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Tribological Investigation of the Effects of Particle Volume Fraction, Applied Load and Sliding Distance on AA4015/Titania Nanocomposites

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Abstract

The friction and wear properties of AA4015 reinforced with Titania nanoparticles were studied. The test matrix varied volume fraction of Titania, applied load and sliding distance to study the coupled effects on the tribological properties of AA4015/Titania nanocomposites. The nanocomposite samples were tested in dry sliding against a steel counterface. The specific wear rate ranged from 6.24×10^{-6} to 1.17×10^{-5} mm^3/N-m and the friction coefficient ranged from 0.16 to 0.72. Specific wear rate increased with increasing applied load and sliding distance at any volume fraction of Titania nanoparticles in the range tested. The resistance to wear increased with increasing volume fraction of Titania nanoparticles. The 25 vol.%, of Titania has reduced the specific wear rate of AA4015 by 48.26% at applied load of 40N and sliding distance 1000 m and by 54.21% for sliding distance of 1600 m and at applied of 25N.

Keywords: AA4015, applied load, coefficient of friction, sliding distance, specific wear rate, Titania, volume fraction of reinforcement.

1. INTRODUCTION

Metal matrix composites are used for structural applications where high strength and structural stability at elevated temperatures is required [1]. Composite materials are composed at least from two phases, a matrix phase and a reinforcement phase. The reinforcement materials can be oxides [2, 3], carbides [4, 5] or nitrides [6, 7]. Particulate reinforced aluminum matrix nanocomposites continue to show exceptional tribological behaviors, with prior studies showing that the addition of nanoparticles can afford significant improvements in wear resistance. Three mechanisms have been suggested: (a) change in mechanical properties (modulus, strength and toughness), (b) change in tribological properties (hardness, wear rate and morphology of the worn surfaces), and (c) a direct effect of nanoparticles on the wear mechanism [8-10].

Prior works showed that the addition of B_4C [11], Al_2O_3 [12] and Si_3N_4 [13] nanoparticles to Al alloys resulted in an improvement of wear resistance with increasing content of reinforcement in the Al alloy matrices. The results showed that the nanoparticles had an independent effect on the wear rate apart from the effects of matrix alloy, sliding distance, applied load and sliding speed.

This paper elaborates on those results showing the effect of volume fraction Titania, applied load and sliding distance on the tribological behavior of AA4015/Titania nanocomposites.

2. MATERIALS AND METHODS

The matrix material was AA4015. The reinforcement material was Titania nanoparticles of average size 100nm. AA4015/Titania nanocomposites 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. A pin-on-disc type friction and wear monitor (ASTM G99) was employed to evaluate the friction and wear behavior of AA4015/Titania nanocomposites against hardened ground steel (En32) disc. Knoop microhardness was conducted before and after wear tests. Scanning electron microscopy (SEM) analyses were also carried out to find consequence of wear test AA4015/Titania nanocomposites.

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3. RESULTS

As a control, the AA4015 alone was tested under the same conditions as those of AA4015/titania nanocomposites. The hardness of the composites before and after wear tests were measured on Knoop hardness tester and the results are plotted in figure 1. The hardness increases with increase of Titania content in AA4015 matrix alloy. It is also observed that the hardness of the nanocomposites increases after the wear test. This may be due work hardening of the composites. The specific wear rate is plotted versus applied load in figure 2 for Titania-AA4015 nanocomposites with 0, 5, 10, 15, 20 and 25 vol.% of Titania. In all cases specific wear rate is lowest with 25 vol.% Titania loading for the compositions tested. The 25%, 20%, 15%, 10% and 5% volume fractions of Titania have reduced the specific wear rate of AA4015 by 48.26%, 43.36% , 40.58%, 37.82% and 33.07%, respectively, for applied load of 40N. Contours of constant specific wear rate are plotted versus volume fraction of Titania and applied load in figure 3 to facilitate the visualization of trends. For any given volume fraction of Titania, as applied load increases, the specific wear rate increases. The optimum volume fraction of Titania tends to increase with increased applied load. It is seen from the figure 2 and 3 that the specific wear rate of the unreinforced alloy specimens increases more rapidly with applied load compared to the AA4015/Titania composite specimens.

