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Probability Analysis Based on Normal Distribution for Optimistic Wear Rate of AA2024/Zirconia Metal Matrix Composites

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ABSTRACT : *The effect of zirconia) on dry sliding wear behavior of 2024 aluminum alloy has been experimentally investigated. AA2024/ZrO_2 metal matrix composites were fabricated with ZrO_2 nanoparticles in 10%, 15%, 20% and 30% based on volume fractions using a stir casting technique. The dry sliding wear tests were conducted using pin-on-disc wear test machine. Tests were conducted at different applied loads, sliding distances and sliding times. The results reveal that incorporation of zirconia nanoparticles leads to significant improvement in wear resistance of 2024 aluminum alloy. The optimistic volume fraction of ZrO_2 in the AA2024 matrix should not fall below 12.5% to withstand the influence of other variables all levels stated in this work.*

Keywords -*AA2024, zirconia, wear, volume fraction of reinforcement, sliding distance, applied load, sliding speed.*

I. INTRODUCTION

Aluminum matrix composites have been emerged as advanced materials for several potential applications in aerospace, automobile, defence and other engineering sectors [1, 2] because of their high specific strength and stiffness, superior wear resistance [3-6].Out of different automobile components, aluminum matrix composites have been found to be a more promising material, in brake drums, cylinder blocks, cylinder liners, connecting rods, pistons, gears, valves, drive shafts, suspension components, etc. The wear rates of the composites were lower than that of the matrix alloy [7]. The rate of wear increases with increasing load, but it varies from linear to rapid increase for all the test materials, i.e., mild and severe wear regime [8-10]. The common parameters varied for studying the wear behavior of metal matrix composites are applied load or pressure, sliding speed, sliding distance and reinforcement volume fraction[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

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

whereΔW 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

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

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 order to develop an empirical wear models for AA3003/titanium nitride composites and to optimize the wear rate based on the probability statistical tests, the wear tests were performed on pin-on-disc equipment. The design of experiments was based on Taguchi techniques[14].

II. MATERIALS AND METHODS

The matrix material was AA2024. The reinforcement material was zirconia (ZrO_2) nanoparticles of average size 100nm (Fig. 1). The AA2024/ZrO_2 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 T6 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 AA2024/ZrO_2 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 AA2024/ZrO_2 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
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

III. RESULTS AND DISCUSSION

The Knoop hardness was conducted on AA2024/ZrO_2 composite specimens (Fig.) before and after wear tests. The hardness values increase after wear test. The increase in hardness may be attributed to the reinforcement effect of zirconia and work hardening during wear test on the pin-on-disc machine.

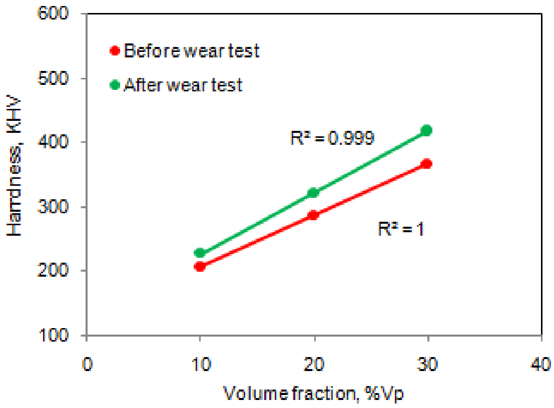

Fig.1: Hardness of AA2024/ZrO_2 composites after wear test.

Table 3: ANOVA summary of the effective stress

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	1.83E-02	1.43E-02	1.13E-02	8.15E-06	1	8.15E-06	1.72E+14	52.89
B	1.33E-02	1.42E-02	1.65E-02	1.76E-06	1	1.76E-06	3.71E+13	11.41
C	1.58E-02	1.48E-02	1.35E-02	8.89E-07	1	8.89E-07	1.87E+13	5.77
D	1.19E-02	7.54E-05	4.40E-02	4.61E-06	1	4.61E-06	9.73E+13	29.93
e				1.90E-19	4	4.74E-20	1.00	0.00
T	5.93E-02	4.34E-02	8.52E-02	1.54E-05	8			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.

