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Wear Loss Evaluation of Silicon Nitride-Hexagonal Boron Nitride Composite using Taguchi Method

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Abstract

Objective: Research in the field of bio-tribology is trying to evaluate biomaterials with minimum wear. Recently Silicon nitride (Si_3N_4) is suggested as an alternative for hip/knee joint replacement. With the addition of hexagonal boron nitride (hBN) in Si_3N_4, its wear properties can be improved.

Methods/Analysis: In this paper, an attempt has been made to evaluate the sliding wear behavior of Si_3N_4-hBN composite against alumina and steel (ASTM 316L) so as to minimize its wear loss. An attempt has been made to find the effect of hBN addition on wear performance of Si_3N_4. The experiments were conducted according to Design of Experiments (DoE)-Taguchi method to evaluate the effect hBN addition.

Findings: Taguchi analysis presents 15N load and 8% volume of hBN against alumina, while 15N load and 12% volume of hBN against steel is optimum to minimize wear loss of Si_3N_4.

Keywords: Design of experiments (DoE); Taguchi method; Silicon nitride (Si_3N_4); Hexagonal boron nitride (hBN); Alumina; Steel

Introduction

Biomaterials in body environment are expected to work satisfactorily, where the pH value of body fluid varies from 1 to 9. Friction, wear, and lubrication of artificial joints are an important consideration to optimise the performance of these man-made joints to improve its function and life. The first metal-on-metal (CoCr-CoCr) total hip replacement (THR) was unsatisfactory because of high friction forces and high rate of wear. Titanium alloys and stainless steel are frequently used in THR. The main risk with metal alloy implants is the release of metal ions due to wear and which creates an adverse effect like aseptic loosening. Therefore metal-on-UHMWPE bearing became advantages or preferable to the metal-on-metal system. Ceramic bearings were first introduced as alternatives to polyethylene (PE) bearings in THR about a decade after Sir John Charnley introduced the first durable THR with a metal-PE articulation. In 1965, the first Al_2O_3 material dedicated for hip joint was patented, and pioneering application of bio-ceramic was replacing traditional metallic femoral heads of hip prostheses using high density and pure alumina. The Al_2O_3 and ZrO_2 like oxide have a lengthy history in the field of hip and knee joint replacement providing a tougher bearing surface with low wear rate. Initially, in the engineering field, Si_3N_4 was proposed as a substitute for conventional materials in extreme operating conditions, due to its hardness, excellent chemical and stability under a broad range of temperature, low density, low thermal expansion, high specific stiffness, corrosion resistance, high elastic modulus and low friction properties [1]. Biocompatibility and material properties of Si_3N_4 have made it attractive alternative in the biomedical field also [2]. Bearings made of ceramics have low wear properties that make them a suitable alternative for total hip arthroplasty (THA) and total knee arthroplasty (TKA). When compared to cobalt chrome (CoCr)-on-polyethylene (PE) articulations, ceramics offer drastic reductions in bearing wear rates. Alumina and zirconia ceramics are familiar with the orthopaedic field in total joints for several decades [3]. Currently, Si_3N_4 is applicable in the biomedical field for various applications like bearing for spine disc surgery and prosthetic hip and knee joints also been developed with Si_3N_4 [4,5]. Bal & Rahaman [6] covered scientific rationale for the use of Si_3N_4 in the orthopaedic application.

Hexagonal boron nitride (hBN) is solid situ lubricating material with biocompatibility [7-9]. Incorporating solid lubricant in Si_3N_4 can be considered for improving the tribological performance of Si_3N_4 by the formation of an oxide of hydrated layers (H3BO3 and BN(H2O)x) has a significant effect on the tribological performance of Si_3N_4-BN composites, reducing the wear coefficient. Carrapichano et al. [10] conducted sliding wear test on pin-on-disc tribometer for Si_3N_4-BN composite in a self-mated pair, with 10, 18 and 25% vol. of BN in Si_3N_4. They concluded that addition of Boron up to 10% improved tribological properties of Si_3N_4 and further addition affect to mechanical properties of Si_3N_4. Chen et al. [11] investigated sliding wear behaviour of the Si_3N_4-hBN composite with 0, 5, 10, 20 and 30 volume % of hBN in Si_3N_4 against Si_3N_4 using pin-on-disc (PoD) tribometer. They reported that friction coefficient reduces up to 0.19 for 20% volume of hBN in Si_3N_4.

