Tribological Properties of WS_2 Nanoparticles Lubricants on Aluminum-Silicon Alloy and Carbon Steels

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Abstract

The rheological properties of nanometric tungsten disulphide (WS_2) nanoparticles oil lubricants and its tribological performance with two hypereutectic Al-Si alloy and carbon steel are examined. These two oils are used to reduce wear and friction and to explore the actions via tribological pin-on-disk tests. The pin was made from hypereutectic Al-Si alloy on steel disk, taking into consideration the effect of loads (10, 20, 30 N) and different speed (200, 300, 400 rpm). Oils with and without WS_2 nanoparticles reveal the loss rate due to friction. The results show that WS_2 nanoparticles oil-dispersed lubricants are capable of reducing wear, improved by a mechanism which was characterized not only by the viscosity of the WS_2 nanoparticles suspensions but also the promotion of contact's surface as combined anti-corrosion, as well as effective reduction of friction on the surface film. Therefore, a lubricant added to nanoparticles can protect the piston surface.

Keywords: Lubricating oil, anti-wear and friction, nanoparticles, tribological chemistry, piston

Introduction

Recent years have proved that the use of different types of nanoparticles on a large scale can reduce friction and wear under conditions of high-speed loading [1], and such nanomaterials can improve the effect of lubrication [2]. The use of these nanoparticles added on metal surfaces is to prevent direct contact between the surfaces during mating [3], prevent a rise in temperature during the loads and reduce shear stress where most additives are phosphorus, sulfur, chlorine and other species [4], that are environmentally friendly materials and play an active role in improving the technology of traditional lubricants to reduce wear of the aircraft [5], as well as to reduce friction and corrosion [6]. These additives interact with metals to produce a film produced by a chemical reaction at the contact between the surfaces [7] to reduce the shear stress [8,9]. Chang *et al.* [10] have studied the tribological properties of TiO_2 nanolubricant on piston and cylinder surfaces. They concluded that the lubricant added with TiO_2 nanoparticles can protect the piston ring surface. Chou and Lee [11] have observed the rheological properties of nanodiamond-dispersed oil lubricants and their tribological performance with two carbon steels and an aluminum alloy where they found the promotion of contact surface's toughness due to the embedded nanodiamonds from the lubricant. On the other hand, the wear mechanism of the aluminum alloy is mainly dominated by the viscosity of the nanodiamond suspensions. Zhang *et al.* [12] have investigated the effect of Cu nanoparticles (NPs) on the tribological behaviors of serpentine powders (SPs) suspended in diesel oil. They concluded that there is an optimum mass ratio of Cu NPs to SPs is 7.5:92.5. With the addition of the above mixture to oil, the tribological properties can be significantly improved compared with those of the oil containing SPs alone. Kopeliovich [13] studied tribological properties of alumina reinforced composites. In some cases the friction coefficient of the composite is lower than that of matrix material. Additionally hard alumina particles in a metal matrix composite decrease the probability of seizure between the sliding counterparts due to the abrasive effect of the particles. Gu *et al.* [14] have searched the application of CeO_2 and $CaCO_3$ nanoparticles in lubricating oils and found that the tribological chemical reactions resulting from the friction surface formed calcium metal, cerium metal and oxides film. Finally, Kao *et al.* [15] have prepared and tested the friction of a vehicle brake tandem master cylinder. They investigated the behavior of the elastomeric seal, and found that the nonaluminum oxide brake fluid with its ball shape can highly reduce the friction coefficient to avoid seal excessive wear and reduce slick slip in brake applications. The main favorable benefit of the WS_2 nanoparticles was attributed previously to the three following effects; (a) rolling friction [16,17], (b) the WS_2 nanoparticles serve as spacers, which eliminate metal to metal contact between the asperities of the two mating metal surfaces [16,17] and (c) third body material transfer [18] nanometric tungsten disulphide (WS_2) nanoparticles appear to have excellent tribological properties within a definite load range (PV ≈ 150 Nm/s) in comparison to typical metal dichalcogenides [19]. Reshak and Auluck [20] have studied the electronic properties of $2H$-WSe_2 intercalated with Cu. They concluded that there is a weak hybridization between the Cu states and W and Se states. They [21] have researched the new materials WS_xSe_{2-x} ($x = 0.5$ and 1.5) that possess second harmonic generation (SHG). It has been shown that these materials can be used as nonlinear crystals.