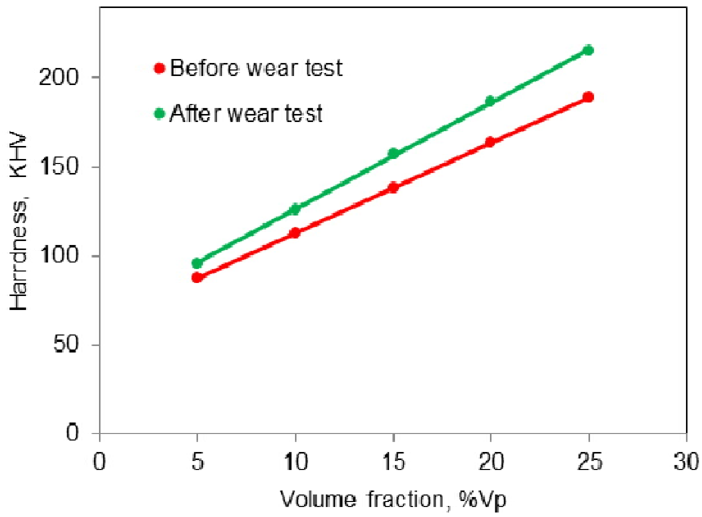

Figure 1 Hardness of AA4015/Titania nanocomposites before and after wear test.

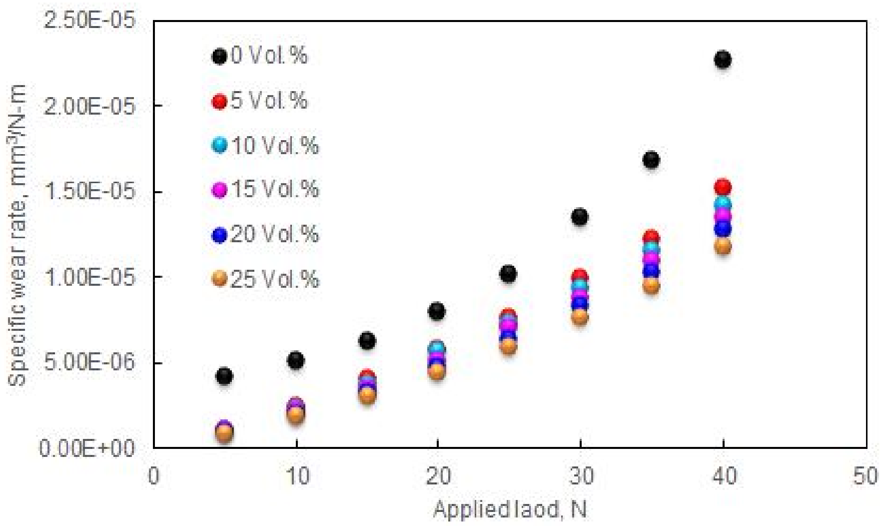

Figure 2 Specific wear rate plotted vs. applied load for Titania–AA4015 nanocomposites with six volume fractions. All the samples were tested for sliding distance of 1000 m.

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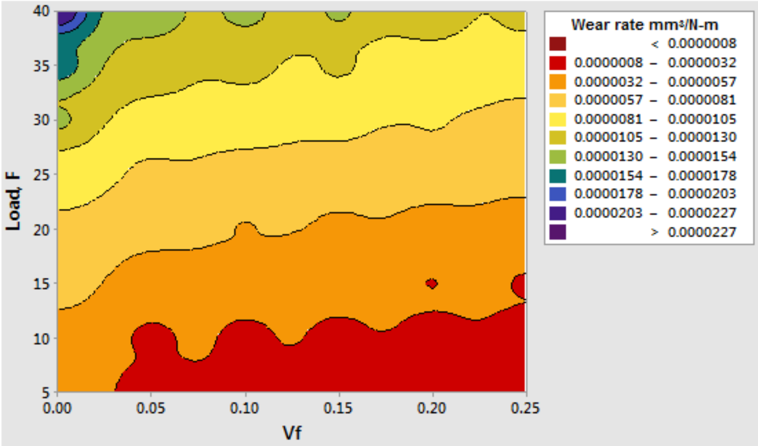

Figure 3 Contour plot of Specific wear rate vs. reinforcement vol.% and applied load. All the samples were tested for sliding distance of 1000 m.

The specific wear rate is plotted versus sliding distance in figure 4 for Titania-AA4015 nanocomposites with 0, 5, 10, 15, 20 and 25 vol.% of Titania. The specific wear rate is highest with the sliding distance of 1600 m for the compositions tested. The 25%, 20%, 15%, 10% and 5% volume fractions of Titania have reduced the specific wear rate of AA4015 by 54.21%, 49.22%, 44.95%, 42.15% and 38.06%, respectively, for sliding distance of 1600 m. Contours of constant specific wear rate are plotted versus volume fraction of Titania and sliding distance in figure 5. For any given volume fraction of Titania, as sliding distance increases, the specific wear rate increases. The optimum volume fraction of Titania tends to increase with increased sliding distance. As anticipated, the wear loss of the unreinforced increases with increasing sliding distance.

