4	0.58	0.0351
8	2	4	3	0.52	0.0298
9	3	1	3	0.53	0.0484
10	3	2	4	0.50	0.0226
11	3	3	1	0.61	0.0415
12	3	4	2	0.49	0.0324
13	4	1	4	0.55	0.0304
14	4	2	3	0.51	0.0221
15	4	3	2	0.59	0.0204
16	4	4	1	0.43	0.0296

2.4 Desirability Function Analysis (DFA)

Desirability function analysis (DFA) was the most extensive method used in many industries for multi response optimization problems. The steps in DFA will change the multiple response problem into a single response problem. As a result, the single response problem termed as composite desirability (d_G) was obtained by converting the complicated multi-response problem. (Derringer and Suich, 1980).

Step 1: Calculation of Individual Desirability Index (di)

The first step in DFA is to calculate the individual desirability index for all the responses. The equations were chosen based on the type of response characteristic. For the higher-the-better, the desirability function index can be obtained using Eq. (2). The value of Ŷ is expected to be the higher-the-better. When the Ŷ exceeds a specified criteria value, which can be viewed as the requirement, the desirability value equals to 1; if the Ŷ is less than a specified criteria value, which is unacceptable, the desirability value equals to 0.

$$d_i = \begin{cases} 0, & \hat{y} \le y_{min} \\ \left(\frac{\hat{y}-y_{min}}{y_{max}-y_{min}}\right)^r, & y_{min} \le \hat{y} \le y_{max}, \quad r \ge 0 \\ 1, & \hat{y} \ge y_{max} \end{cases} \quad (2)$$

where the y_{min} represents the least tolerance limit of Ŷ, the y_{max} represents the greatest tolerance limit of Ŷ and r refers to the weight.

For the lower-the-better, the desirability function can be expressed as in Eq. (3). The expected value of Ŷ is to be the lower-the-better while Ŷ is less than a specified criterion value, then the desirability value will be equal to 1; if Ŷ exceeds a specified criterion value, then the desirability value will be equal to 0.

$$d_i = \begin{cases} 1, & \hat{y} \le y_{min} \\ \left(\frac{\hat{y}-y_{max}}{y_{min}-y_{max}}\right)^r, & y_{min} \le \hat{y} \le y_{max}, \quad r \ge 0 \\ 0, & \hat{y} \ge y_{max} \end{cases} \quad (3)$$

where the y_{min} refers to the lower tolerance limit of Ŷ, the y_{max} refers to the upper tolerance limit of Ŷ and r refers to the weight.

Step 2: Following the calculation of individual desirability index, using Eq. (4) all the individual desirability indexes are united to form a single value called composite desirability.

$$d_G = \sqrt[w]{(d_1^{w_1} * d_2^{w_2} \ldots\ldots\ldots\ldots\ldots * d_i^{w_i})} \quad (4)$$

where d_i is the individual desirability index for the property y_i, w_i refers to the weight of the property in, and w is the summation of the individual weights.

Step 3: Finally, the optimum combination of parameter and their levels should be determined.

The greater value of composite desirability implies better product quality. Hence, the parameter effect and the optimum conditions for each parameter are estimated based on the analysis of composite desirability (d_G).

Thus, on the basis of the composite the parameter effect and the optimum level for each parameter are estimated.

3. RESULTS AND DISCUSSION

3.1 Effect of Process Parameters on Responses

The influence of process parameters on coefficient of friction and specific wear rate are shown in the Figure 2 & Figure 3 respectively. From the Figure 2 it is noticed that the coefficient of friction decreases with increasing the fiber percentage (wt. %). The minimum coefficient of friction can be achieved when the parameter combination is at fiber weight percentage of 15, load of 40 N, and sliding distance of 450 m.

From the Figure 3 it is observed that the specific wear decreases with increasing the fiber percentage (wt. %), load, and sliding distance. The minimum value of specific wear rate can be achieved when the parameter combination is at fiber weight percentage of 15, load of 40 N, and sliding distance of 600 m.

