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Tribological Properties of Carbon Nanocapsule Particles as Lubricant Additive

An experimental investigation is performed into the tribological properties of mineral oil lubricants containing carbon nanocapsules (CNCs) additives with various concentrations (wt.%). Friction characteristics and wear behaviors at contact interfaces are examined by the block-on-ring tests, high-resolution transmission electron microscopy (HRTEM), and mapping (MAP) analysis. The results suggest that the addition of CNCs to the mineral oil yields an effective reduction in the friction coefficient at the contact interface. Molecular dynamics (MD) simulations clarify the lubrication mechanism of CNCs at the sliding system, indicating the tribological properties are essentially sensitive to the structural evolutions of CNCs. [DOI: 10.1115/1.4027994]

Keywords: carbon nanocapsules, lubrication, lubricant additive

1 Introduction

Solid lubricant powders were among one of the earliest lubricant additives. Mabery [1] and Salomon et al. [2] performed friction tests to investigate the tribological properties of micrometer-sized graphite and molybdenum disulfide (MoS_2) powder. Recently, the development of nanotechnology opens unique opportunities to manipulate various lubricant mechanisms to achieve these desirable attributes of nanomaterial additives.

Kroto et al. [3] fabricated various types of monolayer carbon structure through the laser vaporization of graphite, and discovered fullerene, a form of carbon molecule. Kratschmer et al. [4] prepared fullerene (C_{60}) particles using argon ion beam sputtering, and examined their physical structure using infrared spectroscopy and X-ray diffraction measurements. Feng [5] reported that C_{60} particles have many favorable properties including a low surface energy, a high chemical stability, low friction, and a high load bearing capacity. Xue and Zhang [6] modified C_{60} particles in stearic acid using the Langmuir technique and conducted friction testing on glass plates. These results showed that C_{60} has improved tribological properties and yields an effective reduction in friction- and wear-related losses at the contact interface. However, due to the inherent hollow structure of single-walled fullerene molecules, they cannot sustain much compressive stress, and are prone to collapse [7–9], while the stability of structures is usually required in real application.

A sequential or hierarchical structure has been known to have a large part in determining bulk material properties of biological [10] and synthetic [11] structures. In this regard, the hierarchically onionlike material with a spherical shell geometry enables larger mechanical rigidity and may be more suitable for nanoscale applications, in particular in cases under drastic compression. Similar to carbon, the transition-metal dichalcogenides (e.g., MoS_2 and WS_2) form tubular and fullerene-like nanostructures.

Tenne [12] prepared multilayer MoS_2 and WS_2 nanoparticles using a saturated calomel electrode synthesis technique. Rapoport et al. [13] compared the tribological properties of hollow nanoparticles of WS_2 (HN- WS_2) with those of two solid lubricants, namely 2H- MoS_2 and 2H- WS_2 . The results showed that HN- WS_2 outperformed both solid lubricants in terms of a lower friction coefficient and a reduced wear. Rapoport et al. [14] investigated the feasibility of three inorganic fullerene-like materials (2H- MoS_2 , 2H- WS_2 , and IF) as additives to lubricants. The HRTEM analysis results indicated that the IF nanoparticles underwent compressional deformation and fracture. Cizaire et al. [15] examined the lubrication properties of IF- WS_2 particles by means of friction testing at a high load (1.1 GPa) in a vacuum environment. The results showed that the IF- WS_2 particles yielded an effective reduction in the friction coefficient. Chhowalla and Amarutunga [16] conducted friction testing under a high contact load using a sputtered MoS_2 nanoparticle film. The experimental results revealed that the MoS_2 nanoparticles resulted in a low friction coefficient, a low wear rate and an improved surface lubrication effect. Rapoport et al. [17] examined the behavior of WS_2 nanoparticles under severe contact conditions and showed that as the level of WS_2 nanoparticle addition increased, the friction coefficient reduced, giving rise to an improved wear resistance and a higher load bearing capacity. The scanning electron microscopy (SEM) analysis indicated that a large quantity of WS_2 particles adhered to the surface and filled in the friction scratches.