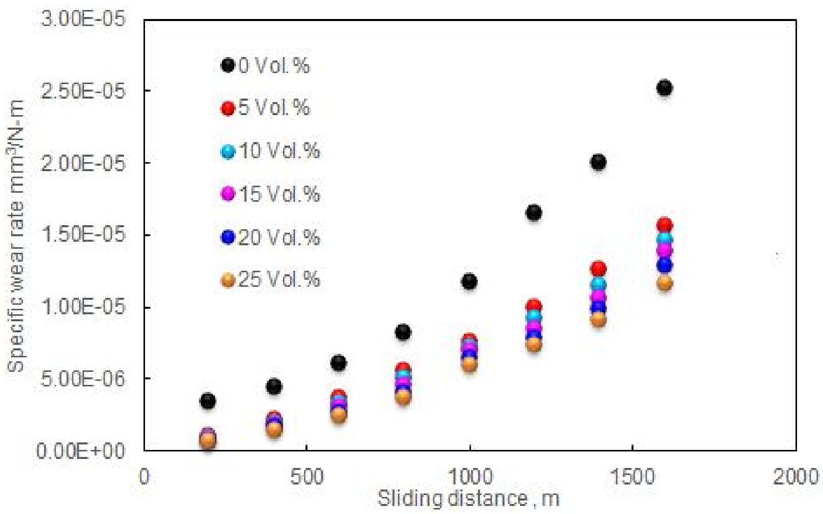

Figure 4 Specific wear rate plotted vs. sliding distance for Titania–AA4015 nanocomposites with six volume fractions. All the samples were tested for applied load of 25 N.

Friction coefficient is plotted versus applied load in figure 6 for Titania–AA4015 nanocomposites. The 5%, 10%, 15%, 20% and 25% volume fractions of Titania have increased the COF (coefficient of friction) of AA4015 by 12.50%, 31.50% , 50.00%, 68.75% and 93.75%, respectively, for applied load of 40N. For any given volume fraction of Titania, as applied load increases, the COF decreases. Friction coefficient is plotted versus sliding distance in figure 7 for Titania–AA4015 nanocomposites. The 5%, 10%, 15%, 20% and 25% volume fractions of Titania have increased the COF of AA4015 by 6.25%, 25.00% , 43.75%, 75.00% and 87.50%, respectively, for sliding distance of 1600 m. For any given volume fraction of Titania, as sliding distance increases, the COF decreases.

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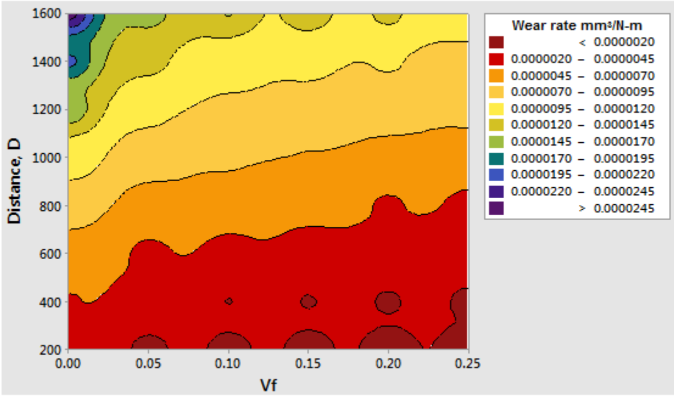

Figure 5 Contour plot of Specific wear rate vs. reinforcement vol.% and sliding distance. All the samples were tested for applied load of 25 N.

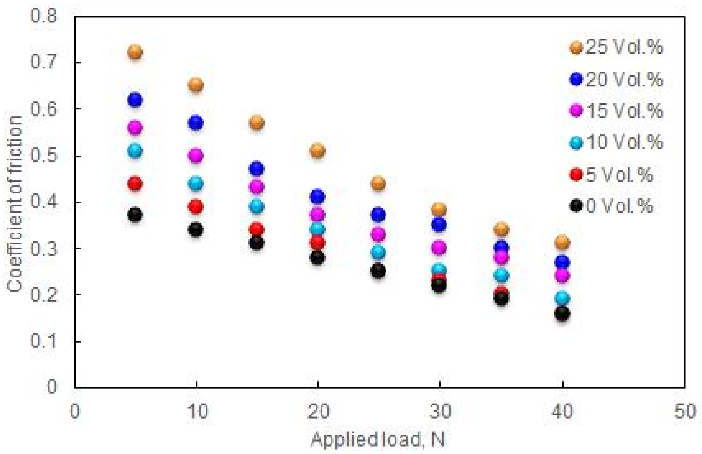

Figure 6 Coefficient of friction plotted vs. applied load for Titania–AA4015 nanocomposites with six volume fractions. All the samples were tested for sliding distance of 1600 m.

