INVESTIGATION ON ABRASION WEAR RESPONSE OF HYBRID COMPOSITES USING TAGUCHI EXPERIMENTAL DESIGN AND ANN

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Abstract: This paper describes the development of hybrid composites consisting of polyester reinforced with E-glass fiber and alumina particulates. Four different composite samples are prepared with 0, 5, 10 and 15wt. % of Al_2O_3. The abrasion wear response of these composites is investigated. For this purpose the abrasion test is conducted by following design of experiment approach using Taguchi's orthogonal arrays. Taguchi approach enables to determine optimal parameter settings that lead to minimization of wear rate. The results indicate that sliding velocity, normal load and filler content are the significant factors. The experimental results are in good agreement with the values from the theoretical model. An artificial neural network (ANN) approach is also applied to predict the wear rate of the composites and compared with the theoretical results. This study reveals that addition of hard particulate filler improves the wear resistance of glass-polyester composites significantly.

Key words: Abrasion Wear modeling, Al_2O_3, Taguchi design, Theoretical model, ANN.

1. Introduction:

In recent years, fiber reinforced polymer composites (FRPCs) have generated wide interest in various engineering fields including tribological applications such as cams, clutches, brakes, bearings, wheels, rollers, seals and gears due to their good combination of high specific strength, high modulus, low density and better wear resistance [1]. Therefore, the mechanical and tribological behavior of these materials should be studied systematically. Wear can be defined as damage to a solid surface, generally involving progressive loss of material, due to relative motion between that surface and contacting substance or substances [2]. Among various types of wear, abrasive wear situations occurs in numerous equipments such as vanes and gears, in pumps handling industrial fluids, sewage and abrasive contaminated water, chute liners abraded by coke, coal and mineral ores; bushes and seals in agricultural and mining equipments [3]. Carbon, glass, aramide and graphite fibers are most common fibers used for reinforcement in polymer matrix composites [4-6]. It is evident form literature that in general, short fiber reinforcement led to the deterioration in abrasive wear resistance of the matrix [7] while on the other hand the bi-directional fabric reinforcement offers an improved abrasion resistance of the polymers [8]. Abrasive wear resistance of glass fiber-vinyl ester composites filled with silicon carbide is better than graphite filled composite system [9]. Similarly, tungsten carbide (WC) filled glass epoxy composites shows excellent wear resistance as compare to silica (SiO_2) filled glass epoxy composites [10]. Commonly used fillers materials in fiber reinforced polymer composites are graphite, molybdenum disulphide, tungsten carbide, silicon carbide and alumina. Graphite and molybdenum disulphide posses self-lubrication properties and they are widely used in bearing liner applications. Silicon carbide (SiC) and alumina (Al_2O_3) have been extensively used in abrasive machining processes such as grinding, honing, water-jet cutting and sand blasting due to their high hardness [11].The present work is focused on the preparation of glass fabric-polyester composites reinforced with alumina (Al_2O_3) and to investigate the wear behavior of these composites under abrasive situations. The mechanical characterization of these composites is also performed so as to have an insight about this aspect. An economical and viable experimental strategy based on Taguchi's parameter design has been used to analyze the effect of various parameters and their interactions. This experimental procedure has been successfully applied earlier for solid particle erosion behavior and dry sliding characteristics of polymer-matrix composites [12, 13]. In the present work, another novel technique, artificial neural network (ANN) is also used to predict minimum wear rate. ANN is a technique inspired by the biological neural system and has been used to solve a wide variety of complex, nonlinear problems in various fields [14, 15].

2. Experimental Details:

2.1 Composite preparation

Bi-directional E-glass fiber mats are reinforced in polyester resin and four different weight proportions of alumina powder (0 wt%, 5 wt %, 10wt% and 15wt%) with average size of 80-90 micron are added as the filler material to prepare the composites C1, C2, C3, and C4 respectively. The composition and designation of the composites prepared for this study are listed in Table 1 and shown in Figure 1. The fabrication of the composite slabs is done by conventional hand-lay-up technique followed by light compression molding technique. The bi-directional E-glass fiber and polyester resin possess Young's modulus of 72.5GPa and 3.25GPa respectively and a density of 2600kg/m^3 and 1350kg/m^3 respectively. Each ply of fiber is of dimension 200×200 mm^2. A wooden mould of 210×210×40 mm^3 dimension is used. A releasing agent (Silicon spray) is used to facilitate easy removal of composites from the mold after curing. The castings are put under load of about 25 kg for about 24 hours for proper curing at room temperature. Specimens of suitable dimensions are cut using a diamond cutter for wear characterization. Utmost care has been taken to maintain uniformity and homogeneity of the composites.