Although full-core inorganic multilayer nanoparticles such as those described in Refs. [6,13,15] have good antifriction properties, their tribological performance reduces under high loading conditions due to an irreversible change in the nanoparticle shape and structure. As a result, hollow-core fullerene materials (e.g., C_{60}), characterized by fully reversible deformation, low surface energy, and the potential for chemical modification, have attracted increasing attention in recent years [18,19]. However, it is difficult to mass produce uniform C_{60} molecules with a single-walled structure. Accordingly, in the present study, CNCs with an onion-like hollow-core structure are prepared using a novel pulsed arc discharge method [20]. The tribological properties of the CNCs

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when added to mineral oil lubricant in concentrations ranging from 0.01 to 0.1 wt.% are investigated by means of block-on-ring tests, HRTEM, SEM, energy dispersive spectroscopy (EDS), and MAP analyses.

2 Experimental Procedures

The CNCs were prepared by a pulse plasma arc discharge method under the following conditions: an argon gas (maintained between 1 and 2 atm) was introduced into an arc chamber containing a graphitic cathode and anode. A DC pulse current (60 Hz; ~ 20 V, and ~ 120 A) was applied to the chamber for a carbon arc reaction to take place. After 30 min, a deposit was formed on the cathode about 3–4 cm long and had the same diameter as the graphitic anode. The deposit on the cathode was collected and suspended in water by surfactant encapsulation, then passed through a 0.22 μm filter to separate the CNCs and carbon nanotubes. Finally, the surfactant was removed from CNCs using high speed centrifugation. The deposits contained roughly 70% CNCs before purification and at least 95% after purification [20,21]. The modification of the CNCs for lubricant is disclosed as follows. First, CNCs are suspended in hydrogen peroxide (H_2O_2) by sonication method to form black homogeneous solution, and then add ferrous sulfate solution slowly, with stirring, to generate hydroxyl radicals by the Fenton reaction (i.e., reaction of ferrous ion (Fe^{2+}) with hydrogen peroxide). The hydroxyl radical is very chemically reactive towards C=C double bonds of CNCs, and will add to the graphene layers of CNCs form a hydroxyl group covalently bound to the CNC surface via a free-radical addition. After hydroxylsis, the CNCs become very soluble in water to form black homogeneous solution with solubility of ~ 1 mg/ml. High resolution TEM image shows that the chemical functionalization does not cause noticeable damages in the inner graphene layers or the integrity of CNCs. Infrared (IR) absorption spectrum of the water-soluble CNCs shows distinct broadband absorption of hydroxyl groups at $\sim 3400\text{ cm}^{-1}$, C=C double bond strength at 1385 and bending mode at 1030 cm^{-1} . The second step, the hydroxyl modified CNCs (CNC-(OH) $_n$) can be further grafted with the alkyl chains by reaction with equivalent C18 stearic acid in an acidic solution with reflux. After purification, a lube oil additive CNC-(OCOC $_{18}$) $_n$ was prepared [6,22]. The suspension of base oil and CNC particles was thoroughly mixed with ultrasound (500 W, 60 Hz) for several hours. Then, the surface energy of the CNC particles was also reduced by means of wet-mechanical grinding. The HRTEM image presented in Fig. 1 shows that the CNC

Fig. 1 HRTEM image showing spherical multilayered structure of CNCs with particle size ranging from 30 to 100 nm

Fig. 2 Block-on-ring friction and wear test machine. (Schematic illustration).

Table 1 The element compositions of SKD11 materials for block-on-ring tests

Element	Content (%)
Carbon (C)	1.50
Silicon (Si)	0.25
Manganese (Mn)	0.45
Chromium (Cr)	12.0
Molybdenum (Mo)	1.0
Vanadium (V)	0.35

particles have a onionlike structure with the particle size ranges from around 40 to 80 nm. The CNCs were added to the lubricant in concentrations of 0.01, 0.03, 0.05, 0.07, and 0.1 wt.%, respectively. The tribological properties of the various lubricants are then evaluated using a block-on-ring friction and wear testing machine [23] with the configuration shown in Fig. 2. The block-on-ring tests were performed using SKD11 materials, where the element compositions of SKD11 materials have been displayed in the Table 1. Table 1 displays that the SKD11 workpiece has been well-controlled with a relatively low carbon content, implying the influences of the carbon content originated from SKD11 on the following EDS analyses can also be reasonably ignored. Moreover, to isolate the lubricant effect of the CNC additives on the tribological properties between the sliding pairs, all of the SKD11 workpiece have been prepared using identical fabrication conditions in order to specify the lubricant improvement through CNC additives. The hardness of the blocks ranged from 32 to 35 HRC, while that of the rings ranged from 63 to 65 HRC (nitride treatment). All of the SKD11 materials were ground and polished to a final surface roughness of $R_a = 0.2\text{ }\mu\text{m}$. The related experimental parameters are summarized in Table 2. Accordingly, the mineral lubricant is with oil viscosity $cSt = 151.7$, while that of the pressure-viscosity coefficient $VI = 95$. The Hertzian contact load (pressure) was assigned two different values, namely 650 N (261 MPa) and 1000 N (323 MPa). The film thicknesses are predicted according to an elastohydrodynamic lubrication model (EHL) [24]. The ratio of oil film thickness to the surface roughness, λ , is 0.549 and 0.532, respectively [23–25].

