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WEIGHT LOSS FUNCTIONS FOR TOLERABLE WEAR RATE OF AA1100/BN METAL MATRIX COMPOSITES

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ABSTRACT

In this study, the effects of BN amount on hardness and wear behaviors of AA1100-BN composites produced by stir casting route were investigated. Within the scope of work, different amount of BN (10, 20 and 30%) added to AA1100 matrix. Wear tests were performed in a pin on type wear apparatus under 10,20, 30 N with different sliding speeds 2, 3 and 4 m/s, at three different sliding distances (500, 750 and 1000 m). A plan of experiments in terms of Taguchi technique is carried out to acquire data in controlled way. An orthogonal array (L9) and the analysis of variance are employed to investigate the influence of process parameters on the wear of these composites. Weight loss functions were designed to determine the lower and upper safety limits of wear rate based on 87th percentile of Weibull probability tests. It was found that in terms of weight loss, there was a good agreement between the theoretical and the experimental value of wear rate with an error of 1.014%. Moreover, volume fraction of BN, applied load, sliding speed and sliding distance exerted the tolerable wear rates of 0.01441, 0.01490, 0.01286 and 0.01535 mg/m, respectively.

Key words: AA1100, applied load, boron nitride, sliding distance, sliding speed, volume fraction of reinforcement, wear, Weibull probability, weight loss function

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1. INTRODUCTION

Particulate reinforced aluminum matrix composites are attractive materials due to their strength, ductility and toughness [1]. In these composites, various carbides, oxides and nitrides such as SiC [2], B_4C [3], Al_2O_3 [4], Si_3N_4 [5], AlN [6] have been used as reinforcement phase. The composites have been considered as potential application in the tribological field for such as piston, rotor brake and cylinder liner [7, 8]. The dry sliding of aluminum matrix composites has been widely studied. It is well known that hard ceramic particles improve wear resistance as compared to unreinforced matrix material [9, 10]. The wear rate is related to sliding velocity, particle size, hardness, and normal load, chemical composition of the matrix material, particle volume fraction and particle homogeneity [11]. Rhee [12] found that the total wear of a polymer-matrix is a function of the applied load F, speed V and sliding time t according to

$$\Delta W = KF^{a}\mathrm{V}^{\mathrm{b}}\mathrm{t}^{\mathrm{c}} \tag{1}$$

Where ΔW is the weight loss of the friction material and K, a, b and c are empirical constants. F is the applied load; v is the sliding speed; and t is the sliding time. In earlier work, the author [13] has defined the total wear of a metal matrix composite as a function of reinforcement volume fraction, applied load, sliding speed and sliding distance according to

$$W = K{v_f}^{a}F^{b}V^{c}S^{d} \tag{2}$$

where a, b, c and d are power law coefficients of reinforcement volume fraction (v_f), applied load (F), sliding speed (V) and sliding distance (S), respectively. K is the empirical constant.

In this study, AA1100–BN composites were fabricated by stir casting route by adding BN reinforcement phase at different proportions, and the effect of the reinforcement phase amount on the wear behavior of the composites was investigated. In order to find the tolerable wear rate based on weight loss functions and the probability statistical tests, the wear tests were performed on pin-on-disc equipment. The design of experiments was based on Taguchi techniques [14].

2. MATERIALS AND METHODS

The matrix material was AA1100. The reinforcement material was boron nitride (BN) nano particles of average size 100nm. AA1100/BN composites were fabricated by the stir casting process and low pressure casting technique with argon gas at 3.0 bar. The composite samples were given H18 heat treatment. The heat-treated samples were machined to get cylindrical specimens of 10 mm diameter and 30 mm length for the wear tests. The levels chosen for the controllable process parameters are summarized in Table 1. The orthogonal array, L9 was preferred to carry out wear experiments (Table 2). A pin-on-disc type friction and wear monitor (ASTM G99) was employed to evaluate the friction and wear behavior of AA1100/BN composites against hardened ground steel (En32) disc. Knoop microhardness was conducted before and after wear tests. Optical and scanning electron microscopy analyses were also carried out to find consequence of wear test AA1100/BN composite specimens.

