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Citation: AIP Conference Proceedings **2018**, 020003 (2018); doi: 10.1063/1.5058240
View online: https://doi.org/10.1063/1.5058240
View Table of Contents: http://aip.scitation.org/toc/apc/2018/1
Published by the American Institute of Physics

Integrated Taguchi-Artificial Neural Network Approach for Modeling and Optimization of Wear Performance of Si_3N_4-hBN Composite

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Abstract. During action or movement in the artificial joint there is generation of wear particles creating a serious issue like aseptic loosening of joint. Silicon nitride (Si_3N_4) is proposed as an alternative material for knee/hip joint replacement. Si_3N_4 against steel (ASTM 316L) is a material combination in the category of ceramic on metal (CoM) for artificial joint. The work covered in this paper, try to obtain the optimum value of % hexagonal boron nitride (hBN) by volume to be mixed in Si_3N_4 to reduce wear against steel. The experiments were planned as per design of experiments (DoE) Taguchi method to obtain the optimum combination of % volume of hBN and load. Taguchi analysis presents 12% volume of hBN and 15N load is optimum to minimize wear loss. Using experimental results, artificial neural network (ANN) model trained, tested and implemented to predict results of volumetric wear loss (VWL) at different loading condition.

INTRODUCTION

Various mechanical elements are sliding/rolling against each other result in contact stresses and loss of material from surface known as wear loss. Minimization of wear loss is one of the objectives in the area of tribology study. Biocompatible nature of Si_3N_4 has proposed its application in the field of orthopedics [1]. Last 5 decades study in the area of orthopedics is trying to investigate various biomaterials for hip/knee joint replacement with minimum wear loss and subsequently extending joint life [2]. With favorable wear rate Si_3N_4 offers an alternative to oxide ceramic having high value of fracture toughness and resistant to crack propagation [3, 4]. Si_3N_4 has shown material properties that are compatible with the orthopaedic bearing showing excellent wear resistance. It is always expected to minimize the wear particle generation to avoid joint failure. Johanna Olofsson *et al.* [5] carried out sliding contact wear test using Si_3N_4 and CoCr disc against Si_3N_4 and Al_2O_3 ball in the presence of biolubricant. Si_3N_4 sliding against Si_3N_4 showed the generation of tribofilm on Si_3N_4 minimizing friction and wear in biolubricant in comparison to other pairs. Biocompatibility of Si_3N_4 with low wear rate proposed it as a suitable material for joint replacement. The tribological performance of Si_3N_4 can be improved with addition of solid lubricant. Hexagonal boron nitride (hBN) is known biocompatible solid lubricating material [6, 7, 8]. Generation of hydrated layers (H_3BO_3 and $BN(H_2O)_x$) shows minimum wear coefficient with improved tribological performance of Si_3N_4- BN composites. Wei Chen *et al*. [9] studied wear performance of Si_3N_4-hBN composite having 0, 5, 10, 20 and 30 volume % of hBN in Si_3N_4 against Si_3N_4 using PoD tester. They concluded that with 20% volume of hBN in Si3N4, friction coefficient reduces up to 0.19.

Nik Mizamzul and Shahrul Kamaruddin [10] optimized injection moulding parameters: melt temperature, packing pressure, injection time, packing time for flexural modulus and flexural strength of injection moulded part using Taguchi method. Ghalme *et al.* [11] evaluated the wear performance of Si_3N_4 hBN composite using Pin-on-disc setup. They implemented DoE- Taguchi method to evaluate the optimum combination of % vol. of hBN with load for minimizing wear of silicon nitride against alumina in dry environment. Umit Yalchin *et al.* [12] optimized cutting parameters: feed rate, depth of cut, cutting speed and coolant in face milling for cutting force, surface

Proceedings of the 1st International Conference on Mechanical and Materials Science Engineering
AIP Conf. Proc. 2018, 020003-1–020003-6; https://doi.org/10.1063/1.5058240
Published by AIP Publishing. 978-0-7354-1736-6/$30.00

roughness and temperature. For this optimization, they used Taguchi method and ANN; trained with only eight experiments of Taguchi method.