3 Results and Discussion

It is well-known that the mobility and tribological properties of nanoparticle containing lubricant will be significantly changed by the formation of nanoparticle aggregation. In order to avoid an

Table 2 Experimental parameters used in block-on-ring friction wear tests

Conditions	Friction lubrication					
Base lubricant	Mineral oil					
Environment	Ambient air 50% humidity					
Contact type	Block-on-ring					
Experimental time (min)	30					
Load (N)	650	1000				
Maximal contact pressure (MPa)	261	323				
Sliding velocity (m/s)	0.55	1.1	1.65			
CNC particle concentration (wt.%)	0.01	0.03	0.05	0.07	0.1

Fig. 3 High-resolution SEM and TEM images showing surface dispersion of CNC particles in lubricants with different CNC concentrations: (a) 0 wt.%, (b) 0.01 wt.%, (c) 0.03 wt.%, (d) 0.05 wt.%, (e) 0.07 wt.%, and (f) 0.1 wt.%

aggregation effect on the tribological properties of the present lubricants, all of the samples were prepared using identical surface functionalization to enhanced colloidal stability and homogenous distribution of nanoparticles in the base-oil. In this study, the six lubricant samples were titrated on a silicon surface and analyzed using SEM. The results showed that the dispersion morphology of

CNC nanoparticles in the samples containing 0.05, 0.07, and 0.1 wt.% CNC addition were evenly distributed on the silicon surface (see Fig. 3). The present results imply that the effectiveness of the surface energy modification processes in reducing the aggregation of CNC particles within the lubricant. Thus, the effectiveness of the wet-mechanical grinding and chemical

Fig. 4 Variation of friction coefficient over time as function of CNC concentration. Note that the load and sliding velocity have values of 650 N and 1.65 m/s, respectively.

modification processes in breaking up the CNC particle clusters is further confirmed.

Stability, or a lubricant's ability to keep its originally tribological performance after long-term operation, is a key criterion in assessing lifetime reliability of lubricant systems. The present study has investigated the time-related effect on the different lubricants with various CNC concentrations in order to enhance the design quality of future endurance lubricants. Figure 4 shows the variation over time of the friction coefficient of the different lubricant samples given a contact pressure of 650 N and a sliding velocity of 1.65 m/s. It is noted that the addition of the CNCs to the mineral oil lubricant has a relatively time-insensitive characteristic and yields an effective reduction in the friction coefficient. In addition, it is seen that the minimal friction coefficient is obtained using a CNC addition of 0.05 wt.%. Finally, in this study, the average friction coefficients have been estimated through classical block-on-ring tribological tests at a sliding velocity of 1.65 m/s for 30 min.

Fig. 5 Variation of friction coefficient with CNC particle concentration given sliding velocities ranging from 0.55 to 1.65 m/s and a constant contact load of 650 N

In order to investigate the relative influences of sliding velocities and CNC concentrations on the tribological properties of the current lubricants, we conduct block-on-ring test under various sliding velocities in the range of 0.55 m/s–1.65 m/s and consider a series of lubricants with various CNC concentrations varying from 0 wt.% to 0.1 wt.%. As shown in Fig. 5, it shows that the lubricants with CNC nanoparticle addition have a lower friction coefficient than the pure oil lubricant. In fact, the main favorable benefit of the nanoparticle as oil additives is attributed decidedly to the following two effects, namely, ball bearing mechanism [26,27] and third body materials forming mechanism [28]. Specifically, the present frictionless phenomenon can be most likely attributed to the fact that a ball bearing effect induced by the spherulike multilayered structure of the CNC particles [29–32]. As shown in Fig. 6, further evidence shows that the bearing effect [33] of CNC particles existed between the rubbing surfaces, the surface polishing and the increase in carbon-based lubricant layer due to the deformed CNC nanoparticles were the main reasons for

Fig. 6 Penetration and filling behavior of CNC particles in lubricants with CNC particle concentrations of: (a) 0.01 wt.% and (b) 0.05 wt.%.