Table 1: Designations and detailed compositions of the composites

Designation	Composition
C_1	Polyester (60wt.%) + glass fiber (40 wt.%)
C_2	Polyester (55 wt.%) + glass fiber (40 wt.%) + alumina (5 wt.%)
C_3	Polyester (50 wt.%) + glass fiber (40 wt.%) + alumina (10 wt.%)
C_4	Polyester (45 wt.%) + glass fiber (40wt.%) + alumina (15 wt.%)

Fig.1: Fabricated composite samples

2.2 Abrasive wear test

For evaluating the performance of composites under three body abrasion conditions, wear tests are carried out as per ASTM G65 [16] using dry abrasion test rig (TR-50) supplied by DUCOM Ltd. The dry sand/rubber wheel (diameter 228.6mm) abrasion test involves the abrading of test specimen with a grit of controlled size and composition. The abrasive is introduced between test specimen and a rotating wheel with a chlorobutyl rubber tyre. The test specimen is pressed against a rotating wheel at a specified force by means of a lever arm while a controlled flow of grit abrades the test surface. The test duration and force applied by the lever arm is varied. The specimens are weighed before and after the test and loss in mass is recorded. Specific wear rate in volume loss basis can be expressed as

$Ws = \frac{\Delta M}{\rho . l . N}$ Where, ΔM is the mass loss in test duration in grams, ρ is the density of the composite l is the (gm/cm^3), abrading distance (m) and N is the normal load. The specific wear rate is defined as the volume loss of the specimen per unit sliding distance per unit applied load.

2.3 Experimental design

The Taguchi method is a commonly adopted approach for optimizing design parameters. Taguchi method provides the designer with a systematic and efficient approach for experimentation to determine near optimum settings of design parameters for performance, quality and cost [17-19]. Since experimental procedures are expensive and time consuming, there is a need to satisfy the design objectives with least number of experiments. From literature review it reveals that parameters viz., fiber loading, normal load and sliding distance largely influence the abrasive wear characteristics of polymer composites. Thus, the impact of these three is studied using L16 orthogonal design. The control factors and parameter settings are listed in Table 2. Four control factors viz. sliding velocity, filler (alumina) content, normal load and sliding distance each at four levels are selected in accordance with L16 orthogonal array design [20-22]. All tests are carried out at room temperature. In the conventional full factorial design, 44=256 number of experiments are required to conduct for the minimum wear rate where as in Taguchi design of experiment only 16 number of experiments are required, thus offering a greater advantage with respect to cost and time of experiment. The S/N ratio for minimum wear rate is coming under “Lower is better” (LB) characteristics and the logarithmic transformation of loss function is shown below as:

$\frac{S}{N} = -10log_{10}\left[\frac{1}{n}\left(\sum y^2\right)\right]$ where, n is the number of observations and y is the observed data.

Table 2: Control factors and levels of the variables used in the experiment.

Control Factor	Level				
	I	II	III	IV	Units
A:Sliding velocity	0.5	0.75	1.0	1.5	m/s
B:Normal load	5	10	15	20	N
C:Alumina content	0	5	10	15	Wt.%
D:Distance of Sliding	100	200	300	400	M

3. Results and discussion

3.1 Wear analysis using experimental design

The specific wear rates obtained for all the sixteen test runs along with the corresponding S/N ratio are presented in Table 3. The overall mean S/N ratio is found to be -4.2096 dB. The values obtained by using MINITAB 14 software, specially used for design of experiment applications. The response analysis of all the factors for the S/N ratio is presented in Table 4. It is found that the sliding velocity is the most significant factor followed by filler content and normal load. Sliding distance is the least significant factor for specific wear rate of the composite samples under this study. The effects of individual factors are shown in Figure 2. The analysis of the results leads to the conclusion that factor combination of A1, B3, C4 and D1 gives minimum specific wear rate in dry abrasion situations.