In this work, to best of our knowledge, there is not available in the literature, an investigation of tribological properties of WS_2 nanoparticles for aluminum-silicon casting alloy and carbon steels, on the different types of wear rate and friction coefficient. It was attempted to use nanomaterials to improve the effect of lubrication on the friction and wear to provide an approach for evaluation the surface finishing operations. All of these are divided into the following: Section 2 details the experimental process, while the results and discussion are given in section 3. Finally, section 4 concludes the results.

Materials and methods

Chemical analysis was conducted for the aluminum-silicon casting alloy, also density, hardness and tensile strength are studied due to its wide use in industry, particularly in pistons as well as the cylinders. The obtained chemical analysis is given in the **Table 1**. The testing of the mechanical properties including hardness is given in **Table 2**, while the friction coefficients and wear factors are reduced using WS_2 nanoparticles as given in **Table 3**. To know the composition of microscopic samples using field emission scanning electron microscopy (FE-SEM) images of the produced WS_2 nanoparticles, it is combined with energy dispersive X-ray spectroscopy (EDX). Also, the scanning electron microscopy (SEM) images give greater magnification and better depth. SEM is a specialized method using a variable-pressure sample chamber. This technique allows direct evaluation of samples that are nonconductive or vacuum sensitive. Aluminum-silicon casting alloy was cleaned before starting an actual test of the wear process and the hard substance washed with acetone and well dried. The height and weight of samples was measured accurately to provide a very precise and digital recording of all data using a stopwatch to set a time slip and post-test.

A pin-on-disk tribological test rig was used for the investigation. The upper specimen was a fixed (10 mm) diameter Al-16Si casting alloy; surface roughness average (R_a) = 0.2 ± 0.05 taking into consideration the WS_2 nanoparticles µm, and Vickers hardness (H_v) = 112.65 ± 12 kg/mm^2, on disc, made of AISI 1045 steel (Ra = 0.15 ± 0.05 µm, H_v= 312 ± 20 kg/mm^2), were tested. For the commercial oil, an addition of 0.05 g/l WS_2 nanoparticles gives the best reduction of wear for the Al-Si casting alloy [20], without size. The whole assembly was immersed in an oil bath with 20 ml lubricant at each run. The applied load was (10, 20, 30 N) and the sliding speed (200, 300, 400 rpm) equivalent to (1.32, 1.885, 3 m/s). The wear tests were run for 360 min and the sliding distance was kept at 216 m. The friction force was recorded during the wear tests. Specimens were ultrasonically cleaned in acetone for 5 min before and after wear tests. More than three wear tests were repeated under the same lubrication conditions. The wear tracks were observed by SEM. Surface roughness was also measured by a stylus surface analyzer, with the effective measure length 0.250 mm and the cutoff length, 0.05 mm. The work hardening of contact surfaces due to the friction shear was identified and determined by micro-Vickers indentation test. Wear rate (W_R) was estimated by measuring the mass loss (ΔW) in the specimen after each test. Care was taken after each test to avoid entrapment of wear debris in the specimen. It is calculated that ΔW to sliding distance *(SD)* using:

$$W_R = \Delta W / SD \qquad (1)$$

The volumetric wear rate (W_v) of the composite is related to density (ρ) and the abrading time (t), using:

$$W_v = \Delta W / \rho t \qquad (2)$$

Specific wear rate (W_s) is employed. This is defined as the volume loss of the composite per unit sliding distance and per unit applied normal load. Often the inverse of specific wear rate expresses in terms of the volumetric wear rate as:

$$W_s = W_v / SD\, Fn \qquad (3)$$

The friction force was measured for each pass and then averaged over the total number of passes for each wear test. The average value of friction coefficient (μ) of the composite was calculated from:

$$\mu = Ff / Fn \qquad (4)$$

where Ff is the average friction force and Fn is the applied load with an assumption that the temperature is constant at 31 °C.

Table 1 Compositional analysis of Al-Si casting alloy.

