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Influence of Debris on Wear Rate of Metal Matrix Composites

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Abstract

Wear failures are very distinctive in terms of wear behavior. Very often a key to solve wear failure is by detailed examination of worn parts and studying the behavior of the material. The hardness of the wear material, or, the hardness of the worn surface, is an important factor in determining the resistance of a material to wear. For wear mechanisms involving plastic deformation, the formation of wear debris is vital. In the present work, the AA3003/TiN metal matrix composites were manufactured at 10%, 20% and 30% volume fractions of TiN nanoparticles. The pin-on-disc wear test was conducted with different combinations of reinforcement, sliding distance, normal load, sliding speed as per the design experiments proposed by Taguchi. Based on the experimental results an empirical model was established. Laboratory wear studies indicate that the wear resistance is roughly proportional to the volume fraction of TiN nanoparticles added to AA3003 matrix material. As the wear processes involves plastic deformation, the wear behavior is influenced by sliding distance, sliding speed and applied load. The increase of wear rate is by catastrophic breakage of sub-surfaces and interfaces due to too high a load applied on the composite pin. The increase of wear rate is also by work hardening on account of long sliding distance during wear test. During pin-on-disc wear test, the in-between areas of composite pin and steel disc become filled with compacted debris. The debris, by limiting metal-to-metal contact between pin and disc and possibly taking up some of the movement between the surfaces, has reduced further wear of AA3003/TiN composites.

Introduction

Metal matrix composites are being increasingly used in aerospace and automobile industries owing to their superior mechanical and tribological properties[1, 2]. Aluminum metal matrix composites reinforced with particulates exhibit excellent strength at higher temperatures, low coefficient of friction and thermal expansion, good wear resistance and stiffness compared to base alloys[3-6]. The titanium nitride (TiN) has a high melting point (2950°C), high hardness, high-temperature chemical stability and excellent thermal conductivity properties. But at temperatures above 500°C, it starts to form titanium oxides in air. Titanium nitride powders with a particle size from nano to micrometers are used as additive in the production of wear-resistant sintered materials.

Studies regarding wear behavior of aluminum metal matrix composites have been carried out by several researchers by varying the reinforcement volume fraction in the range of 5-25% [7-9]. 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 [10-13]. Rhee[14] 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

$$\Delta W = KF^a V^b t^c \qquad (1)$$

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 [15] 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

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

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 study the influence debris, the wear tests were performed on pin-on-disc equipment. The design of experiments was based on Taguchi techniques[16].

Experimental

The matrix material was AA3003. The reinforcement material was titanium nitride (TiN) nanoparticles of average size 100nm (figure 1). AA3003/TiN 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 AA3003/TiN composites against hardened ground steel (En32) disc. Knoop microhardness was

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conducted before and after wear tests. Optical and scanning electron microscopy analyses were also carried out to find consequence of wear test AA3003/ TiN composite specimens.

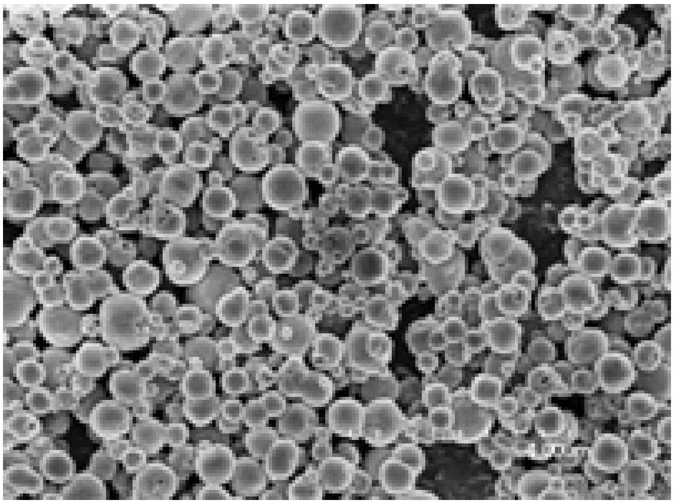

Figure 1: Titanium nitride nano powder.