Materials and Methods

DOE-Taguchi methodology

Taguchi method is a form of DOE developed by Genichi Taguchi used for planning experiments and to investigate how different parameters affect the mean and variance of a process performance characteristic [12]. Ferit et al. [13] analysed the wear behaviour of boronised AISI 1040 steel effectively using DOE-Taguchi design method. Amar et al. [14] implemented DOE-Taguchi design technique to evaluate the tribo-performance of polyesterhybrid composites. The result presented that glass-polyester composite without any filler suffers greater erosion loss than the hybrid composite with alumina filling. Lastly, the results were optimized using a genetic algorithm. Iihan & Suleyman [15] optimised turning parameters in CNC turning using Taguchi method and response surface analysis, presented efficiency and effectiveness of Taguchi method in the field of optimization. The experimental design proposed by Taguchi involves the use of orthogonal arrays to organize the control factors affecting the process and the levels at which they should be varied. It allows for the collection of the necessary data to determine which factors affect product quality significantly with a minimum number of experiments, saving time and resources. With knowledge of a number of parameters and the number of levels, the proper orthogonal array can be selected. The parameters /factors and their corresponding levels selected for the experiment as shown in Table 1.

Load and % volume of hBN are two factors chosen at five levels as shown in Table 1. Therefore L_{25}(level^{factor}= 5^2) orthogonal array selected using Minitab 17 software for conduction of experiment. The orthogonal array provides a set of well-planned experiment with the minimum number.

Table 1: Designed experimental factors and levels.

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

Preparation of samples

Si_3N_4-hBN composites prepared with 4, 8, 12 and 16% volume of hBN mixed in Si_3N_4. The mixing of Si_3N_4 and hBN is performed with a ball mill. The pin samples were prepared at uni-axial hot-pressing at 30MPa, 1600 °C and 60min dwell time with dimensions of 10mm diameter and 15mm long. Table 2-4 shows the properties of sintered specimens, properties of alumina disc and steel disc respectively.

Table 2: Properties of sintered sample*

Sample	1 (4% hBN)	2 (8% hBN)	3(12% hBN)	4(16% hBN)	5 (0% hBN)
Density (gm/cc)	1.96	1.96	1.93	1.84	2.04
Vickers Hardness (MPa)	2775.88	2318.17	1741.07	907.96	7484.51

*Testing at Central Glass and Ceramic Research Institute, Kolkata (India)

Table 3: Typical Mechanical Properties of Alumina disc.

Designation	Purity	Density (gm/cc)	Max. Service Temp. (oC)	Avg. Surface Roughness (µm)
Alumina (Al_2O_3)	99.80%	3.9	1800	1.791

Table 4: Typical Mechanical Properties of Steel disc.

Designation	Density (gm/cc)	Mod. of Elast. (GPa)	Mean Coeff. of Therm Exp. (10^{-6}/K)	Avg. Surface Roughness (µm)
Steel	7.95	186.4	18.5	0.242
ASTM 316L				

Experimental setup

The wear tests were conducted on Ducom TRLE-PMH400 pin on disc tribo meter having a maximum normal load capacity of 200N. Tests were performed according to ASTM F732 standards [16]. During wear test composite used as pin specimen against alumina disc and steel disc as counter face rotating at a speed of 200rpm (each test conducted for two times). Tests were performed at room temperature in a dry environment without lubricant condition.

Results

Signal-to-Noise (S/N) ratio analysis

Experiments were carried out on Pin-on-Disc tribo meter with two input parameters and wear volume loss of a sample as

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output. Wear volume loss calculated for sliding distance covered by pin during 20min duration and speed of disc 200rpm at corresponding wear track diameter. Table 5 shows the average value of volumetric wear loss (VWL) for all 25 experiments (each experiment conducted two times). The experimental results are further transformed into Signal-to-Noise (S/N) ratio. Taguchi's S/N ratios, which are logarithmic, the function of desired output and serves as an objective function for optimization. The standard S/N ratios used are: Smaller is Better (SB), Nominal is Better (NB), and Higher is Better (HB). The significance of controllable factor is investigated using S/N ratio approach. A smaller of wear volume loss is expected to extend joint life. Therefore in this study S/N ratio with Smaller the Better methodology was used for wear volume loss and calculated as follow:

Table 5: Results for Volumetric Wear Loss (VWL) and S/N ratio.