Si	Mg	Cu	Fe	Ni	Mn	Sn	Pb	Zn
16.69	1.176	1.304	1.130	1.224	0.024	0.012	0.026	0.012

Table 2 Investigated hardness, density and tensile strength of Al-Si casting alloy.

Hardness	**112.65 VHN**
Density	**2.72 gm/cc**
Tensile strength	**250 MPa**

Table 3 Friction coefficient and wear factors for specimens tested in two base stocks, the commercial oil with and without WS_2 nanoparticles.

Lubricant	**μ**	**$W_R \times 10^{-6}$ (N/m)**	**$W_V \times 10^{-12}$ (m^3/sec)**	**$W_s \times 10^{-13}$ (m^3/N·m)**
Conventional engine oil	0.266 ± 0.009	0.08418	2.880	2.180
Conventional engine oil + WS_2 nanoparticles	0.24 ± 0.011	0.06313	2.459	1.863

Results and discussion

Nanoparticles can contribute to stronger, lighter, cleaner and "smarter" surfaces and systems. Nanoparticles can improve adhesion. In addition, the stiffness can also be improved by use of nanoparticle-strengthened steels. Moreover, ultra-thin transparent coatings can be applied to displays to avoid glare or condensation. The microscopic structure and the composition of microscopic samples are examined and shown in **Figure 1**. It is shown that using WS_2 nanoparticles, the produced oil is smoother and more uniform. The micrographs wear surface is shown in **Figure 2.** It is observed that at specific velocity and load, the wear rate decreased as skidding distance increases. We have used the following materials manifesting:

- ■ 190 ml of distilled water.
- ■ 3 ml of hydrochloric acid.
- ■ 2 ml of hydrofluoric acid.

Figure 1 shows the dispersion of WS_2 nanoparticles to determine its effectiveness in reducing the wear rate as well as the specific aim to reduce the friction of the alloys of hypereutectic Al-Si alloys and carbon steel compared with the use of oils without WS_2 nanoparticles. **Figure 2** shows that a reduce wear rate of 0.006313×10^{-6} N/m compared with a wear rate of 0.08418×10^{-6} N/m without WS_2 nanoparticles, which is attributed to an increase in viscosity. Two (aluminum-silicon) casting alloy and carbon steels, AISI 1045, were investigated in this study.

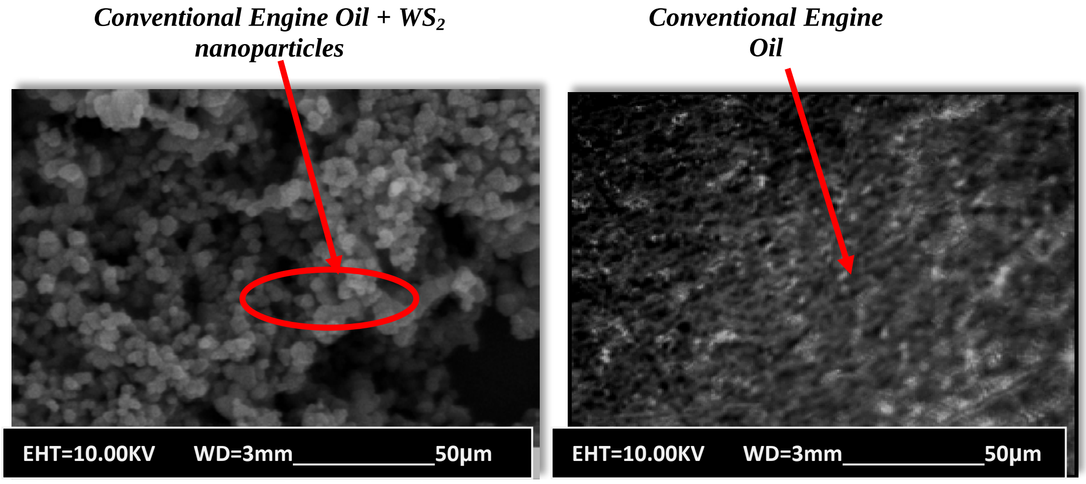


Figure 1 FE-SEM images of the produced WS_2 nanoparticles.