Table 1 Wear parameters and levels

Factor	**Symbol**	**Level–1**	**Level–2**	**Level–3**
Reinforcement, Vol.%	A	10	20	30
Load, N	B	10	20	30
Speed, m/s	C	2	3	4
Sliding distance, m	D	500	750	1000

Table 2 Orthogonal array (L9) and Control Parameters

Treat No.	**A**	**B**	**C**	**D**	**S/N ratio, dB**
1	1	1	1	1	17.86866
2	1	2	2	2	17.23976
3	1	3	3	3	16.71213
4	2	1	2	3	16.95646
5	2	2	3	1	17.59566
6	2	3	1	2	16.83625
7	3	1	3	2	17.32163
8	3	2	1	3	16.34569
9	3	3	2	1	17.11156

3. RESULTS AND DISCUSSION

The normal distribution for the volume fraction of BN, applied load, sliding speed and sliding distance on the wear rate is shown in Fig.1. The shape of the distribution is known as a normal distribution. This graph says the wear rate of 0.014 mg/m is much more likely to occur for the process variables chosen in the present work. The applied load and sliding distance can cause the wear rate in the range of 0.012 to 0.016 mg/m, while volume fraction of BN and sliding speed in the range of 0.013 to 0.015 mg/m. If the width of the normal distribution is wide, the wear rate is high for the variable under consideration.

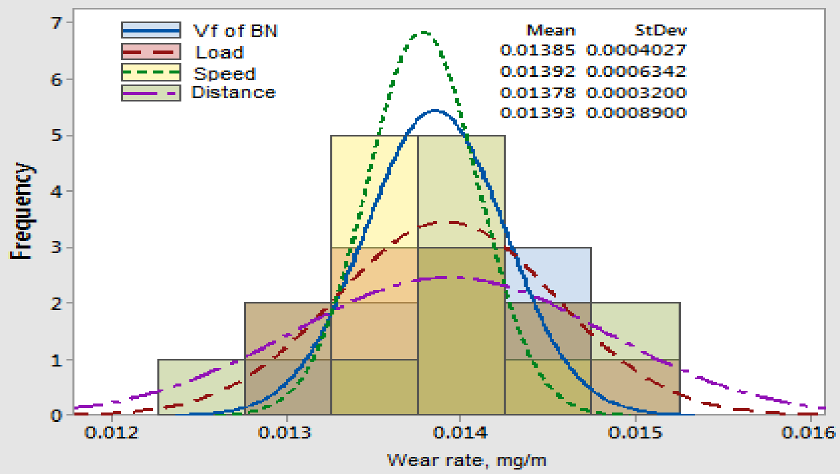


Figure.1 Normal Distribution of Process Variables on Wear Rate.