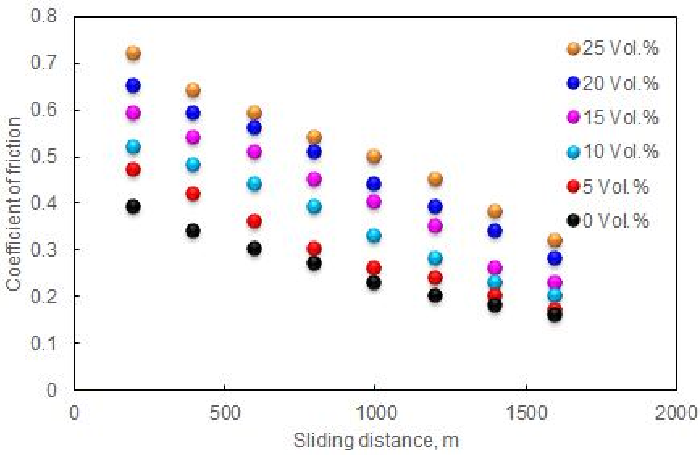

Figure 7 Coefficient of friction plotted vs. sliding distance for Titania–AA4015 nanocomposites with six volume fractions. All the samples were tested for applied load of 25 N.

4. DISCUSSION

There are a number of hypotheses regarding the mechanisms for reduced wear rate and increased friction in metal matrix composites [14-18]. Wear takes place by gradual removal of adhered derbies of material picked up by the contacting surfaces during frictional interaction. Also, wear is due to the removal of sheared layers resulting from excessive plastic deformation. According to Archard's law of wear, the volume of worn material removed V_w is directly proportional to the load F, the total sliding distance L and inversely proportional to the hardness H, as given below:

$$V_w = K\frac{FL}{H} \qquad (1)$$

where, *K* is the wear coefficient. *K* represents the proportion of the plastically deformed volume that is removed by the wear process. For mild wear, $10^{-8} > K > 10^{-4}$ and for severe wear, $10^{-4} > K > 10^{-2}$. The computed *K* values at different applied loads and sliding distances are plotted in figures 8 and 9 respectively.

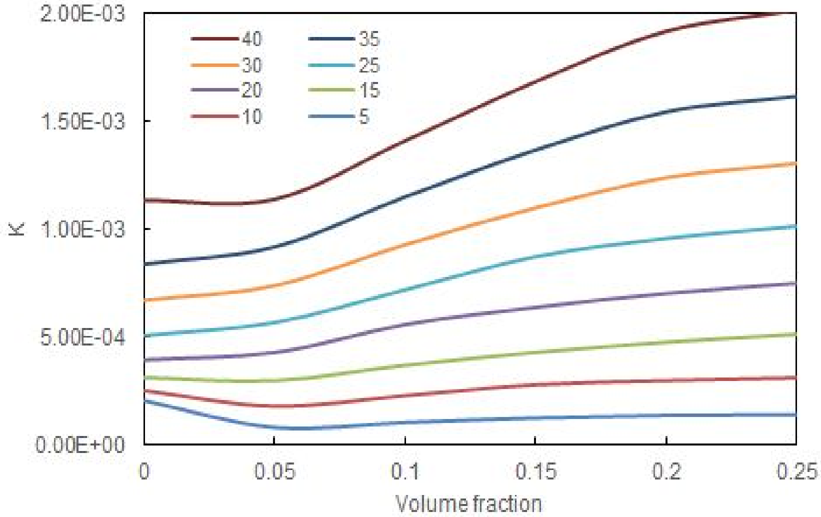

Figure 8 The *K* values of the Archard's law of wear attributed to applied load

Computed values of *K* are range from 10^{-5} for small applied loads and short sliding distances to 10^{-3} for heavy applied loads and long sliding distances. As observed from figure 8 and 9, above 25 N of applied load and 1000 m of sliding distance, the wear is severe in AA4015/Titania nanocomposites. The main reason is the formation of debris comprising of platelets of AA4015 matrix and detached Titania nanoparticles. Explicitly, wear debris resulting from mild wear consists of fine platelets (0.01-1 µm), many of them aluminum oxides as shown in figure 10 (a). In contrast, the debris resulting from severe wear comprises of much larger (20-200 µm) as shown in figure 10(b). The detached Titania nanoparticles, owing to poor bonding between matrix and nanoparticles, act as abrasive medium producing further wear. Abrasive wear takes place when hard Titania nanoparticles rub under load against a relatively softer surface. Depending on the interfacial shear strength, ridges form along the sides of wear track due to ploughing (figure 11). The interfacial shear strength decreases with increase in volume fraction of Titania nanoparticles. Hence, there is likelihood of forming ridges in the AA4015/Titania nanocomposites consisting of 20 to 25 vol.% Titania nanoparticles.