The volumetric wear rate is reduced for oils using WS_2 nanoparticles at specific velocity and load as shown in **Figure 3**. For the Al-Si casting alloy, the addition of WS_2 nanoparticles reduces the volumetric wear loss. However, the volumetric wear rate increases as load increases even with or without WS_2 nanoparticles. This supports a direct correlation of wear rate with load. This result is consistent with the results obtained by Rapoport *et al.* [22].

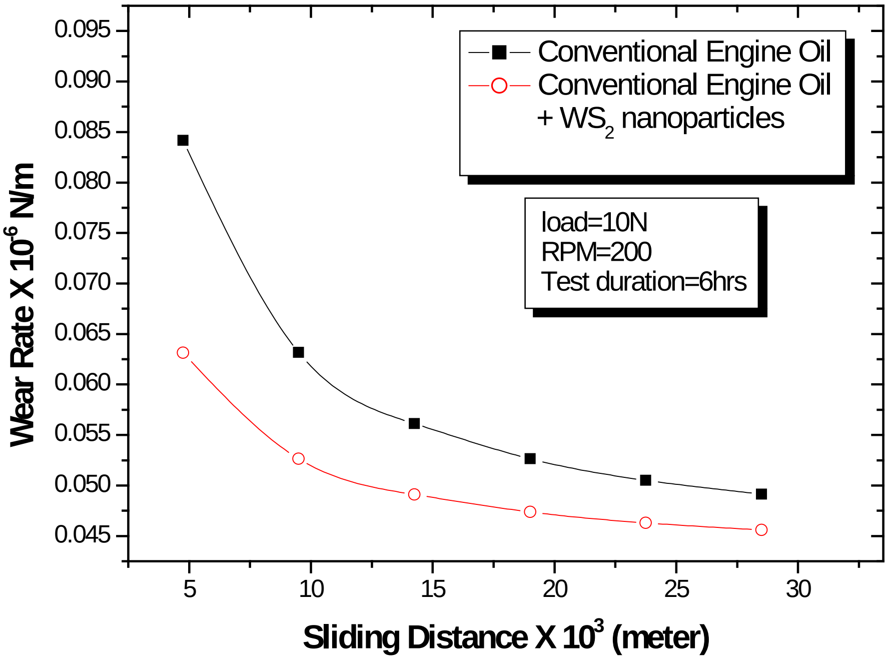


Figure 2 Variation of wear rate with sliding distance of 200 rpm at 10 N.