Expt. No.	Load (N)	% Vol. of hBN	Avg. Vol. Loss Against Alumina (mm3/m)	S/N Ratio (dB)	Avg. Vol. Loss Against steel (mm3/m)	S/N Ratio (dB)
1	5	4	0.302	10.39	0.667	3.516
2	5	8	0.199	14.02	0.065	23.71
3	5	12	0.244	12.23	0.038	28.39
4	5	16	0.033	29.43	0.421	7.516
5	5	0	0.505	5.926	0.498	6.05
6	10	4	0.201	13.95	0.221	13.09
7	10	8	0.015	36.13	0.148	16.59
8	10	12	0.143	16.84	0.065	23.67
9	10	16	0.021	33.78	0.859	1.319
10	10	0	1.086	-0.72	1.529	-3.69
11	15	4	0.314	10.06	0.062	24.13
12	15	8	0.011	39.09	0.187	14.56
13	15	12	0.103	19.75	0.012	37.98
14	15	16	0.095	20.42	0.483	6.311
15	15	0	1.347	-2.58	0.262	11.65
16	20	4	0.206	13.71	0.549	5.195
17	20	8	0.502	6.016	0.356	8.98
18	20	12	2.279	-7.15	0.211	13.48
19	20	16	0.203	13.83	0.944	0.499
20	20	0	0.316	9.982	0.206	13.72
21	25	4	0.514	5.777	0.115	18.76
22	25	8	2.11	-6.48	0.519	5.668
23	25	12	0.414	7.651	0.475	6.451
24	25	16	0.155	16.18	0.786	2.08
25	25	0	4.12	-12.2	0.467	6.609

$$\left(S/N\right)_{LB} = -10\log_{10}\left(\left(y_1^2+y_2^2+\ldots\right)/n\right) \quad (1)$$

Where,

y_1, y_2 and so on = Experimental results/observation.

n= Number of experiments (i……… n).

Irrespective of the category of the performance characteristic, the higher value of S/N ratio corresponds to a better performance [17]. The maximization of S/N ratio signifies maximization of the desired effect against noise factor. In this study minimization of wear volume loss is a desirable characteristic. Observation of response table of S/N ratio gives an optimal combination of input parameters for required output characteristic.

Response plot

Interaction plot represents interaction effect of control factors: load and % volume of hBN on performance characteristic i.e. Volumetric wear loss.

Wear performance of composite against alumina: Figure 1 shows the minimum value of VWL at the interaction of 15N load and 8% volume of hBN and the maximum value of S/N ratio at same combination in Figure 2.

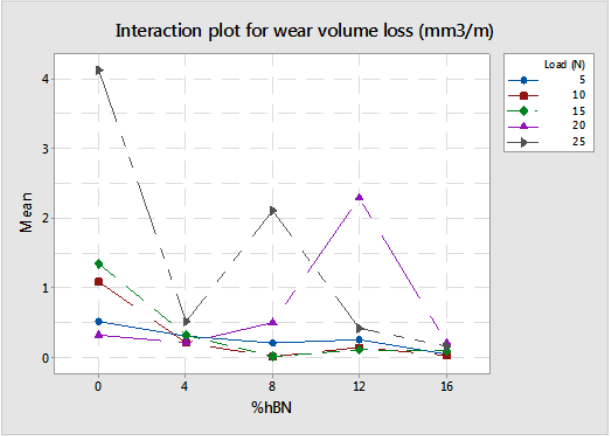

Figure 1: Interaction Plot for Volumetric Wear Loss (mm³/m).

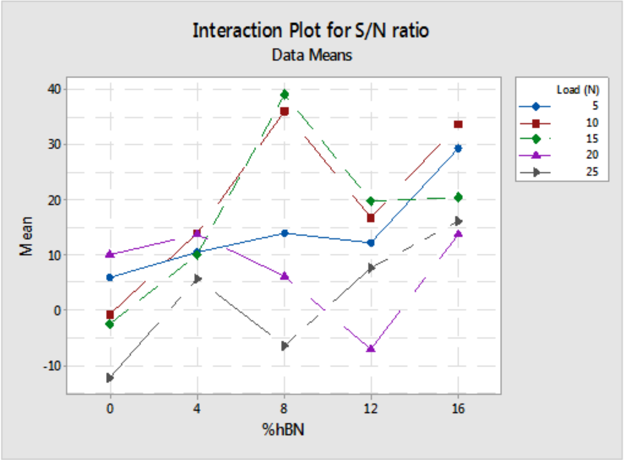

Figure 2: Interaction Plot of S/N ratio for Volumetric Wear Loss.