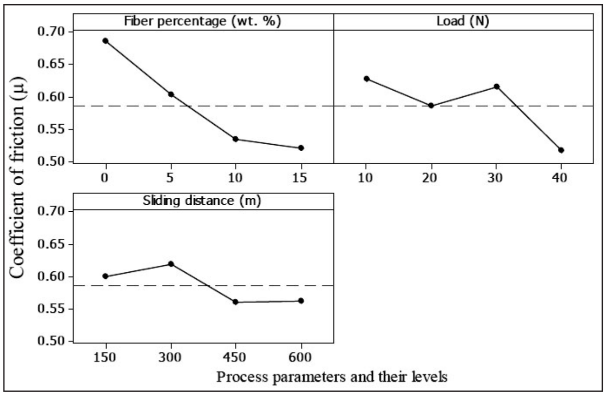

Fig 2. Effect of Parameters on Coefficient of Friction

3.2 Multi-response Optimizations Using DFA

For every response, the individual desirability index (d_i) was calculated based on the required quality characteristics. As all the responses are belong to minimization type, hence the smaller-the-better-type Eq. (3) was chosen. After calculating individual desirability for each response, composite desirability values were calculated with the help of Eq. (4) by considering equal weightage for both the responses and presented in Table 5.

Table 5: Individual Desirability and Composite Desirability

Exp. Run	Individual desirability index (di)		Composite desirability (d_G)
	Coefficient of friction (µ)	Specific wear rate (mm^3/N-m)	
1	0.0000	0.0000	0.0000
2	0.0968	0.4862	0.2915
3	0.1935	0.7939	0.4937
4	0.3871	0.8708	0.6290
5	0.1613	0.5394	0.3504
6	0.3871	0.6999	0.5435
7	0.5161	0.8604	0.6883
8	0.7097	0.9107	0.8102
9	0.6774	0.7341	0.7058
10	0.7742	0.9791	0.8767
11	0.4194	0.7996	0.6095
12	0.8065	0.8860	0.8462
13	0.6129	0.9050	0.7590
14	0.7419	0.9839	0.8629
15	0.4839	1.0000	0.7419
16	1.0000	0.9126	0.9563

3.2.1 Effect of Process Parameters on Composite Desirability

The parameter effect on composite desirability for aramid and palm fibers reinforced with Nylon hybrid composites are shown in Table 6 and graphically shown in Figure 4. From Table 6 and Figure 4, the best combination of various parameters for the combined objective of minimized coefficient of friction and specific wear rate were identified as A4 B4 C4.

3.2.2 ANOVA for Composite Desirability

The results of ANOVA for the composite desirability are shown in Table 7. From the Table 7, it was observed that the fiber weight percentage (Percentage contribution, P = 56.19%) is the most significant process parameter affecting the multiple performance characteristics for aramid and palm fibers reinforced with Nylon hybrid composites followed by load (P = 26.68%) and sliding distance (P = 14.74%).

Table 6: Response Table for Composite Desirability (d_G)

Variable	Level-1	Level-2	Level-3	Level-4	Delta	Optimum levels
A	0.3536	0.5981	0.7595	**0.8300**	0.4765	A4
B	0.4538	0.6436	0.6334	**0.8104**	0.3567	B4
C	0.5273	0.5575	0.7181	**0.7382**	0.2109	C4

Table 7: Results of the ANOVA for Composite Desirability (d_G)

Variables	Sum of squares (SS)	Degree of freedom	Mean square (MS)	F- test	% Contribution, *P*
A	0.5365	3	0.1788	47.06	56.19
B	0.2548	3	0.0849	22.35	26.68
C	0.1407	3	0.0469	12.34	14.74
Error	0.0228	6	0.0038		2.39
Total	0.9548	15			100
S = 0.0617249	R-Sq = 97.61%	R-Sq (adj) = 94.01%			

Table 8. Results of Confirmation Test

Initial machining parameters		Optimal machining parameters Using GRA	Optimal machining parameters Using DFA
Levels	A1 B2 C2	A4 B4 C4	A4 B4 C4
Coefficient of friction (μ)	0.71	0.45	0.45
Specific wear rate (mm^3/Nm)	0.0745	0.0217	0.0217
Grey relational grade (GRG)	0.4248	0.9308 (improvement in GRG = 0.5060)	-
Composite desirability (d_G)	0.2915	-	0.9616 (improvement in d_G = 0.6701)