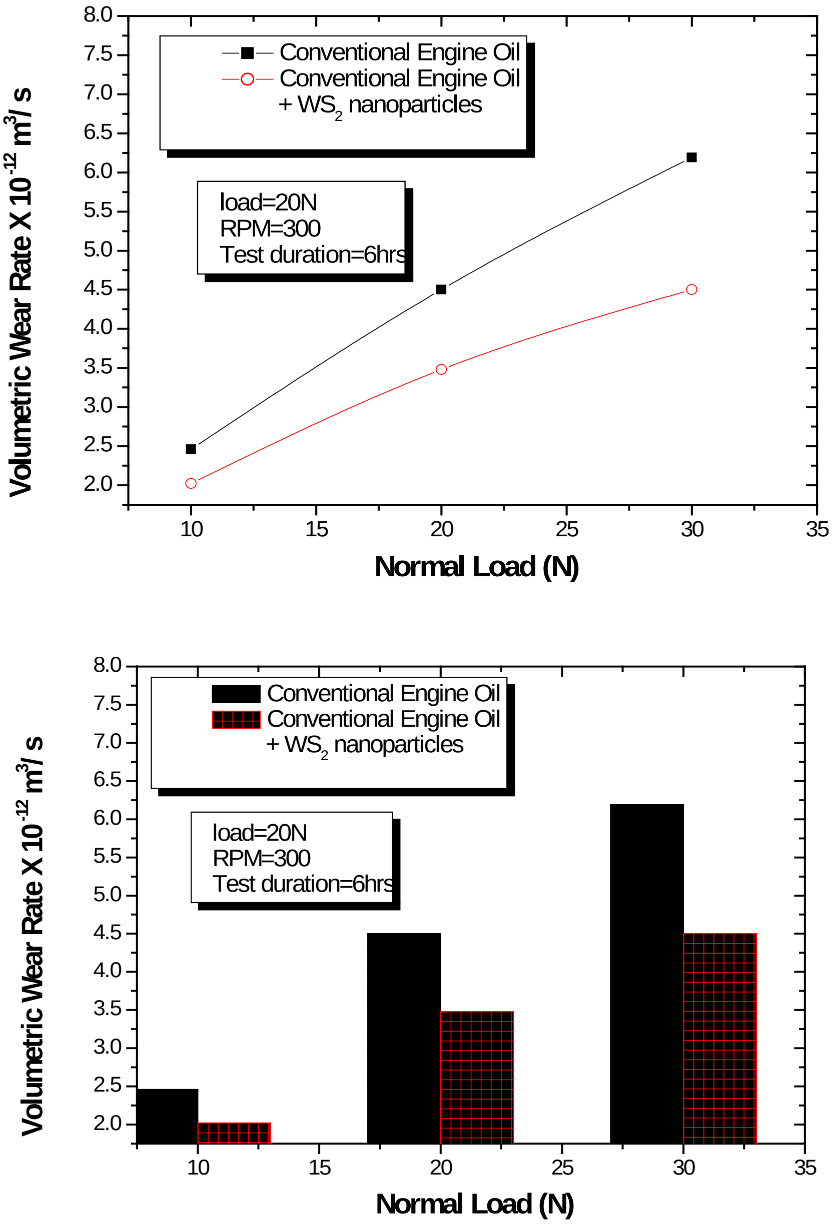


Figure 3 Variation of volumetric wear rate with normal load of 20 N at 300 rpm.

Figure 4 shows the variation of specific wear rate with sliding velocity. The plot shows that the specific wear rate of the composite decreases rapidly using WS_2 nanoparticles. It is clear that the rate of specific wear increases initially without WS_2 nanoparticles and decreases as the sliding velocity increases. The friction coefficients of two specimens tested in various lubricants are shown in **Figure 5**. Each value was derived from more than two repeated tests. The measured values indicate that the WS_2 nanoparticles in lubricants enhance the strength of surfaces and reduce the friction rate, the weighted and volumetric wear.

Friction coefficient using WS_2 nanoparticles is lower than the same coefficient without WS_2 nanoparticles (**Table 3**). It is known that WS_2

nanoparticles cause a reduction in friction coefficient and temperature that lead to reduce the wear rate. The investigation of the micro hardness can evaluate the change of the contact surfaces toughness. The capability of the lubricant is to promote the material's toughness and to reduce the influence of friction coefficient. These findings are in agreement with the findings of Greenberg *et al.* [23]. Micro hardness's are illustrated in **Figure 6**.

It is shown that the grooves are smaller using WS_2. The 2D profilometry image on the wear track of Al-16Si casting alloy couples shows wider and deeper traces of wear as shown in **Figure 7** which revealed greater material losses from the pin, this is due to deep fluctuations in the friction curve which could be attributed to strong adhesion between the contact regions.