3.2 Factor setting for minimum specific wear rate

For the present investigation, an attempt has been made to find out optimal setting of control factors for minimum specific wear rate. The single objective optimization requires quantitative determination of the relationship between specific wear rate and control factors. In order to derive the specific wear rate in terms of a mathematical model, the following equation is suggested: W= K0 + K1×A + K2 ×B + K3×C……….(3)

W is the specific wear rate in mm3/N-m and Ki (i= 0,1,3) are the model constants. A is the sliding velocity (m/s), B is the normal load (N) and C is the filler content (wt.%). The constants are calculated using non-linear regression analysis with the help of SYSTAT 7 software and the following relation is obtained:

W= 1.013 +1.066×A – 0.007×B – 0.038×C ………(4)

The correctness of the calculated constants is confirmed as high correlation coefficient (R2) to the tune of 0.968 is obtained for specific wear rate and therefore the model is quite suitable to use for further analysis.

Table 3: Experimental design using L16 orthogonal array

Test Runs	(A)	(B)	(C)	(D)	Ws	S/N ratio
1	0.5	5	0	100	1.401	-2.92876
2	0.5	10	5	200	1.364	-2.69629
3	0.5	15	10	300	1.227	-1.77689
4	0.5	20	15	400	1.081	-0.67651

5	0.75	5	5	300	1.878	-5.47391
6	0.75	10	0	400	1.885	-5.50623
7	0.75	15	15	100	1.113	-0.92990
8	0.75	20	10	200	1.265	-2.04181
9	1.0	5	10	400	1.785	-5.03276
10	1.0	10	15	300	1.405	-2.95353
11	1.0	15	0	200	2.127	-6.55535
12	1.0	20	5	100	1.919	-5.66150
13	1.25	5	15	200	1.845	-5.31993
14	1.25	10	10	100	2.036	-6.17556
15	1.25	15	5	400	2.149	-6.64473
16	1.25	20	0	300	2.233	-6.97777

Table 4: Response Table for Signal to Noise Ratios

Level	A (m/s)	B(N)	C (wt.%)	D(m)
1	-2.020	-4.689	-5.492	-3.924
2	-3.488	-4.333	-5.119	-4.153
3	-5.051	-3.977	-3.757	-4.296
4	-6.279	-3.839	-2.470	-4.465
Delta	4.260	0.849	3.022	0.541
Rank	1	2	3	4

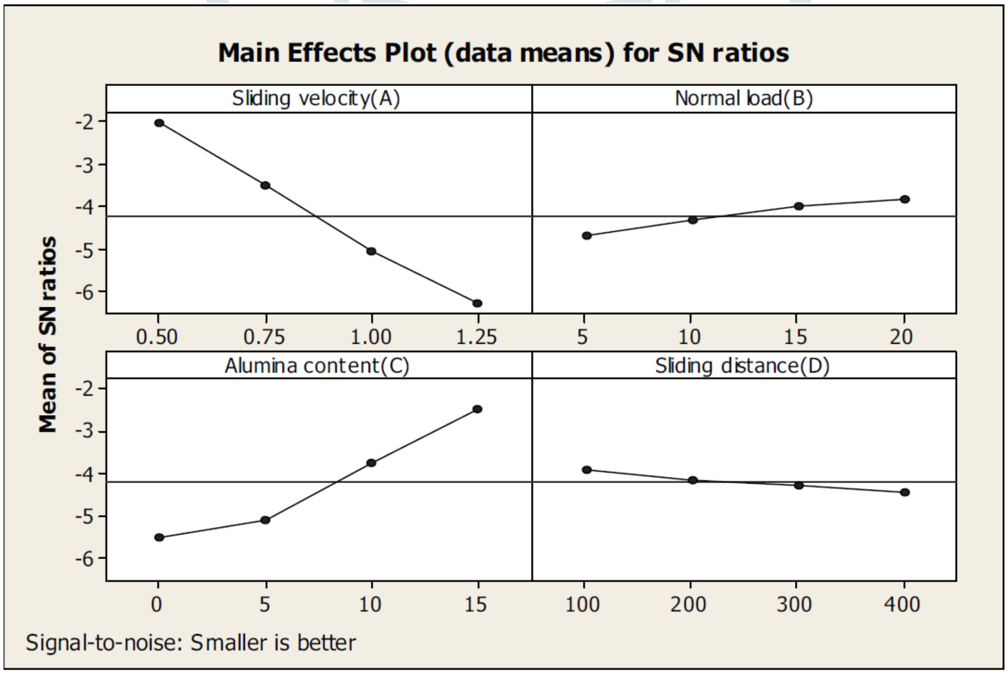

Fig. 2: Effects of control factors on specific wear rate.