3.1Effect of Reinforcement, Normal Load, Sliding Speed, Sliding distance on Wear Rate

The analysis of variance (ANOVA) is presented in Table 3. The percent contribution indicates 52.89%, 11.41%, 5.77% and 29.93% of variation in the wear rate by the reinforcement volume fraction of ZrO_2, applied load, sliding speed and sliding distance, respectively. The major contributions are from the vol.% ZrO_2 and sliding distance. The R-squared values of %reinforcement, normal load, sliding speed and sliding distance are, respectively, 0.9984, 0.9872, 0.8675 and 0.9882. The trend of mean values obtained by Taguchi techniques is same as that of R-squared values.

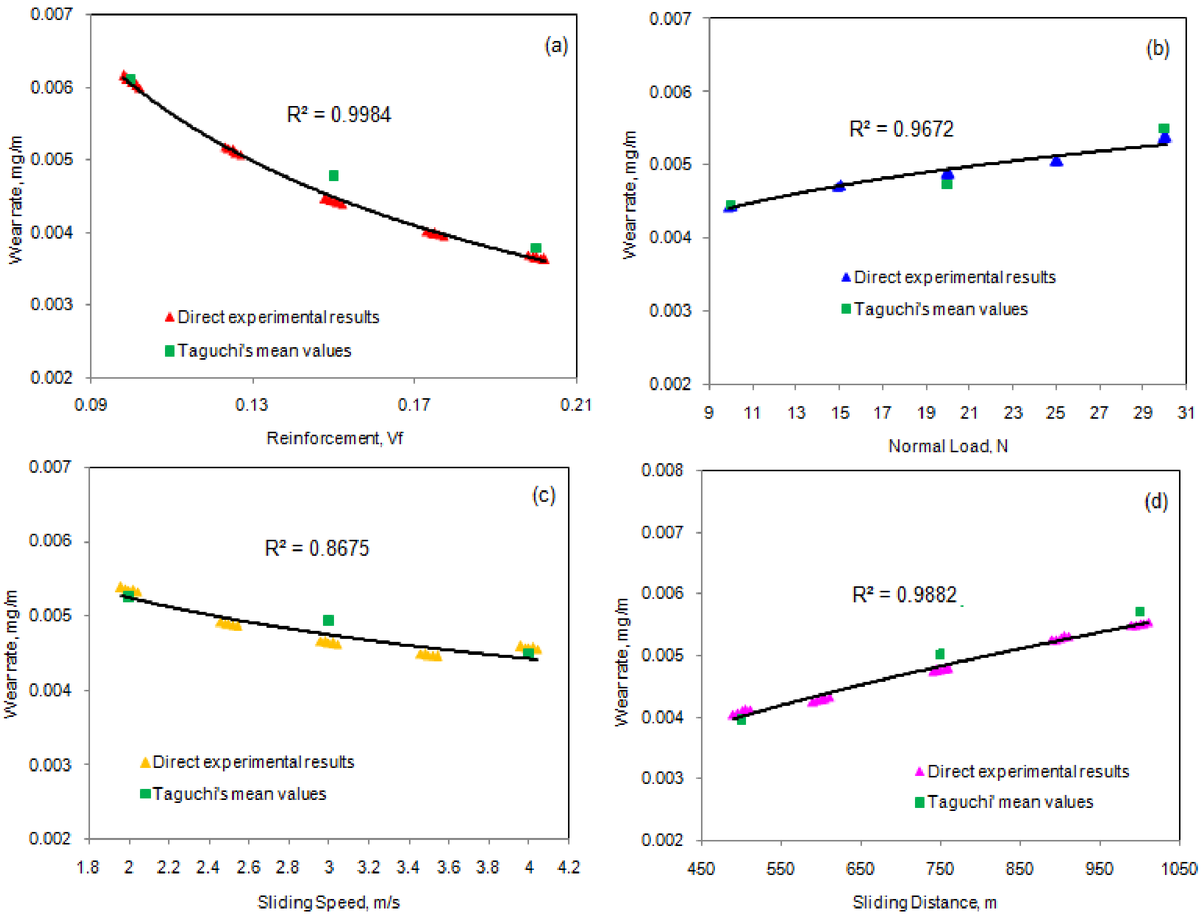

Fig. 2: Influence of process parameters on wear rate.

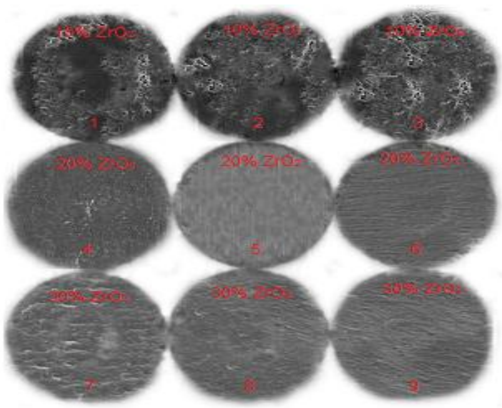

Fig. 3: Worn surfaces of AA2024.ZrO_2 composites.