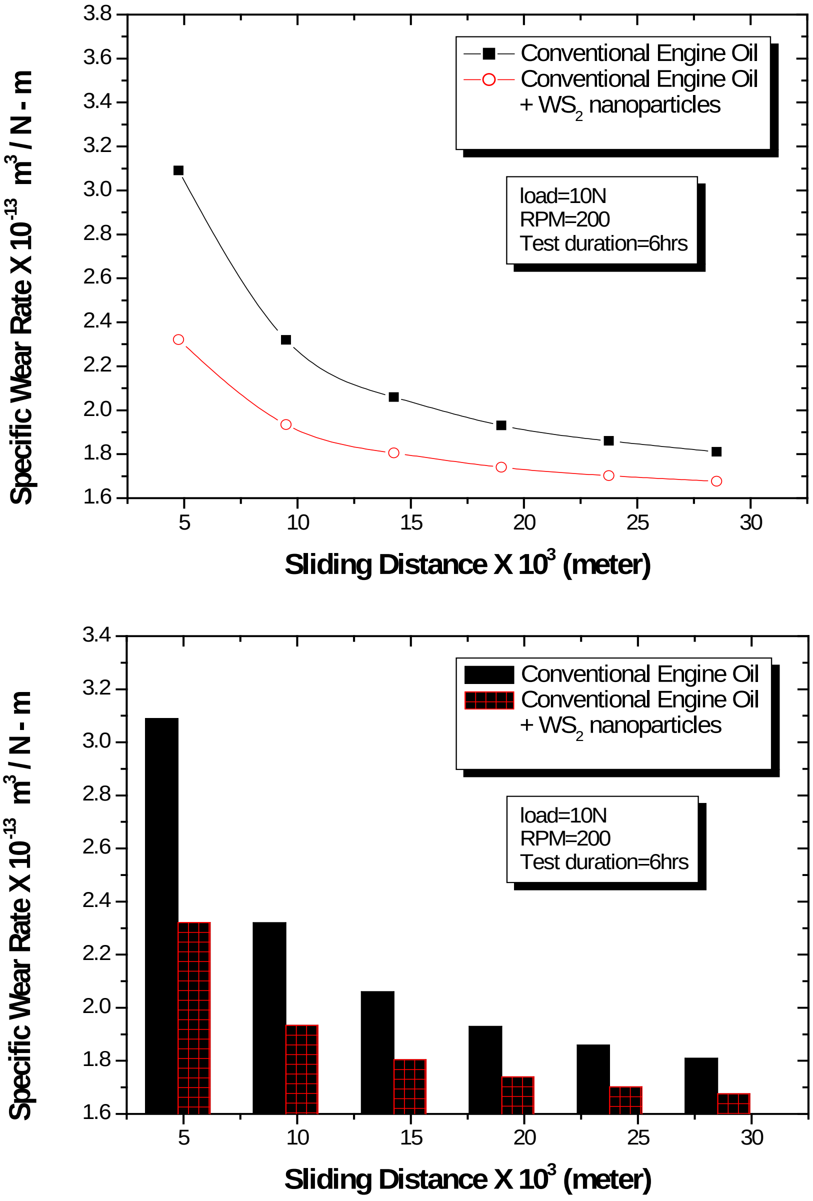


Figure 4 Variation of specific wear rate with sliding velocity of 200 rpm at 10 N.