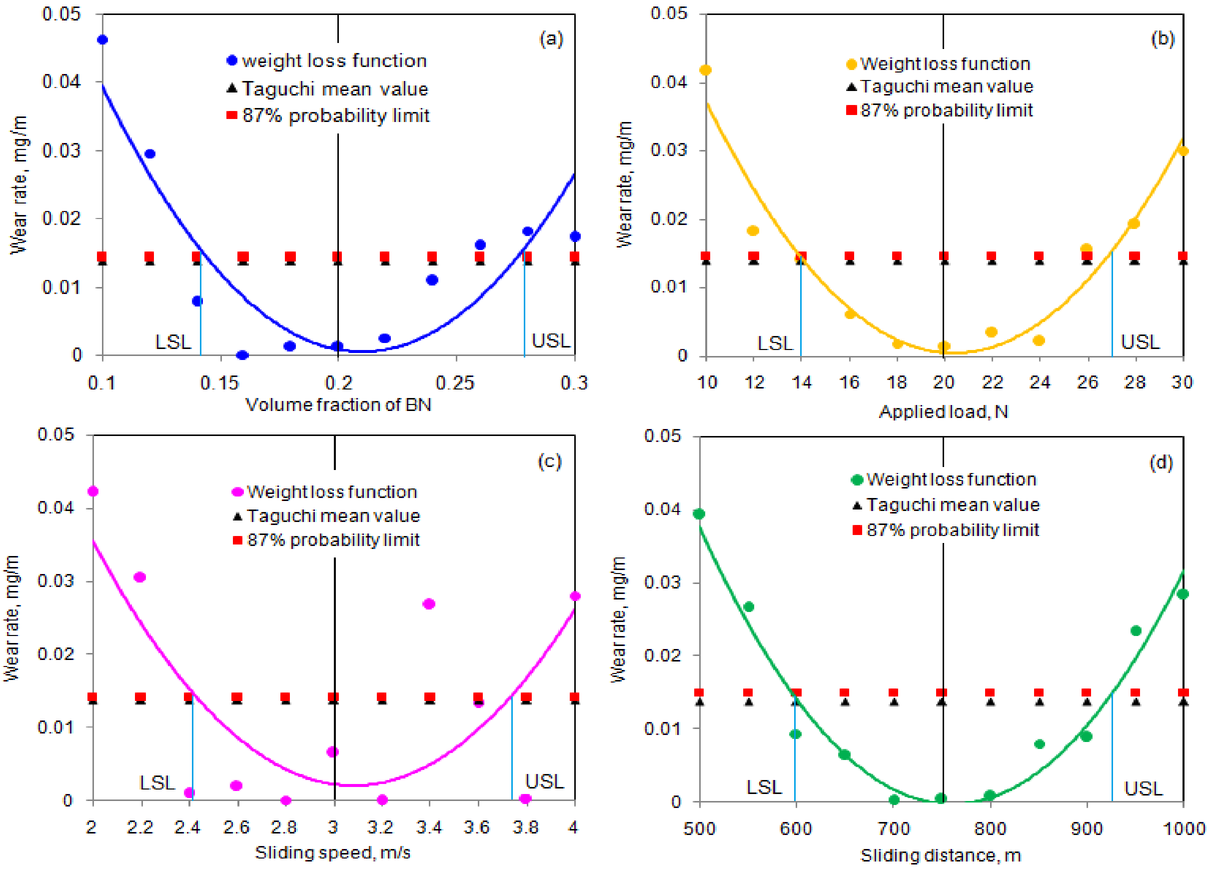


Figure.2 Weight Loss Functions: (a) Reinforcement, (b) Applied Load, (c) Sliding Speed and (d) Sliding Distance.

3.1. Weight Loss Functions

The Taguchi loss function quantifies the variability present in a process. For the AA1100/BN composites, the weight loss function is constructed using the wear rate as a reference value. The weight loss function is as follows:

$$W_L = k\left(W_y - W_m\right)^2 \qquad (3)$$

In this equation, W_L is the loss associated with a particular weight value W_y, W_m is the nominal value of the specification, and the value of k is a constant depending on the wear rate at the specification limits and the width of the specification. The weight loss associated with any AA1100/BN composite can be computed depending on the values of applied load, sliding speed, sliding distance and volume fraction of BN. For the variables mentioned in the present work, the weight loss functions are constructed as shown in Fig.2. If the AA1100/BN composite reaches the end of the operating line with wear rate exceeding the upper safety limit (USL) or lower safety limit (LSL), the composite should be scrapped. The average wear rates per variable are 0.01368, 0.01396, 0.01372 and 0.01381 mg/g of volume fraction of BN, applied load, sliding speed and sliding distance, respectively.