3.3 Wear analysis using neural computation

The wear behavior of materials is considered as a complex and non-linear problem with respect to its parameters and operating conditions. In order to obtain minimum wear rate, appropriate combination of operating parameters have to be planned properly. Therefore techniques like artificial neural network (ANN) are needed to study the interrelated effect of parameters on the wear process [14, 15]. It is a technique that involves database training to predict input-output correlation. In the present study, sliding velocity, normal load and alumina content are taken as the three input parameters and specific wear rate as output parameter. Experimental result sets are used to train the neural network. The database of the network is divided into three categories i.e. (i) a validation category which is required to define the neural network and adjust the number of neurons for each layer, (ii) a training category, which is used for adjustment of network weights and (iii) a test category, which is used to the set that validates the results of the training protocol. The input variables are normalized so as to lie same range group of 0 to1. The output layer has one neuron to represent specific wear rate. About 75% of the experimental result data are used to train the network and different ANN structures with varying number of neurons in the hidden layer are tested at constant cycles, learning rate, error tolerance, momentum parameter, noise factor and slope parameter. Based on least error criterion, one structure is selected for training of input-output data are tabulated in Table 5. The three layer neural network used in this work is shown in Figure 3. The learning rate is varied in the range of 0.001-0.1 during training of input-output data. In the present work, the number of neurons in the hidden layer is varied and optimized to 8. Software NEURALNET have been used for neural computation with back propagation algorithm.

Table 5: Selected input parameters for training of the neural network

Input parameters for Training	Values
Error tolerance	0.01
Learning rate (β)	0.002
Momentum parameter (α)	0.002
Noise factor (NF)	0.001
Number of epochs	10,00,000
Slope parameter	(£) 0.6
Number of hidden layer neuron	(H) 8
Number of input layer neuron	(I) 3
Number of output layer neuron	(O) 1

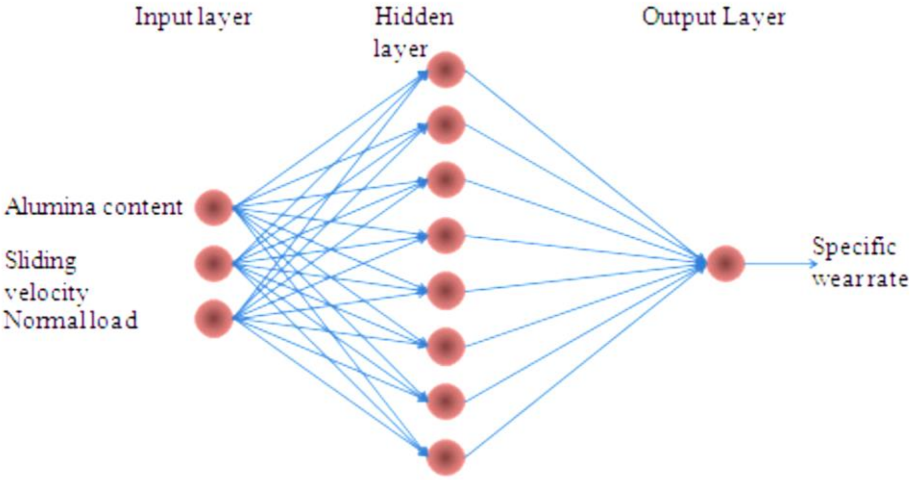

Fig. 3: Three layer neural network

Table 6: Comparison of experimental and ANN results

Test run	Specific wear rate (mm3/N-m)		Error (%)
	Result obtained from experiment	Result obtained from ANN	
1	1.401	1.511	7.85
2	1.364	1.453	6.52
3	1.227	1.352	10.18
4	1.081	1.189	9.99
5	1.878	1.951	3.88
6	1.885	1.933	2.54
7	1.113	1.243	11.68
8	1.265	1.359	7.43
9	1.785	1.887	5.71
10	1.405	1.576	12.17
11	2.127	2.304	8.32
12	1.919	2.048	6.72
13	1.845	1.936	4.93
14	2.036	2.097	2.99

15	2.149	2.316	7.77
16	2.233	2.498	11.86

4. Conclusions

Based on the present investigation, the following conclusions can be drawn as: (i) The use of neural network model to simulate experiments with parametric design is effective, efficient and helps to predict the abrasion wear rate of alumina based glass polyester composites under different test conditions. (ii) The analysis of abrasion wear test results using a Taguchi technique suggests that the sliding velocity, filler content and normal load in this sequence is the significant factors influencing the specific wear rate. (iii) The predicted and experimental values of specific wear rate shows good agreement and validate the remarkable capability of a well trained neural network for these kinds of processes.

5. References

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