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

Results and Discussion

Five composite samples for each trial were tested on random basis according to design of experiments (figure 2a). As per visual inspection of worn surfaces, the matrix removal was observed on AA3003/10 vol.% TiN composite specimens; deep scratches were revealed on AA3003/20 vol.% TiN composite specimens; and detached TiN nanoparticles were exposed on AA3003/30 vol.% TiN composite specimens (figure 2b). The Knoop hardness was conducted on AA3003/TiN composite specimens (figure 3) before and after wear tests. The hardness values increase after wear test. The increase in hardness may be attributed to the reinforcement effect of TiN and work hardening during wear test on the pin-on-disc machine.

Effect 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 48.59%, 12.76%, 6.43% and 32.22% of variation in the wear rate by the reinforcement volume fraction of TiN, applied load, sliding speed and sliding distance, respectively. The percent contribution of a particular variable indicates whether the performance of that variable is sensitive to bring variation in the wear rate. The major contribution is from the vol.% TiN seconded by the sliding distance. The R-squared values of %reinforcement, normal load, sliding speed and sliding distance are, respectively, 0.9976, 0.9736, 0.7712 and 0.9855. The trend of mean values obtained by Taguchi techniques is same as that of R-squared values.

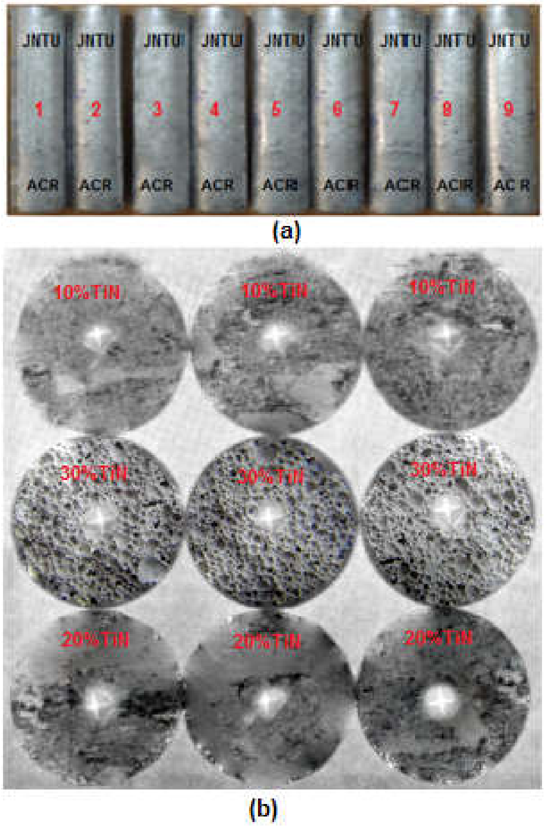

Figure 2: AA3003/TiN composite specimens: (a) before wear tests and (b) worn surfaces after wear tests.