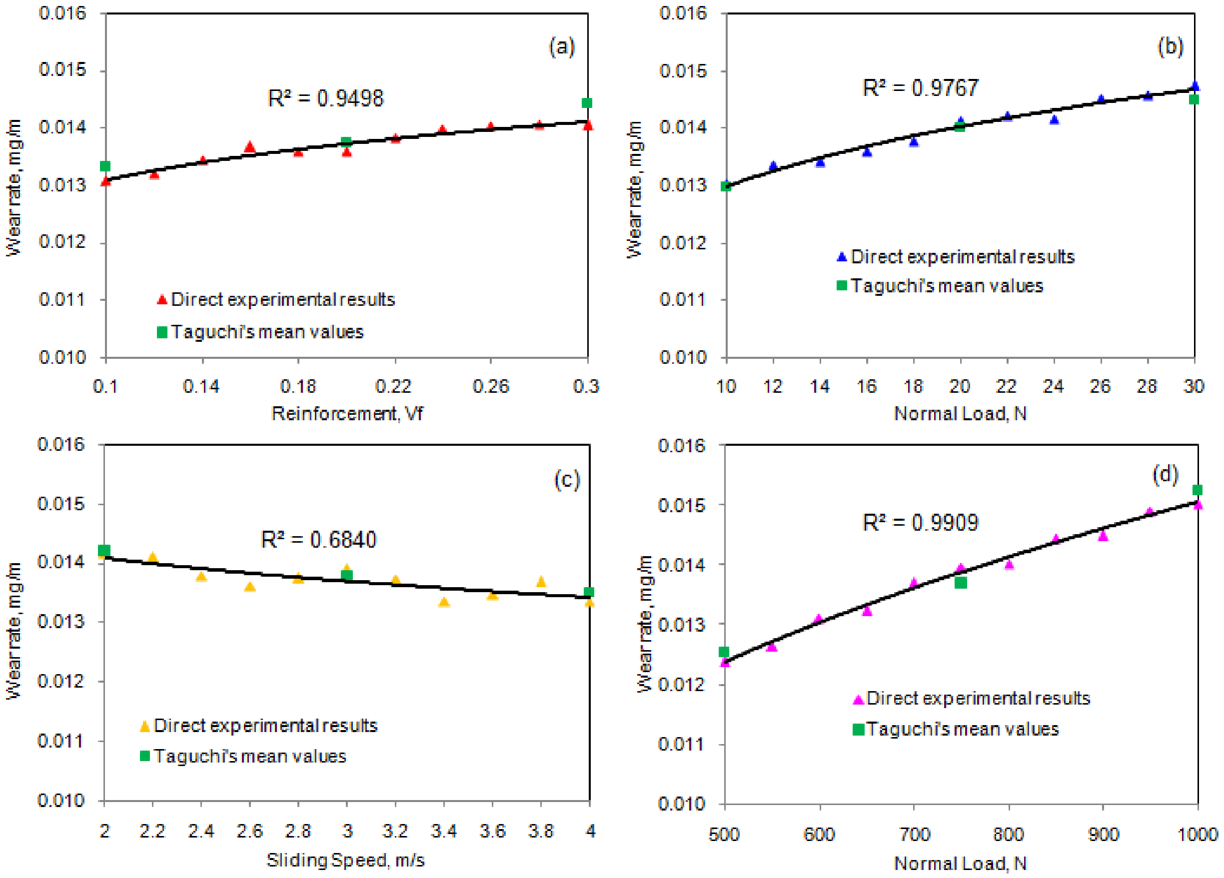


Figure.3 Influence of Individual Process Parameters on Wear Rate (keeping other Parameters at Level-2).