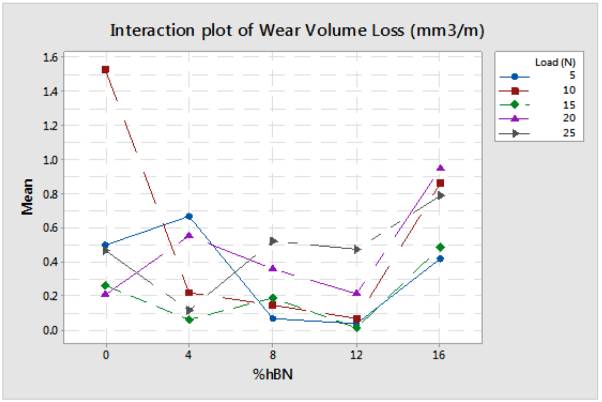

Figure 3: Interaction Plot for Volumetric Wear Loss (mm³/m).

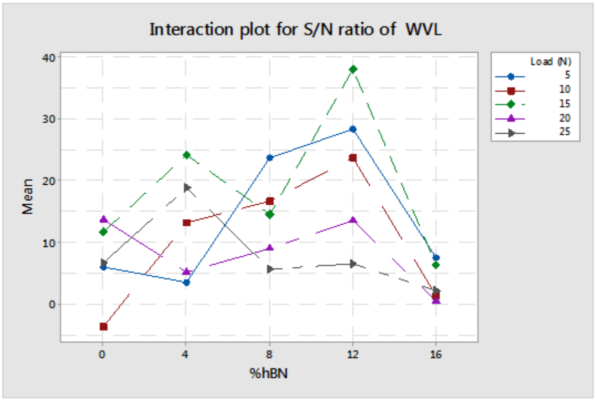

Figure 4: Interaction Plot of S/N ratio for Volumetric Wear Loss.

Wear performance of composite against steel: Figure 3 shows the minimum value of VWL at the interaction of 15N load and 12% volume of hBN and the maximum value of S/N ratio at same combination in Figure 4.

Analysis of variance (ANOVA)

ANOVA is statistically based, objective decision- making a tool for detecting any difference in average performance of groups of items tested. It was developed by Sir Ronald Fisher in the 1930's as a way to interpret the results from agricultural experiments [18]. ANOVA is a statistical technique which breaks total variation down into accountable sources; total variation is decomposed into its appropriate components. This technique determines the variability (variance) in data rather than analysis of data. Table 6 & 7 presents ANOVA table for wear testing against alumina counter face and steel counter face respectively.

Table 6: ANOVA table for wear testing against alumina counter face.

Source	DF	Seq. SS	% Contr.	Adj. SS	Adj. MS
Load (N)	4	5.075	23.51	5.075	1.2687
% Vol. of hBN	4	5.05	25.48	5.0501	1.3752
Load* % Vol. of hBN	16	11.012	51.01	11.012	0.6882
Error	0	---	----	----	
Total	24	21.58	100		

Table 7: ANOVA table for wear testing against steel counterface.

Source	DF	Seq. SS	% Contr.	Adj. SS	Adj. MS
Load (N)	4	0.3921	13.06	0.3921	0.098
% Vol. of hBN	4	1.0519	35.04	1.0519	0.2629
Load* % hBN	16	1.5578	51.89	1.5578	0.0973
Error	0	---	---	---	
Total	24	3.001	100		

In ANOVA table [19]:

The degree of freedom (DF) is a measure of amount independent information available from given set of data. DF for concerning factor is one less than the number of levels.

The sequential or adjusted sum of squares (Seq SS/Adj SS) of factor measures the variability in data contributed by that factor. Total SS is SS of an individual factor and SS of error.

$$S_{eq}SS_{factor} = \sum n_i(\bar{y}_i - \bar{y})^2 \quad (2)$$

$$S_{eq}SS_{total} = \sum_i \sum_j (y_{ij} - \bar{y}_t)^2 \quad (3)$$

$$S_{eq}SS_{total} = \sum_i \sum_j (y_{ij} - \bar{y})^2 \quad (4)$$

Where mean of all observations at ith factor level, mean of all observations, yij value of jth observation at the ith factor level, ni number of observations for the ith factor level.

Wear performance of composite against alumina: from ANOVA table 51.01% contribution is due to combined effect of load and % volume of hBN while alone % volume of hBN has 25.48% contribution to wear performance.

Wear performance of composite against steel: from ANOVA table 51.89% contribution is due to combined effect of load and % volume of hBN while alone% volume of hBN has 35.04% contribution to wear performance.