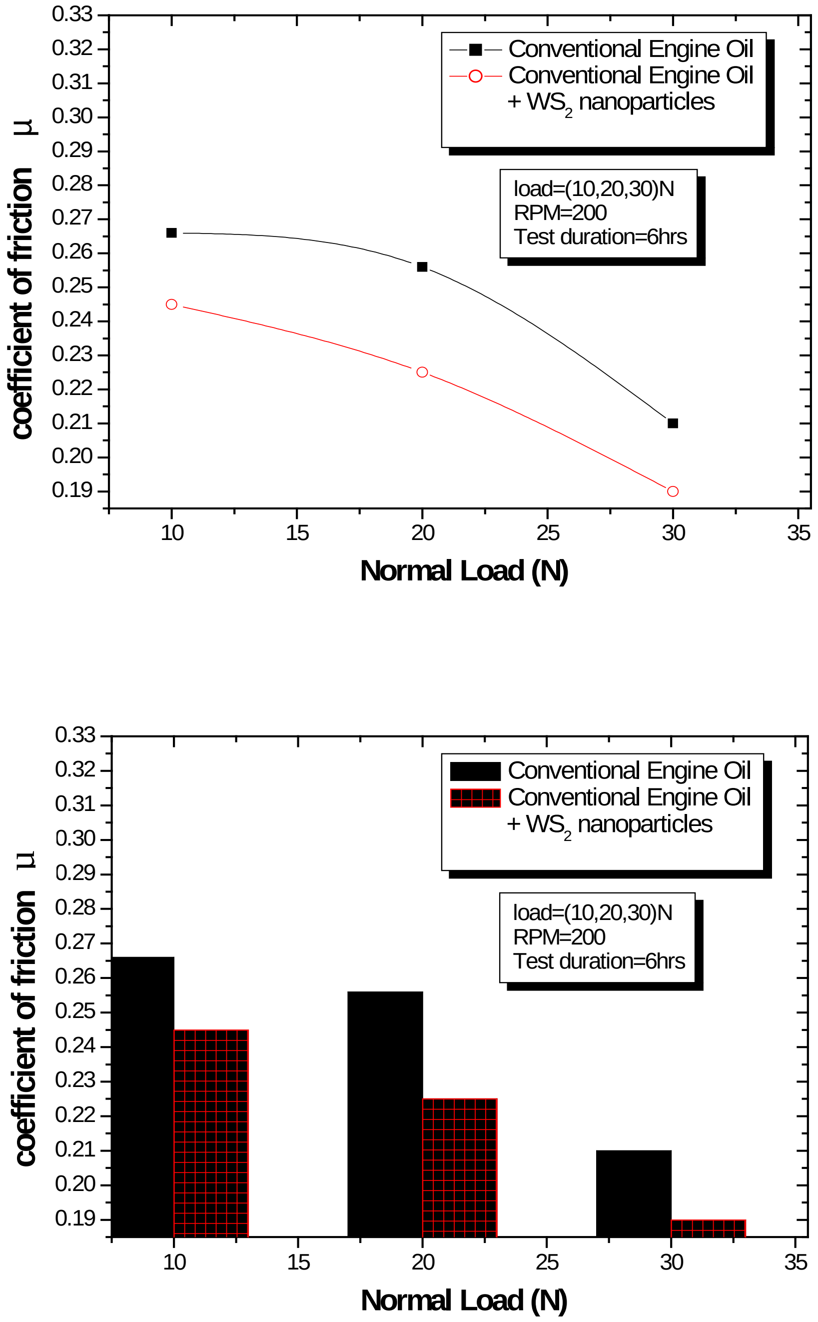
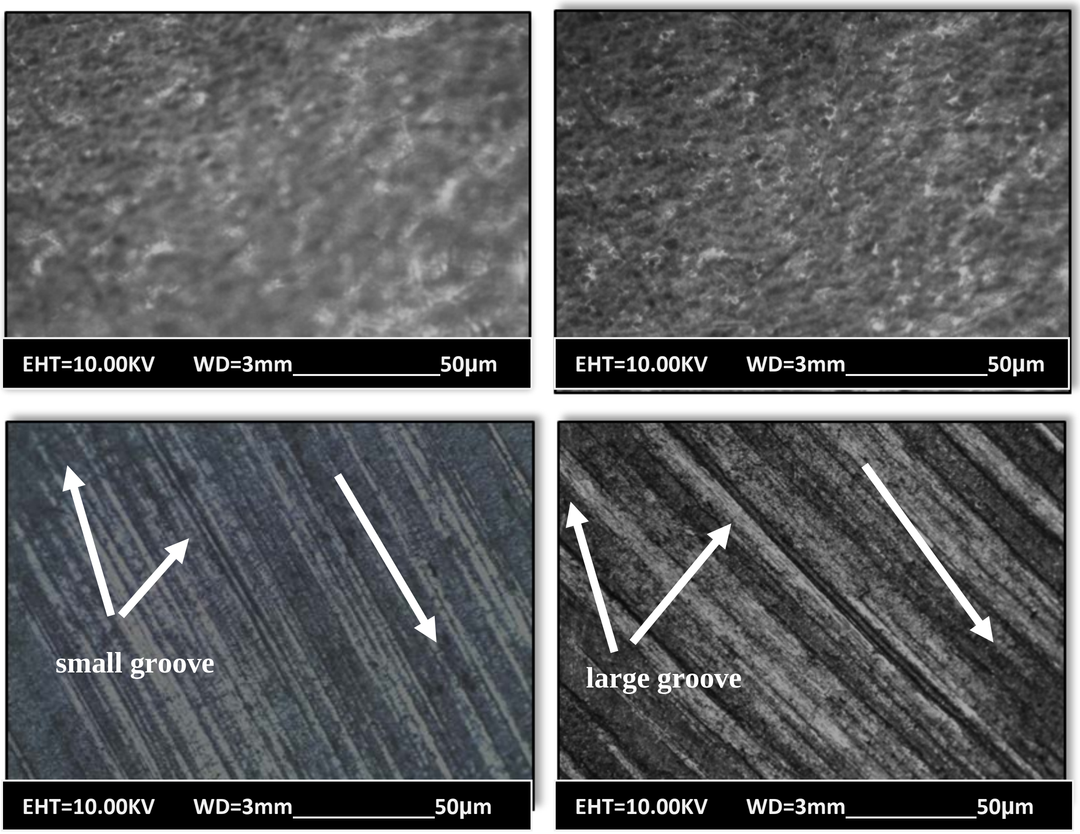


Figure 5 Variation of friction coefficient with normal load of 400 rpm at 30 N.