3.2. Effect of Reinforcement, Normal Load, Sliding Speed, Sliding Distance on Wear Rate

The wear rate is increased with increase volume fraction of BN in AA1100 matrix (Fig.3a). The knoop hardness values are 56 and 45, respectively, for AA1100 and BN. The Knoop hardness was conducted on AA1100/BN composite specimens (Fig.4) before and after wear tests. The hardness values decrease after wear test. The decrease in hardness may be attributed to the reinforcement effect of BN and work hardening during wear test on the pin-on-disc machine. As seen from Fig.3b, an increase in wear rate is with increase of applied load on the test specimen. This is because at higher load, the frictional thrust increases, which results in increased debonding and sub-surface fracture. Adhesion behavior is caused by welding due to rubbing between the opposing asperities on the rubbing surfaces of the counter bodies. When the applied load to the contacting asperities is increased, the AA1100 matrix material deforms and adheres to the steel disc forming micro-joints. During motion of the rubbing counter bodies the BN nanoparticles in the composite result in rupture of the micro-joints. Thus some of the material is transferred by the counter body as shown in Fig.5. This effect is called scuffing. The wear rate decreases with increase in sliding speed for the composites (Fig.3c). At high sliding speeds, the wear process was associated with a breakdown of the tribolayer, with wear being controlled by sub-surface cracking (Fig.6). An increase of the surface temperature is also found with the increasing sliding speed, which is ascribed to frictional heating at high sliding speeds. The reduction of wear rate is also due to the increase in coefficient of friction with increasing sliding speed. At high speeds, the slip phenomenon appearing between the pin and the abrasive disc lowers the wear rate. It is also observed from Fig.3d that the wear rate was proportional to the sliding distance. It is observed that with increasing the load and sliding distance, the penetration of hard asperities of the counter surface to the softer pin surface increases and the deformation and fracture of asperities of the softer surface increases.

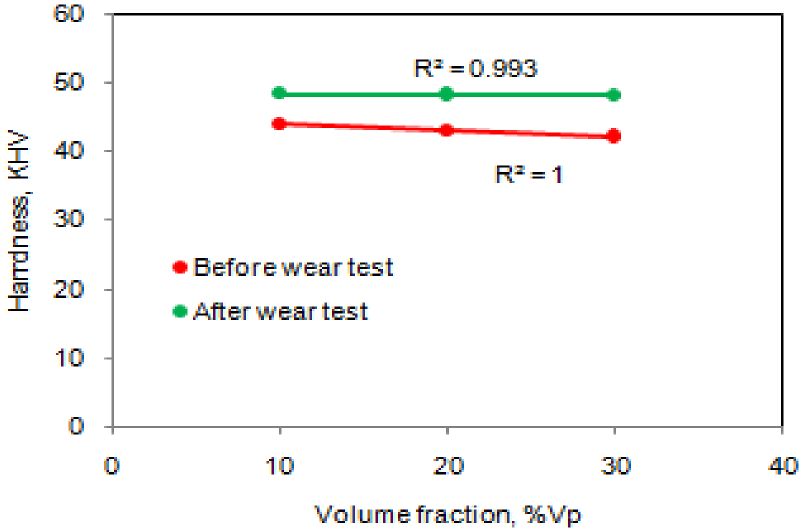


Figure.4 Hardness of AA2024/ZrO_2 Composites after Wear Test.