Fig. 7 Variation of friction coefficient with CNC particle concentration given sliding velocity of 1.65 m/s and the applied loads of 650 N and 1000 N

the reduction in wear and friction. It is also shown in Fig. 6(a) that for a low CNC particle addition (i.e., 0.01 wt.%), the CNC particles pile up the surfaces of the scratch marks on the wear surface. As a result, the friction coefficient is relatively high (see Fig. 6). However, for a CNC particle addition of 0.05 wt.%, the

Fig. 8 Variation of wear volumes with various CNC particle concentrations given the applied loads of 650 N and 1000 N, respectively

particles fully penetrate and fill the scratch marks, as shown in Fig. 6(b). Thus, the antifriction and antiwear properties of the lubricant are significantly enhanced. Specifically, the penetration and filling behavior of the CNC particles are most likely to be governed jointly by the level of CNC addition and the sliding

Fig. 9 (a) TEM, (b) and (c) SEM, (d) and (e) EDS, and (d) MAP analysis results for wear surface given contact load of 650 N. (Note that the CNC concentration is 0.05 wt.% and the sliding velocity is 1.65 m/s.)

velocity [34]. As shown in Fig. 5, it shows that friction coefficients of CNC-based lubricant increase with increasing working speeds. This might be explained by the fact that the stored torque might be maximized due to relatively high rotating speeds, leading to the onset of rolling movement of CNC additives. The speed of the additional nanoparticle plays a key role in increasing the tribological properties of CNC-based lubricants by acting as a “ball bearing” between the sliding pairs. This phenomenon is in good agreement with the findings by Berthoud et al. [35,36].

To better understand a relationship between the tribological properties and contact loads, the typically tribological analyses are employed to estimate the tribological performances and surface morphological characteristics for the representative lubricant samples. Figure 7 shows the variation of the friction coefficient with the CNC particle concentration as a function of the contact load (i.e., 650 N or 1000 N). It is noted that the sliding velocity is equal to 1.65 m/s in both cases. It is seen that for all values of the CNC particle concentration, the friction coefficient increases with an increasing load due to a relative increase in the contact area between the asperities on the two sliding surfaces. The greater load leads to plastic deformation and fracture of the CNC particles. Consequently, the ability of the particles to penetrate and uniformly fill the scratches on the wear surface is reduced. Moreover, the particle structure transforms from the original spherelike multilayered structure to a graphitelike layered structure; prompting a change from a rolling lubrication mode to a sliding lubrication mode [14,37]. In comparison, it is observed that the lubricant efficiency (namely reduction in the friction coefficients) between a mineral oil with and without CNC additives at the different loading conditions were accounted for approximately 25 and 18 percent of friction reduction, respectively.

Wear measurements according to the wear volumes of wear track on the workpieces (see Fig. 8) show that the antifrictional efficiency of the CNC nanoparticles reflects the longevity of friction pairs. Figure 8 shows a comparison of the wear results between the base oil and the same oil containing CNC nanoparticles with various concentrations ranging from 0.01 to 0.1 wt.% under the different loading of 650 N and 1000 N, respectively. The present results show that the wear volumes are sensitive to concentrations of CNC nanoparticles under the representative loading conditions. This phenomenon can be explained by the fact that the CNCs penetrate into the ploughing tracks on the contact surface [17,38,39], protecting the rubbed surfaces from a direct contact and thus increase lubrication mechanism.

Interestingly, a similar trend is also noted for the friction coefficient. It is tempting to associate the higher friction coefficient of contact surfaces with its lower CNC concentrations, which can induce severe damages of a thin near surface layer [40], thus resulting in the extensive removal of materials occurring layer by layer. This phenomenon can be attributed to the fact that a greater extent of plastic deformation and exfoliation induced by asperity junctions [41,42] and interface adhesions [43] as a result of friction mechanism. It should also be noted that at the higher loading condition, there is a dramatic rise in the value of wear volumes of the each lubricant samples. This phenomenon can be attributed to the fact that more the direct contact spots and wear-induced reactivity are induced as CNC additives between the two interfaces are deformed by highly anisotropic stress distribution. A similar observation was also reported for the lubrication mechanism of carbon nano-onions by Bucholz et al. [44].