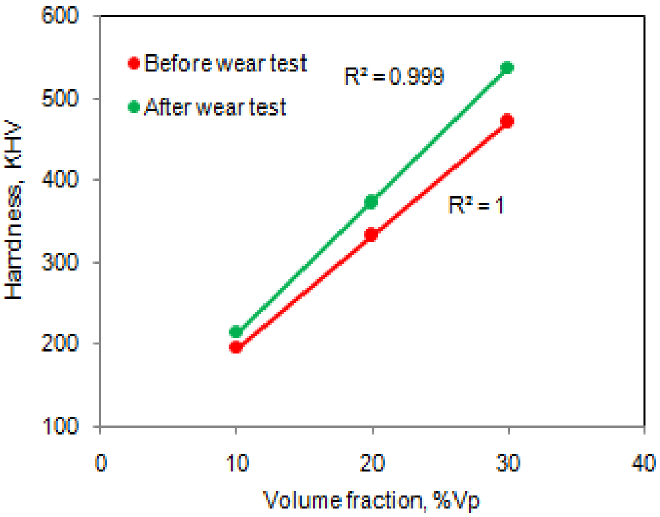

Figure 3: Hardness of AA3003/TiN composites after wear test

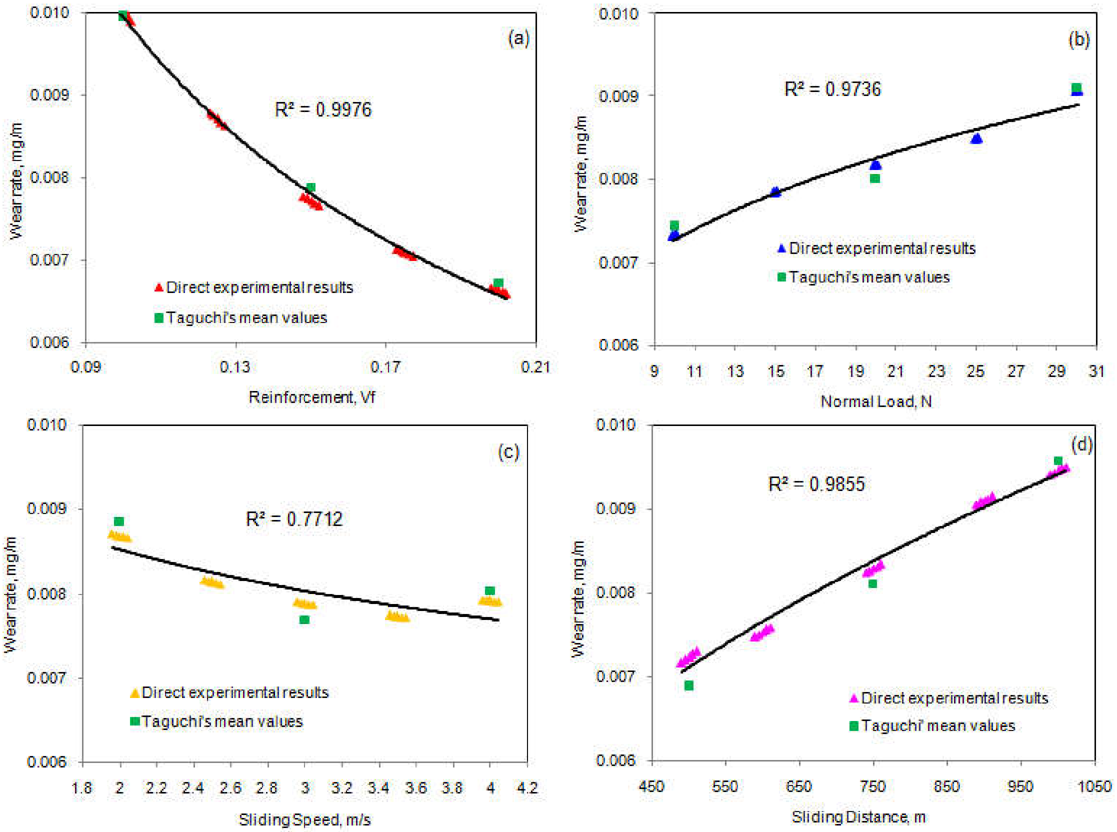

Figure 4: Influence of process parameters on wear rate

Table 3: ANOVA summary of the effective stress

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	2.99E-02	2.36E-02	2.02E-02	1.63E-05	1	1.63E-05	6.00E+14	48.59
B	2.23E-02	2.40E-02	2.73E-02	4.27E-06	1	4.27E-06	1.57E+14	12.76
C	2.66E-02	2.31E-02	2.41E-02	2.15E-06	1	2.15E-06	7.93E+13	6.43
D	2.07E-02	1.97E-04	7.37E-02	1.08E-05	1	1.08E-05	3.98E+14	32.22
e				-1.08E-19	4	-2.71E-20	1.00	0.00
T	9.95E-02	7.09E-02	1.45E-01	3.34E-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.