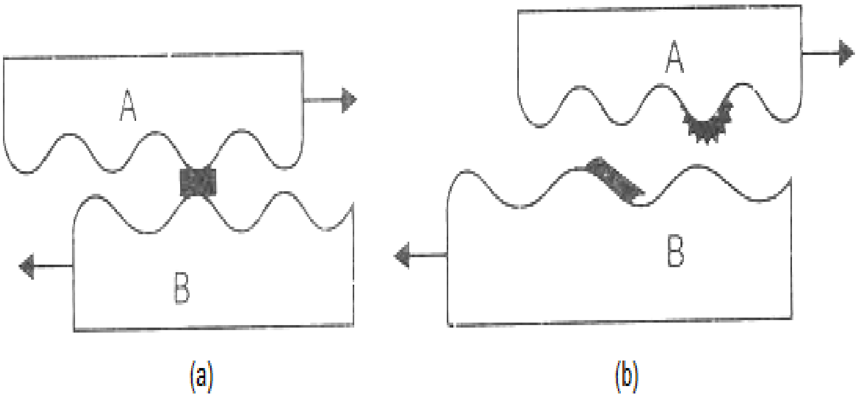


Figure.5 Scuffing Effect

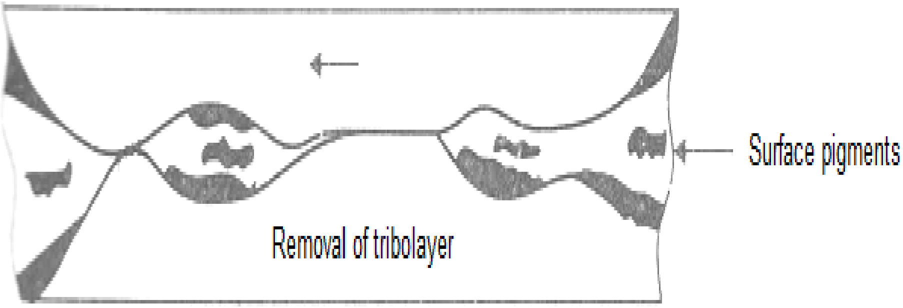


Figure.6 Breakdown and Removal of Tribolayer

The analysis of variance (ANOVA) is presented in Table 3. The percent contribution indicates that the sliding distance (factor D), all by itself contributes 62.93% of variation observed. The applied load (factor B) produces 20.76% variation in the wear rate. The volume fraction of BN (factor A) affords 10.38% variation in the wear rate. The sliding speed (factor C) imposes 4.32% of variation in the wear rate. The R-squared values of %reinforcement, normal load, sliding speed and sliding distance are, respectively, 0.9498, 0.9767, 0.6840 and 0.9909. The relative amounts the percent contributions for the factors are in direct agreement with the slopes of the curves shown in Fig.3 and with the trend of R-squared values.

Table 3 ANOVA Summary of the Wear Rate

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	7.99E-02	8.24E-02	8.65E-02	3.65E-06	2	1.83E-06	29.04	10.38
B	7.78E-02	8.41E-02	8.69E-02	7.31E-06	2	3.65E-06	58.10	20.76
C	8.52E-02	8.27E-02	8.09E-02	1.52E-06	2	7.61E-07	12.10	4.32
D	7.52E-02	8.22E-02	9.14E-02	2.21E-05	2	1.11E-05	176.08	62.93
e	-	-	-	5.66E-07	9	6.29E-08	-	0.00
T	3.18E-01	3.31E-01	3.46E-01	3.52E-05	17	-	-	100.00

Note: SS is the sum of square, v is the degrees of freedom, V is the variance, F is the Fisher's ratio, P is the percentage of contribution and T is the sum squares due to total variation.

3.3. Mathematical Modeling and Probability Analysis of Wear Rate

The mathematical relation between wear and volume fraction of reinforcement, applied load, sliding speed and sliding distance are obtained by curve fitting in terms of power laws as follows:

$$W_{rp} = 0.0012^{-0.7044} \quad (4)$$

$$W_{rf} = 0.0003F^{0.1632} \quad (5)$$

$$W_{rn} = 0.0062V^{-0.2437} \quad (6)$$

$$W_{rd} = 0.0002S^{0.4496} \quad (7)$$

where,

W_{rp} is the wear rate due to vol.% of reinforcement (v_f), mg/m
W_{rf} is the wear rate due to normal load (F), mg/m

W_{rn} is the wear rate due to speed (V), mg/m
W_{rd} is the wear rate sliding distance (S), mg/m.

These individual relations are combined to get over-all equation as follows:

$$W = K{v_f}^a F^b V^c S^d \tag{8}$$

The values of power law coefficients a, b, c and d are, respectively, -0.6035, 0.1825, -0.1449 and 0.4038 from "equations (4) to (7)". By substituting the representative values of V_f, F, N and S and their corresponding power law coefficients on the right side of "equation (8)" and substituting the experimentally obtained wear rates on the left side of "equation (9)", the value of K is determined. The over-all wear rate (mg/m) equation for AA3003/TiN composites is given by

$$W = 4.718 \times 10^{-5}\left({v_f}^{-0.7044} F^{0.1632} V^{-0.2437} S^{0.4496}\right) \tag{9}$$

There is a good agreement between the experiment results and theoretical results obtained from "equation (9)" as shown in Fig.8. In both the cases, the values of trial 8 fall beyond 87th percentile as a consequence of sub-surface cracking and particle debonding.