To clarify the effects of an increasing contact pressure in reducing the penetration and filling behavior of the CNC particles, the wear debris and wear surfaces of the experiment specimens were analyzed using HRTEM, SEM, EDS, and MAP techniques. Figure 9(a) presents the corresponding results for the case of a contact load of 650 N. It is seen that although the outer layers of the CNC particles have minor chipping, the particles basically retain their original spherelike shape (see illustration). Furthermore, the SEM observations reveal that a large number of CNC particles penetrate and fill the scratches on the wear surface (see

Fig. 10 (a) SEM and EDS analysis results for wear surface given contact load of 650 N. (Note that the CNC concentration is 0.05 wt.% and the sliding velocity is 1.65 m/s.

Fig. 9(a)). The EDS analysis results confirm the existence of a high carbon content on the wear surface (wt. %: 80.41, at. %: 94.79) (see Figs. 9(b) and 9(c)). Finally, the MAP analysis results confirm that a large number of CNC particles are distributed on the scratched surface and within the individual scratches (see Fig. 9(d)).

In this study, the EDS analysis results have been provided to confirm the existence of a high carbon content on the wear surface, indicating the lubricants with CNC additives acts as a ball bearing and separator to support frictionless mechanism and facile moving between the mating surfaces. In fact, the carbon content characterized by the present EDS analyses might slightly originate from wear debris (namely SKD 11 materials). In order to avoid confusing, we have displayed the EDS results corresponding CNC additives and wear debris distributed on the scratched surface in the Fig. 10. Significant differences, however, occur for carbon content around the scratching region. Specifically, the EDS results regarding to carbon content might be primarily detected by CNC nanoparticles rather than wear debris, implying CNC nanoparticles act as a ball bearing and separator to provide frictionless mechanism and wear resistance between the mating surfaces.

Figure 11 presents the SEM, EDS, and MAP analysis results for the wear surface given a higher contact load of 1000 N. As shown in Fig. 11(a), CNC particle structures undergo significant plastic deformation and fracture under the effects of the higher load (see illustration). The SEM analysis results show the presence of a graphitelike layer of the wear surface (see Fig. 11(a)). In addition, it is seen that the wear surface contains a large number of scratch marks. The EDS analysis results confirm that the wear surface has a high carbon content (wt. %: 67.06, at. %: 90.08) (see Figs. 11(b) and 11(c)). Finally, the MAP analysis results reveal that only a

Fig. 11 (a) and (b) SEM, (c) EDS, and (d) MAP analysis results for wear surface given contact load of 1000 N. (Note that the CNC concentration is 0.05 wt.% and the sliding velocity is 1.65 m/s.)

small number of CNC particles penetrate the scratches (see Fig. 11(d)). Therefore, the results presented in Figs. 9 and 11 show that an increasing load prompts the deformation and fracture of the CNC particles; thereby limiting their ability to penetrate and fill the scratches on the wear surface and causing a transition of the original rolling lubrication mode to a less-efficient sliding lubrication mode.

To better understand tribological behavior of nanoparticle additives between contact surfaces, the classical MD simulation has been studied to provide microscopic insight of the lubricant mechanism. The lubrication mechanism of the individual C_{60} nanoparticles during the loading–sliding process was investigated at the atomic-scale by means of MD simulations using the model shown in Fig. 12. In constructing the model, the atomic arrangements of the slab and substrate were assumed to be consistent with the (111) diamond lattice, in which the separation distance between the slab and the substrate was varied in order to simulate different sliding conditions [45]. The fullerene particles (C_{60}) were assumed to have a diameter of approximately 7 Å. The C–C interactions within the C_{60} walls were simulated using the Tersoff potential [46]. Meanwhile, the Lennard–Jones (LJ) potential [47] is used to model the C_{60} –carbon and the C_{60} – C_{60} interactions. These potentials have been used successfully in previous studies of the mechanical properties of nanotubes [48–54] chemical functionalization, [55], and the diffusion of gases through CNTs [56,57]. A loading and sliding process is performed with a time step of 0.5 fs, respectively. It is necessary to note that the experimental sliding rate is many orders of magnitude slower than the simulation rate, which is comparable to that used in the present MD simulations. Due to the computational intensity of the congenital problem, many of these simulations were restricted to smaller model sizes or to very high speeds, or to both. However,