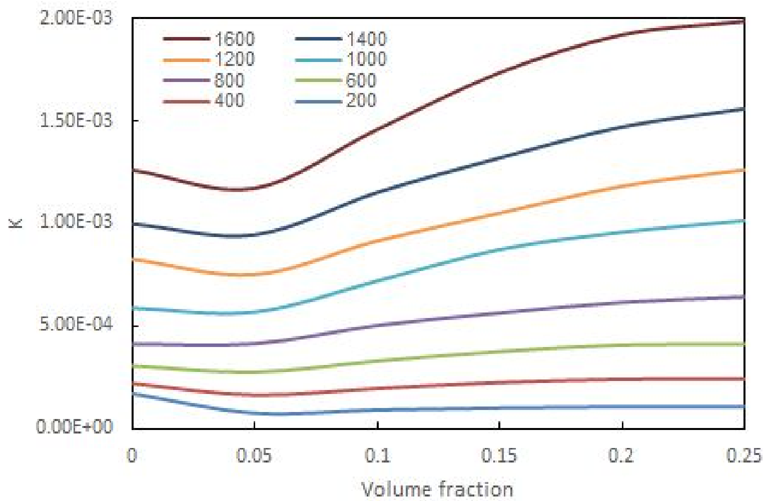

Figure 9 The *K* values of the Archard's law of wear attributed to sliding distance

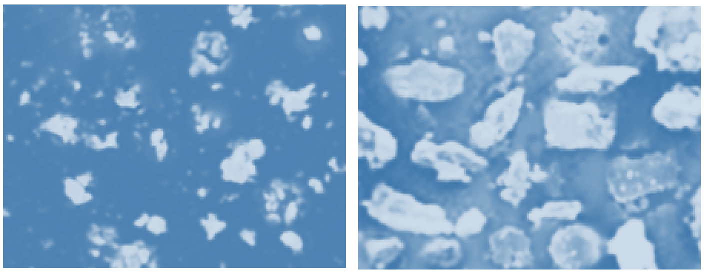

Figure 10 Debris formed during wear tests: (a) for 5 N and 200 m and (b) for 40 n and 1600 m

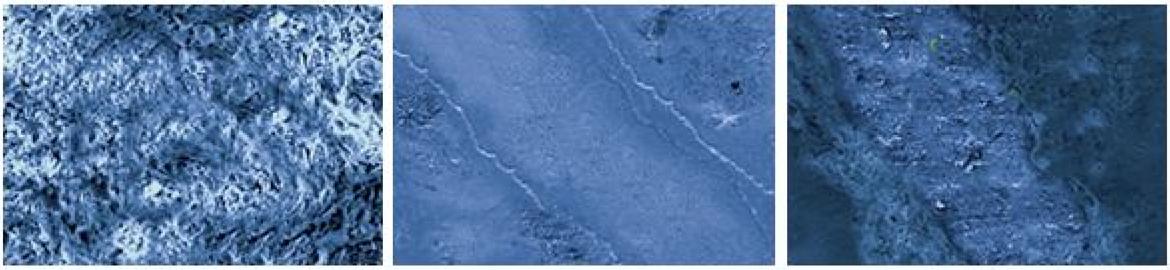

Figure 11 Worn surfaces of AA4015/Titania composites: (a) 25 N and 1000 m and (b) 40 N and 1600 m

5. CONCLUSIONS

The specific wear rate obtained through the present experimentation is reported in this paper. The observed specific wear rate was higher for the unreinforced AA4015 when compared to the AA4015/Titania reinforced nanocomposites. Wear rate was decreased with increasing Titania content in the nanocomposites. The specific wear rate of the nanocomposites as well as the matrix alloy was increased with the increase in applied load and sliding distance. The nanocomposite specimens were demonstrated adhesive wear at lower loads and shorter distances, whereas, in the case of higher applied loads and longer sliding distances, abrasive wear was observed due to delamination. The debond Titania nanoparticles would promote three-body wear mechanism. The 25 vol.%, of Titania has reduced the specific wear rate of AA4015 by 48.26% at applied load of 40N and sliding distance 1000 m. The 25 vol.% of Titania has reduced the specific wear rate of AA4015 by 54.21 for sliding distance of 1600 m and at applied of 25N.

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