The artificial neural system is examples of intelligent machines that have great strength to improve the quality of human being. The neural network models are applicable to find the effect of individual input on the output parameters, in a situation where experimentation is difficult. An artificial neural network was firstly introduced into tribology by Jones *et al.* [13] in 1997. H.K.D.H.Bhadeshia [14] in his work presented an excellent introduction to Artificial Neural Network (ANN) with a review of the application of ANN technique in the field of material science. Rashed F.S. & Mahmoud T.S. [15] implemented artificial neural network (ANN) method to predict the wear behavior of A356/SiC metal matrix composite. Z.Zhang *et al.* [16] used ANN for prediction of erosive wear performance of polymers i.e. polyethylene, polyurethane and an epoxy modified by hygrothermally decomposed polyurethane and found to be suitable for property prediction. Hakan Centinel *et al.* [17] implemented ANN for prediction of wear loss quantities in Mo coatings deposited on iron substrates sliding against AISI 303 counter body. The results of the experiment and neural network prediction were in good agreement.

The wear performance of Si_3N_4 hBN composite against self-mating pair or against alumina is evaluated, but wear performance against medical grade steel-ASTM 316L is not covered. In this work, we have attempted to evaluate the wear performance of Si_3N_4 hBN composite against ASTM 316L steel. Results of experiment present 12% volume of hBN in Si_3N_4 at 15N load can minimize the wear volume loss. This paper presents the application of artificial neural network for validating the set of optimal control factors obtained through experimentation, and to verify that obtained settings for control factors are indeed optimal. Trained ANN simulated for optimal control parameters obtained by Taguchi method and presented an excellent agreement with Taguchi method results.

MATERIALS AND METHODS

Sample Preparation

Si_3N_4-hBN composites sintered with 4, 8, 12 and 16% volume of hBN in Si_3N_4. The ball mill is used for mixing of Si_3N_4 and hBN. The sintering was performed at following conditions:

Uniaxial hot-pressure: 30MPa.Heating: 1600^0C, 60 min dwell time. Additive: Polyvinyl alcohol.

Wear Tester

Ducom TRLE-PMH400 pin on disc tribometer used for wear testing according to ASTM F732 standards [18]. During wear test composite used as pin specimen and ASTM 316L steel disc as counterface rotating at a speed of 200 rpm for 20 minutes duration. ASTM 316L is low carbon medical grade steel used for implant [19, 20]. Wear tests were conducted at atmospheric conditions in a dry environment.

Methodology

Taguchi method is a type of DoE applied for effective planning and conducting experiments. A Taguchi method is applied for designing experiments and evaluates how different factors affect the process performance characteristic. Knowing the number of factors and their levels, the proper orthogonal array can be selected. Table 1 shows the parameters /factors and their corresponding levels for experiments, and experiments planned according to L_{25} orthogonal array.

TABLE 1. Parameters and Levels for Experimentation

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Load (N)	5	10	15	20	25
% Vol. of hBN	4	8	12	16	0

Results and S/N Ratio Analysis

Wear volume loss calculated for sliding distance covered by pin against disc for 20 min duration at 200 rpm. Table 2 shows results of all 25 experiments and correspondingly transformed into S/N ratio. A minimum value of wear is expected to increase the joint life. Therefore in this study S/N ratio with Smaller the Better criterion was used and is calculated as follow:

$$(S/N)_{lb} = -10log_{10}((y_1^2 + y_2^2 + \cdots)/n) \quad (1)$$

Where,
y_1, y_2 and so on= experimental results/observation,
n=number of experiments (i ..n)

TABLE 2. Results for Volumetric Wear Loss (VWL) and S/N ratio

Expt. No.	Load (N)	% Vol. of hBN	Avg. Expt. Volumetric Wear Loss-VWL (mm^3/m)	S/N ratio (dB)
1	5	4	0.667	3.5165
2	5	8	0.065	23.7126
3	5	12	0.038	28.3921
4	5	16	0.421	7.5162
5	5	0	0.498	6.0503
6	10	4	0.221	13.0944
7	10	8	0.148	16.5923
8	10	12	0.065	23.6733
9	10	16	0.859	1.3196
10	10	0	1.529	-3.6906
11	15	4	0.062	24.1322
12	15	8	0.187	14.5641
13	15	12	0.0126	37.9893
14	15	16	0.483	6.3112
15	15	0	0.2615	11.6491
16	20	4	0.549	5.1947
17	20	8	0.355	8.9807
18	20	12	0.212	13.4881
19	20	16	0.944	0.4993
20	20	0	0.2061	13.7196
24	25	4	0.115	18.7642
22	25	8	0.519	5.6887
23	25	12	0.475	6.4505
24	25	16	0.786	2.0827
25	25	0	0.467	6.6092

The higher value of S/N ratio signifies the better performance irrespective of characteristics [21]. From Table 2 expt. 13 shows an optimal combination of 15N load and 12% volume of hBN for minimum wear loss with maximum value of S/N ratio of 37.9893dB.