The strengths of % reinforcement, normal load, sliding speed ad sliding distance are directly proportional to the slope of their graphs presented in Figure4. The wear rate was decreased with increase in hardness of composites owing to increased volume fraction of TiN in AA3003 matrix (figure 4a). TiN nanoparticles minimize the plastic deformation on the wearing surface resulting reduced wear rate. Also, the high volume fraction of TiN provides greater resistance to the propagation of subsurface cracks as compared to the low TiN volume fractions on account of interparticle spacing. As seen from figure 4b, an increase in wear rate is with increase of normal load applied on the test specimen. With increasing applied load the wear behavior of the unreinforced alloy was dominated by extensive plastic flow of the alloy surface and significant wear debris formation. The addition of TiN reduced the wear for the applied load range studied during wear tests. An increase in sliding velocity considerably affects the wear rate. The wear rate decreases with increase in sliding velocity for composites with relatively higher weight fraction (figure 4c). At low sliding speeds, TiN nanoparticles did not appear to influence the wear rate and the wear rate for the composites and matrix alloy was comparable. At high sliding speeds, the wear process was associated with a breakdown of the tribolayer, with wear being controlled by sub-surface cracking owing to adhesive transfer and also by abrasion. It is also observed from figure 4d that the wear rate was proportional to the sliding distance. The higher wear rate was due to the adhesive wear of AA3003/TiN composite material on the sliding disc.

Mathematical Modeling 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:

$$W_{rp} = 0.0025{v_f}^{-0.6035} \tag{3}$$

$$W_{rf} = 0.0048F^{0.1825} \tag{4}$$

$$W_{rn} = 0.0094V^{-0.1449} \tag{5}$$

$$W_{rd} = 0.0006S^{0.4038} \tag{6}$$

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

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 (2) and substituting the experimentally obtained wear rates on the left side of Equation (2), the value of K is determined.

The over-all wear rate (mg/m) equation for AA3003/TiN composites is given by

$$W = 8.495 \times 10^{-5}\left(v_f{}^{-0.6035} F^{0.1825} V^{-0.1449} S^{0.4038}\right) \qquad (7)$$

Significance of Process Parameters on Wear in AA3003/TiN Composites

Figure 5 shows the worn surfaces of the AA3003/TiN composites. The abrasive and adhesive wear mechanisms were recognized based on the worn surfaces. An increase in the reinforcement reduced the wear and the surface observed was smooth. The worn surfaces of AA3003/TiN composites revealed cavities and large grooved regions on the wear surfaces and also-enclosed TiN nanoparticles in the cavities, some of them having been pulled out (figure 5). In the case of the composites subjected to the 10N load the width of the grooves were greater than those on the surfaces worn by the 30N load. There was a change from a mild to a severe wear resulted by an increase in the load due to a greater plastic flow on the pin surface of the specimen under a higher load. The particle pull-out was due to the poor particle/matrix bonding. This was on account of the abrasive-wear mechanism of the composite material while resisting the delamination process. The wear resistance was greater in the case of composites having high volume fraction of TiN.