(a) (b)

Figure 6 SEM images of micrographs of surface wear and toughness of load 10 N & 200 rpm (a) using conventional oil + WS_2 nanoparticles. (b) using conventional oil only.

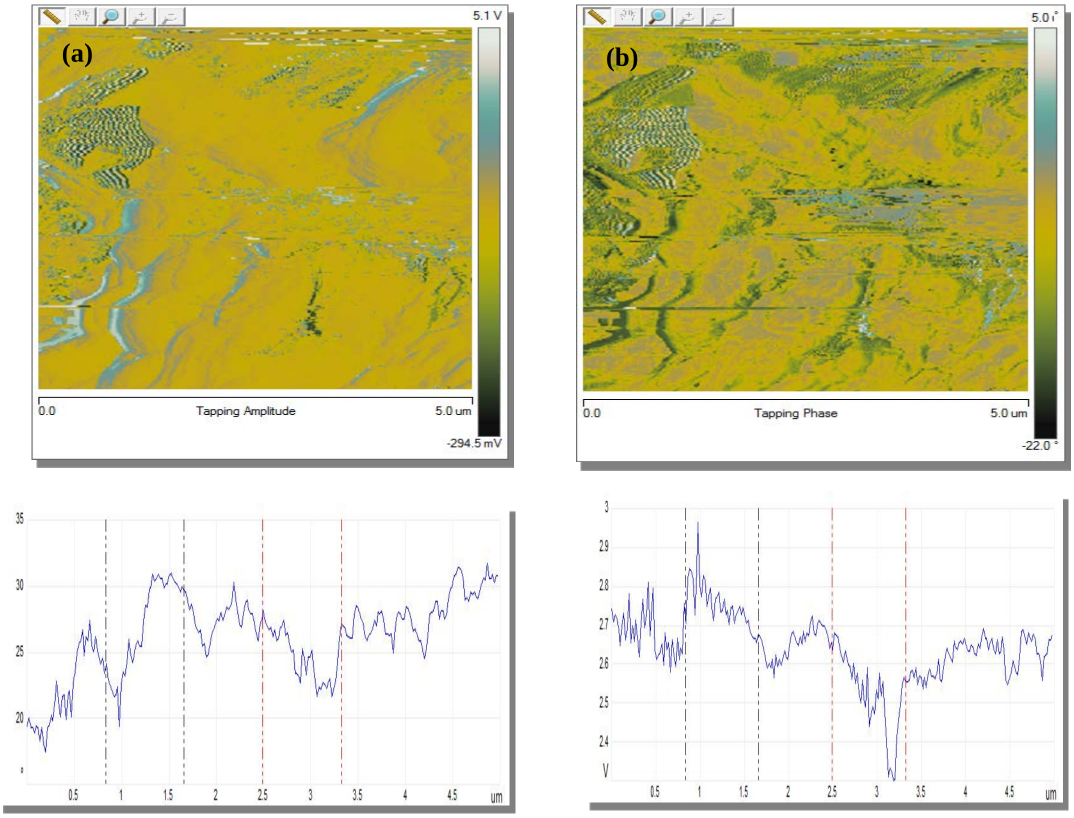


Figure 7 The 2D optical surface profilometry image on the wear track (a) using conventional oil + WS_2 nanoparticles. (b) using conventional oil only.

Conclusions

The use of WS_2 nanoparticles in the conventional oil has improved the tribology behavior of hypereutectic Al-Si alloys with carbon steel by reducing the wear rate and volumetric wear. There are optimal concentrations using WS_2 nanoparticles as an anti wear additive for reducing wear in the base oil. A modification of the rheological lubricating oil is observed by increasing the viscosity, where the particles are dispersed within the oil to format a layer lead to a reduced wear rate, resulting in a better position of the base oil. The friction coefficient was better with the addition of WS_2 nanoparticles due to strength of nano features and promotes the film at low temperatures, which reduces the friction coefficient. Finally, the use of WS_2 nanoparticle enhanced the viscosity of the oil.

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