Conclusion

From the study undertaken on the influence of load and % volume of hBN addition on the room temperature wear

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performance of silicon nitride against alumina and steel, the following conclusions can be drawn:

1. The hBN addition has a significant effect on the wear rate of silicon nitride sliding against alumina as well as steel also.
2. 15N load and 8% volume ofhBN volume of hBN in Si_3N_4 is the optimum combination to minimize wear rate of Si_3N_4 against alumina counter face.
3. 15N and 12% volume ofhBN in Si_3N_4 is the optimum combination to minimize wear rate of Si_3N_4 against steel counter face.
4. ANOVA result shows that interaction of load and % volume of hBN in Si_3N_4 has a significant effect on wear rate followed by % volume of hBN.
5. Si_3N_4-hBN has proposed an alternative for hip/knee joint replacement, from experimental analysis it is clear that suitable combination of load and hBN addition should be considered for replacement of joint.

References

1. Dill JF (1996) Hybrid Bearing Technology for Advanced Turbomachinery: Rolling Contact Fatigue Testing. Jr Eng Gas Turbine Power 118(1): p. 6.
2. Howlett CR, McCartney E, Ching W (1989) The effect of silicon nitride ceramic on rabbit skeletal cells and tissue. An *in vitro* and *in vivo* investigation. Clin Orthop Relat Res 244: 193-204.
3. Bal BS, Garino J, Rises M, Rahaman MN (2007) A review of ceramic biomaterials in total Joint Arthroplasty. Hip Int 17(1): 21-30.
4. Neumann A, Unkle C, Werry C, Herborn CU, Maier HR, et al. (2006) Prototype of silicon nitride ceramic based mini plateosteofixation system for midface. Otolaryngology Head and Neck Surgery 134: 923-930.
5. Bal BS, Khandekar A, Lakshmi NR, Clarke I, Hoffman AA, et al. (2008) Testing of silicon nitride ceramic bearing for total hip Arthroplasty. J Biomed Mater Res B Appl Biomater B 87(2): 447-54.
6. Bal BS, Rahaman MN (2012) Orthopedic applications of silicon nitride ceramic. Acta Biomaterialia 8(8): 2889-2898.
7. Gangopadhyay A, Jahanmir S, Peterson MB (1997) Self-lubricating ceramic matrix composites. In: Jahanmir S (Edt.), Friction and Wear of Ceramics, Marcel Dekker, New York, USA, pp.163-197.
8. Saito T, Imada Y, Honda F (1999) Chemical influence on wear of Si_3N_4 and hBN in water. Wear 236: 153-158.
9. Faiz US, Sergei G, Oleg NA (2013) Boron in Tribology: from borates to ionic liquids. Tribology Letters 51(3): 281-301.
10. Carrapichano JM, Gomes JR, Silva RF (2002) Tribological behaviour of Si_3N_4-BN ceramic material for dry sliding applications. Wear 1070-1076.
11. Wei C, Yimin G, Yong W, Huango QL (2010) Tribological behaviour of Si_3N_4-hBN ceramic materials without lubrication under different test modes. Tribology Transactions 53(6): 787-798.
12. Jiju Antony (2008) Design of Experiment. Elsevier Ltd., (1st edn).
13. Ferit F, Murat K, Mesul D (2011) Application of Taguchi design method to study wear behavior of boronized AISI 1040 steel. International Journal of the Physical Science 6(2): 237-243.
14. Patnaik A, Alok S, Mahapatra SS, Dash RR (2009) Tribo-performance of polyester hybrid composite: damage assessment and parameter optimization using Taguchi design. Materials and Design 30: 57-67.
15. Iihan A, Suleyman N (2010) Multi-response optimization of CNC turning parameters via Taguchi method- based response surface analysis. Measurement 45: 785-794.
16. ASTM F732-00 (2011) Standard Test Method for Wear Testing of Polymeric Materials Used in Total Joint Prostheses,American Society for Testing of Materials, Annual book of ASTM standards 212-217.
17. Kamaruddin S, Zahid AK, Foong SH (2010) Application of Taguchi method in the optimization of injection moulding parameters for manufacturing products from plastic blend. IACSIT International Journal of Engineering and Technology 2(6): 574-580.
18. Philip JR (2005) Taguchi Techniques for Quality Engineering. (2nd edn), Tata McGraw-Hill Publishing Company Limited, New Delhi, India.
19. Sachin G, Ankush M, Bhalerao YJ (2016) Optimization of wear loss in silicon nitride (Si_3N_4)-hexagonal boron nitride (hBN) usingDoE-Taguchi method. Springer Plus 5(1): 1671.