Analysis of Variance (ANOVA)

ANOVA is performed to investigate the control factor affecting performance characteristic and percentage contribution of control factor on performance characteristic [22]. Table 3 shows ANOVA for VWL carried out at 95% level of confidence.

From ANOVA table it is significant that % volume of hBN has 35.04% effect on volumetric wear loss with load and % volume of hBN interaction has 51.89% effect on volumetric wear loss.

TABLE 3. ANOVA for Volumetric Wear Loss

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Load (N)	4	0.3921	13.06%	0.3921	0.09804
% Vol. of hBN	4	1.0519	35.04%	1.0519	0.26296
Load (N)* % Vol. of hBN	16	1.5578	51.89%	1.5578	0.09736
Total	24	3.0018	100%		

Artificial Neural Network (ANN)

Artificial neural networks are the real inspiration of nerve systems and a human brain that are known for their ability to learn and classify data. The use of ANN represents new methodology in various research fields including material science and machining of materials [14, 23]. ANNs are mostly used for pattern recognition, pattern association and classification, constrained optimization and system modeling with application ranging from signal processing to medical diagnosis [24]. Modeling of wear volume loss using the neural network consists of two phases of training and testing with experimental data. The Feed-forward back propagation type network with TRAINLM as training function used for training ANN, and 2 layers feed-forward back propagation ANN with the tangent sigmoid transfer (TANSIG) at output layer used to simulate and predict wear volume loss.

Cross Validating Training

For proper training of ANN needs a large number of data. In this case, we used cross-validate training [25] to train ANN model. From the entire 25 layouts, number 13 experimental data skipped and remained 24 experimental data used for training and testing. Every set of training data consists of 23 inputs for training and one input for testing. Table 4 shows data used to train ANN model along with results of testing.

TABLE 4. Cross validate training data and testing results

Expt. No	Training Data			Testing results
	Load (N)	% Vol. of hBN	Avg. Expt. Volumetric Wear Loss-VWL (mm^3/m)	Testing- VWL (mm^3/m)
1	5	4	0.667	0.4452
2	5	8	0.065	0.04563
3	5	12	0.038	0.02985
4	5	16	0.421	0.4433
5	5	0	0.498	1.1776
6	10	4	0.221	0.666
7	10	8	0.148	0.1149
8	10	12	0.065	0.0679
9	10	16	0.859	0.6464
10	10	0	1.529	1.3709
11	15	4	0.062	0.0621
12	15	8	0.187	0.0621
14	15	16	0.013	0.5656
15	15	0	0.484	0.0621
16	20	4	0.262	0.621
17	20	8	0.549	0.621
18	20	12	0.356	0.621
19	20	16	0.212	0.622
20	20	0	0.944	0.2061
21	25	4	0.206	0.115
22	25	8	0.115	0.5286
23	25	12	0.519	0.5294
24	25	16	0.476	0.5294
25	25	0	0.786	0.719

Confirmation Testing

To check the adequacy and fitness of trained network, confirmation test were conducted for the same condition, and results of confirmation tests are presented in Table 5 along with predicted/simulated results.

From the results of confirmation test, absolute error calculated, it found to be 27.73%. Based on results of testing and simulation, a correlation coefficient (R^2) [26] computed between experimental results and predicted results; it found to be 0.76. This shows the predictive capability of ANN model with reference to experimental results.

TABLE 5. Confirmation testing data and results

Sr. No.	Load (N)	% Vol. of hBN	Expt. VWL (mm^3/m)	Simulated VWL (mm^3/m)
1	15	12	0.013 (Expt. No. 13)	0.011
2	50	12	9.775	5.789
3	100	12	9.968	8.968
4	150	12	9.227	13.062

CONCLUSION

1. From Taguchi S/N ratio analysis and response plot, it is clear that load of 15N and 12% volume of hBN is optimum to reduce wear of silicon nitride.
2. From ANOVA analysis, it is clear that wear of silicon nitride is a outcome of interaction between % volume of hBN and load with percentage contribution on wear volume loss is about 51.89%.
3. ANN model is trained significantly using cross-validating training and testing using only 24 patterns, showing the excellent capability of prediction with a correlation coefficient of 0.94.
4. Simulation and confirmation testing results presented in Table 5, proves the applicability of Taguchi method and ANN in the field of optimization and modeling.

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