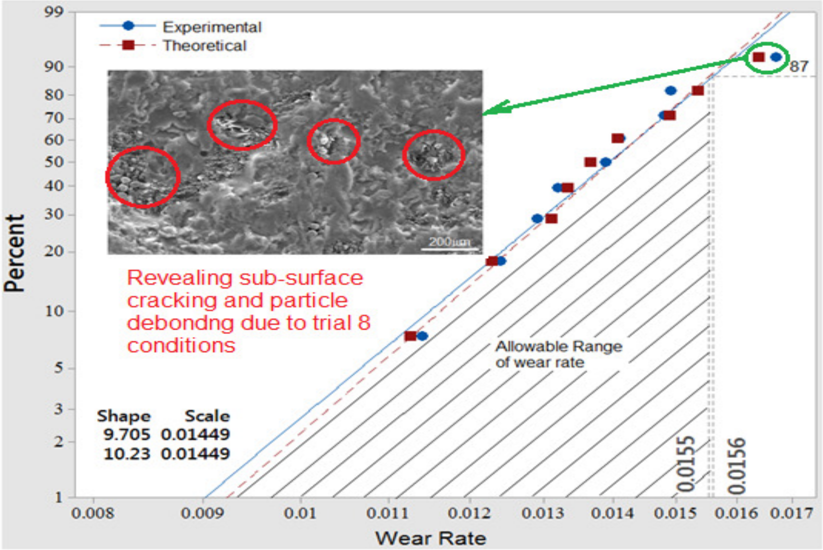
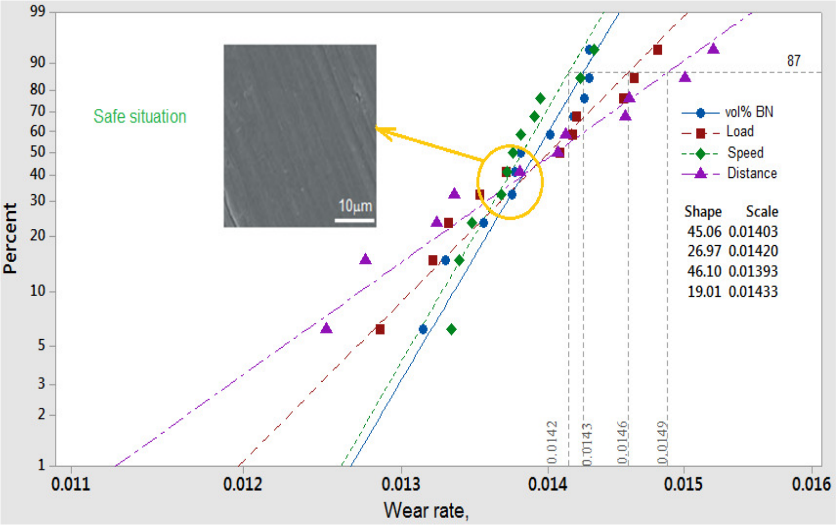


Figure.8 Comparison of experimental and Theoretical Values of Wear Rate.



Figuew.9 Probability Analysis.

The 87th percentile is used as a benchmark for the probability analysis. The probability plots were created for each treatment by fitting with normal distributions and also estimated the 87th percentile for each population as shown in Fig.9. The estimated 87th percentiles for each population are:

- 0.0143 for the volume fraction of BN,
- 0.0142 for the sliding speed,
- 0.0146 for the applied load and
- 0.0149 for sliding distance.

The estimated 87th percentiles indicate the merit of the factors A, B, C and D on the wear rate. This order is also same as that obtained from ANOVA. For the tolerance of 0.025 and with respective shape and scale factors (Fig.9) obtained by the Weibull probability analysis for the factors, the upper and lower safety limits are obtained by the binomial distribution. The lower and upper safety limits for the volume fraction of BN are, respectively, 0.01290 and 0.01441 mg/m (Fig.10a). The lower and upper safety limits for the applied load are, respectively, 0.01239 and 0.01490 mg/m (Fig.10b). The lower and upper safety limits for the sliding speed are, respectively, 0.01286 and 0.01433 mg/m (Fig.10c). The lower and upper safety limits for the sliding distance are, respectively, 0.01181 and 0.01535 mg/m (Fig.10d).