the present MD simulations are nevertheless adequate for generating qualitative estimates. Although the higher loading–sliding speed is employed in the present simulations, this simplification is considered reasonable in the present qualitative investigation. However, an important unresolved issue remains, namely, the extent to which the results would be affected by the application of more robust potentials. The velocity of the atoms at a constant temperature is described by the Maxwell velocity distribution. Meanwhile, the NVT mode [46,58] is used to control the number of atoms N , the volume V , and the temperature T .

In order to elucidate the tribological mechanism of CNC additives in different regimes, the corresponding atomistic

Fig. 12 MD simulation model used to investigate loading–sliding behavior of individual C_{60} nanoparticle

Fig. 13 Atomistic configurations showing three distinct tribological mechanisms of an individual C_{60} nanoparticle during loading-sliding process: (a) rolling ($\curvearrowright$), (b) rolling-sliding ($\curvearrowright$), and (c) sliding ($\rightarrow$).

configurations of the structural transformation of CNC in Figs. 9(a) and 11(a) are schematically shown in Figs. 13(a)–13(c). As shown in Figs. 13(a)–13(c), it is seen that a spherical C_{60} nanoparticle breaks down to form a graphite sheet as the distance between the slab and the substrate gradually reduces. Note that a metastable sphere-to-sheet phase transformation of the C_{60} nanoparticle has been taken place under a relatively higher loading condition (i.e., the spacing between the two wall layers is around 3.9 Å). A similar observation was reported for the toughness of multiwalled CNCs by Asaka et al. [19]. Figure 13(a) shows the C_{60} nanoparticle is tend to rolling movement, implying C_{60} nanoparticle acts as nanoscopic ball bearing between the contact surfaces and provides expected frictionless mechanism. In comparison, Fig. 13(c) shows that the squashed C_{60} nanoparticle locks with the flat mating surfaces; resulting in a higher localized friction at the faceted interface, thus, the C_{60} nanoparticle tends to slide rather than roll. Overall, the present results imply that the tribological mechanism is sensitive to the structural transformation of the CNC additives. Note that this finding is consistent with that reported for individual multilayered carbon nanoparticles under compression by Tevet et al. [29].

4 Conclusion

This study has examined the tribological properties of CNC nanoparticles used as additives in a mineral oil lubricant. It has been shown that a good dispersion of the CNC additives within the lubricant can be achieved by reducing the surface energy of the particles by means of wet-mechanical grinding and chemical modification using stearic acid. Block-on-ring friction sliding tests have been performed using mineral oil lubricant samples containing CNC particles with concentrations ranging from 0.01 to 0.1 wt.%. In general, the results have shown that for the SKD11 blocks and rings used in the present tests, the minimum friction coefficient is obtained using a CNC particle addition of 0.05 wt.% and a sliding velocity of 1.65 m/s. The HRTEM, SEM, EDS, and MAP analysis results have shown that under lower loads (i.e., 650 N), the CNC particles penetrate and fill the scratches on the wear surface. Moreover, the particles retain their original sphere-like structure and therefore provide a rolling lubrication mechanism. However, under higher load conditions (1000 N), significant deformation and fracture of the CNC particles occurs as a result of shear friction effects. As a consequence, the ability of the

particles to penetrate and fill the scratches on the wear surface is reduced. Furthermore, the loss in spherical shape of the CNC particles prompts the lubrication mode to transit from a rolling lubrication mode to a sheetlike sliding lubrication mode. Finally, the MD simulation results have confirmed that the C_{60} lubrication mechanism is sensitive to the structural transformation of the nanoparticles.

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Nomenclature

A	= ampere
Å	= Angstrom (10^{-10} m)
at. %	= atomic percent
atm	= atmosphere
cSt	= centistokes (mm^2/s)
DC	= direct current
HRC	= rockwell hardness
Hz	= hertz
MPa	= million pascal (N/mm^2)
N	= Newton ($\text{kg}\cdot\text{m}/\text{s}^2$)
Ra	= center line average roughness
V	= volt
VI	= viscosity index
W	= watt
wt.%	= weight percent
λ	= oil film thickness to the surface roughness ratio

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