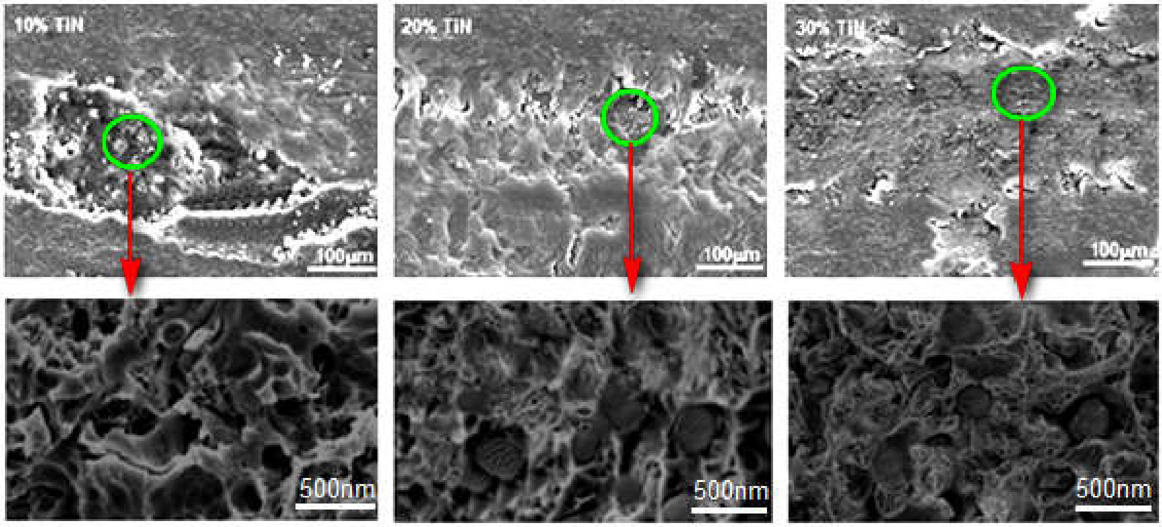

Figure 5: The worn surfaces of AA3003/TiN composites

The role of debris in wear processes is very important because it can build up between the composite pin and steel disc and increase the number of interfaces. At low volume fraction (i.e. 10%) of TiN, the debris was typically in the form of thin platelets (figure 6). The composites containing high volume fraction (i.e. 30%) of TiN, the debris consisted of aluminum coated TiN particles (figure 6). The size and shape of wear debris particles were depend on the volume fraction of TiN, levels of load and sliding velocity. The spherical and cylindrical shapes of debris were resulted due to very small movements and high compressive stresses during the wear test. The occurrence of oxides in the wear debris would indicate that oxygen could play a role in the wear process. The oxides found in debris were formed while the particles were still attached to the pin surface at the contact interface, although oxidation would occur after the particles had been broken away from the wear surface. Not only aluminum, titanium would form titanium oxides in air above 500°C. Increasing applied load tend to accelerate the process of surface and subsurface crack initiation leading to formation wear debris. High sliding speed could involve repeated mauling of the surface, leading to the eventual fracture and removal of wear debris. These debris materials got transferred to the disc surface forming a transfer film on it. The debris removed from the matrix can act as third body abrasive. Third-body formation due to transferred debris separated the composite pin from the steel disc and contributed to the load carrying capacity. Thus, the third-body would decelerate the wear process more. Therefore, the buildup of debris between the surfaces was more likely to reduce additional wear. Based on the hardness of wear rate of AA3003/TiN composites, the sleeves for bearings were fabricated to provide a bearing surface for rotary applications as shown in figure 7.

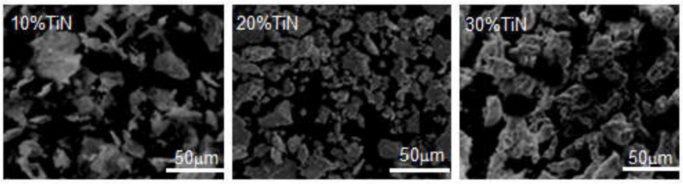

Figure 6: Debris materials of AA3003/TiN metal matrix composites

Figure 7: Application of AA3003/TiN metal matrix composites.

Conclusions

The study on the wear behavior of AA3003/TiN nanoparticles reinforced metal matrix composites could conclude power law relations between the wear rate with volume fraction of Si_3N_4, normal load, sliding speed and sliding distance. The results derived from the predicted mathematical model could match with those results acquired from the wear tests. An increase in volume fraction of TiN nanoparticles has increased the hardness of the AA3003/TiN composites and subsequently enhanced the wear resistance. Wear debris in the form of platelets has reduced the wear rate of AA3003/TiN composites.

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