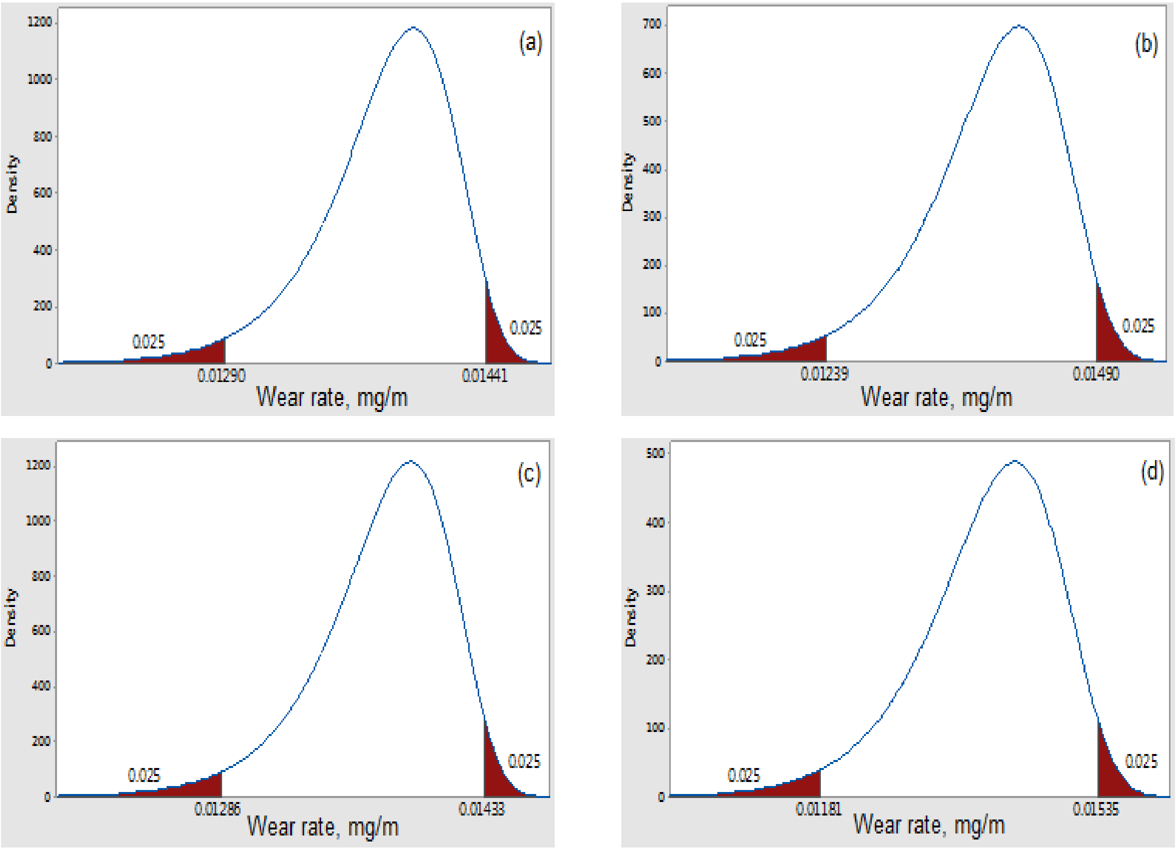


Figure.10 Weibull Distributions

4. CONCLUSIONS

The results derived from the predicted mathematical model could match with those results acquired from the wear tests. At 87th percentile of Weibull probability, the tolerable upper safe limits of wear rate are, respectively, 0.01441, 0.01490, 0.01286 and 0.01535 mg/m for volume fraction of BN, applied load, sliding speed and sliding distance. The wear resistance of the composite is significantly improved, as compared with the base alloy owing to self-lubricant behavior of BN. The wear rate of the composites is very sensitive to the volume fraction of boron nitride.

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