The wear rate was decreased with increase in hardness of composites owing to increased volume fraction of ZrO_2 in AA2024 matrix (Fig.2a). The zirconia nanoparticles minimize the plastic deformation on the wearing surface resulting reduced wear rate. The plastic deformation was higher in the composites having

10%ZrO_2 nanoparticles than that observed in the composites consisting of 30%ZrO_2 nanoparticles (Fig.3). As seen from Fig.2b, an increase in wear rate is with increase of normal load applied on the test specimen. This is because at higher load, the frictional thrust increases, which results in increased debonding and fracture. The wear rate decreases with increase in sliding velocity for the composites (Fig. 2c). At high sliding speeds, the wear process was associated with a breakdown of the tribolayer, with wear being controlled by sub-surface cracking. It is also observed from Fig.2d that the wear rate was proportional to the sliding distance. It appears that cavities were formed in the composite matrix and had aligned parallel to the direction of sliding. Some particles also have chopped off during long sliding. This was particularly observed in the composites comprising of 30%ZrO_2 nanoparticles (Fig.3).

3.2 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:

$$W_{rp} = 0.0012\, v_f^{-0.7044} \tag{3}$$

$$W_{rf} = 0.0003F^{0.1632} \tag{4}$$

$$W_{rv} = 0.0062V^{-0.2437} \tag{5}$$

$$W_{rs} = 0.0002S^{0.4496} \tag{6}$$

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

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

$$W = K{v_f}^a F^b V^c S^d \tag{7}$$

The values of power law coefficients a, b, c and d are, respectively, -0.6035, 0.1825, -0.1449 and 0.4038 from Equations (3) to (6). By substituting the representative values of V_f, F, N and S and their corresponding power law coefficients on the right side of Equation (7) and substituting the experimentally obtained wear rates on the left side of Equation (7), the value of K is determined. The over-all wear rate (mg/m) equation for AA3003/TiN composites is given by

$$W = 4.718 \times 10^{-5}\left({v_f}^{-0.7044} F^{0.1632} V^{-0.2437} S^{0.4496}\right) \tag{8}$$

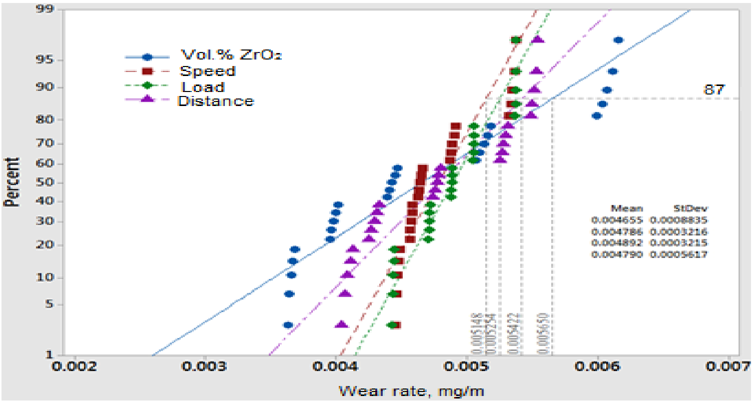

Fig.4: Probability analysis.

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.4. The estimated 87th percentiles for each population are:

- 0.005650 for the volume fraction of ZrO_2,
- 0.005422 for the sliding distance,
- 0.005254 for the applied load and
- 0.005148 for sliding speed.

The slopes of fitted lines in the decreasing order are: volume fraction of ZrO_2< sliding distance < applied load < applied load. This indicates the influence merit of these variables on the wear rate. This order is also same as that obtained from ANOVA. As the 87th percentiles for volume fraction of ZrO_2 is 0.005650 mg/m, the minimum volume fraction of ZrO_2 in AA2024 matrix should be 12.5% to withstand the influence of other variables at all levels.

IV. CONCLUSION

The results derived from the predicted mathematical model could match with those results acquired from the wear tests. An increase in volume fraction of zirconia nanoparticles has increased the hardness of the AA2024/ZrO_2 composites and subsequently enhanced the wear resistance. The minimum volume fraction of ZrO_2 in AA2024 matrix should be 12.5% to withstand the influence of other variables at all levels in the present work.

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