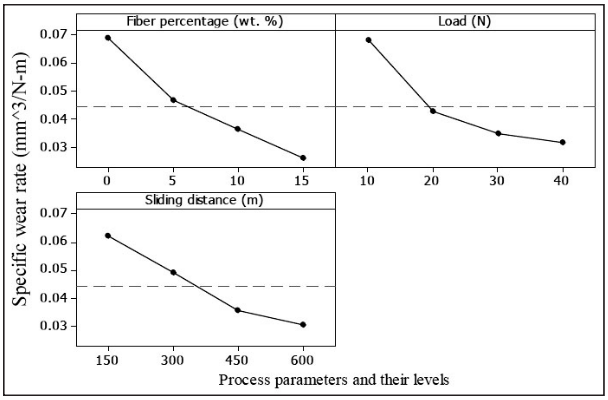

Fig 3. Effect of Parameters on Specific Wear Rate

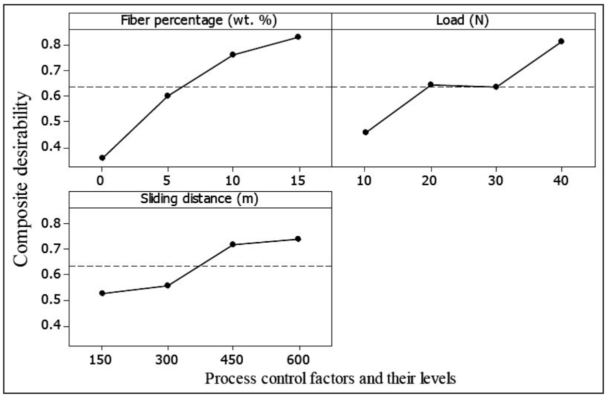

Fig 4. Effect of Process Parameters on Composite Desirability (dG)

3.3 Confirmation Test

Once the optimal level of the process parameters has been identified, the last step is to verify the improvement in the responses using the optimal level of process parameters. Table 8 shows the comparison of the response values obtained for the optimum conditions using DFA with the initial experimental run. The second experiment shown in the Table 4 was considered as the initial designated levels of process parameters and is represented by A1B2C2. From DFA analysis the optimal combination of process parameters identified as A4 B4 C4. As noted from the Table 8, the coefficient of friction and specific wear rate were decreased from 0.71 μ to 0.45 μ and 0.0745 mm^3/N-m to 0.0217 mm^3/N-m respectively. The estimated composite desirability value was increased from 0.2915 to 0.9616 respectively, which are shown in Table 8.

CONCLUSION

The optimization was carried out in two steps. In the first step, both the responses were optimized as multi-objective by using desirability function analysis. From the study, the following conclusions were drawn.

1. The coefficient of friction decreases with increasing the fiber percentage (wt. %). From the main effect plot, it was found that the minimum value of coefficient of friction was achieved when the parameter combination is at fiber weight percentage of 15, load of 40 N, and sliding distance of 450 m.
2. The specific wear rate decreases with increasing the fiber percentage (wt. %), load, and sliding distance. It was noticed from the main effect plot that the minimum value of specific wear rate was achieved when the parameter combination is at fiber weight percentage of 15, load of 40 N, and sliding distance of 600 m.
3. By applying DFA multi-response optimization tool on tribological characteristics of Hybrid composite, the optimum values for minimization of coefficient of friction and specific wear rate were found to be at a fiber weight percentage of 15, load of 40 N, and sliding distance of 600 m.
4. From the results of ANOVA, fiber percentage (wt.%) was identified as the statistical and physical significant parameter followed by load, and sliding distance.
5. Confirmation test results proved that the determined optimum condition of tribological parameters satisfy the real requirements.
6. The adopted multi-objective optimization technique can be applied for the optimization of different responses in tribological study of different materials at different parameter combination.

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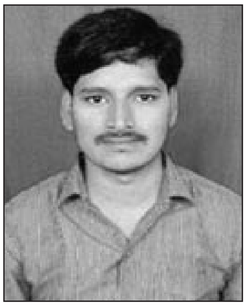

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