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Lubricating Effect of Water-soluble Hexagonal Boron Nitride Nanolubricants on AISI 304 Steel Sliding Pair

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Abstract – In this study, we investigate the tribological behavior of AISI 304 stainless steel pairs under deionized water and hexagonal boron nitride (h-BN) water dispersion lubrication. The specimen friction and wear properties are evaluated using a reciprocating ball-on-flat tribometer. The coefficient of friction remains nearly constant throughout the test under both lubricant conditions. The wear depth of the specimens under h-BN lubrication is smaller than that under deionized water lubrication, indicating the inhibition behavior of h-BN nanolubricants on direct metal–metal contacts. Optical micrographs and stylus profilometer measurements are performed to evaluate the severity of damage caused by the sliding motion and to determine the wear morphology of the specimens, respectively. The results show that h-BN nanolubricants does not have a significant effect on the friction behavior but demonstrates reduced wear owing to their trapping effect between the sliding interfaces. Moreover, scanning electron microscopy and energy-dispersive X-ray spectroscopy images of the specimens were acquired to confirm the trapping effect of h-BN between the sliding interfaces. The results also suggest that the trapped lubricants can distribute the contact pressure, reducing the wear damage caused by the metal–metal contact at the interface. In conclusion, h-BN nanolubricants have potential as an anti-wear additive for lubrication applications. Further investigation is needed to provide direct evidence of the trapping effect of h-BN nanoparticles between the sliding interfaces. These findings could lead to the development of more efficient and effective lubricants for various industrial applications.

Keywords – Reciprocating sliding, Aqueous additive, Nanolubricant, AISI 304 steel

1. Introduction

Friction and wear in machinery and equipment contribute to almost a quarter of worldwide energy consumption, resulting in significant energy and revenue loss for industrial sectors. To address these issues, various lubricants has been used [1-3]. Among the lubricants, hexagonal boron nitride (h-BN) has been regarded as an effective lubricant due to its chemical inertness, thermal stability, high strength, and non-toxicity [4]. Its layered hexagonal crystal structure, which resembles graphite and exhibits covalent bonding in-plane and Vander Waals bonding out-of-plane, is also attributed to its low friction mechanisms. In 2013, the performance of h-BN as an aqueous lubricant was evaluated using a SiC ball and Si flat sliding pair, revealing that even small amounts of h-BN can

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significantly reduce friction and wear[5]. However, the sliding combination of SiC and Si is not a typical pair for mechanical components, so further evaluation of the possible lubricating effect of h-BN in water is needed.

In this study, we investigate the friction and wear of AISI 304 ball and AISI 304 flat specimen pairs under the lubrication environments of DI water and aqueous dispersions of h-BN to compare the effectiveness of both lubricants. As mentioned above, AISI 304 steels are commonly used materials for mechanical components that endure sliding friction, such as gears and screws. To do this, we measured friction force during sliding tests and analyzed wear scars using optical microscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). The aim of this study is to provide insights into the potential of h-BN nanoparticles as an effective lubricant for improving the wear resistance of AISI 304 steel.

2. Experimental Details

2-1. Materials

For the reciprocating sliding tests, AISI 304 steel flats and balls were used. The flats measured 27 mm wide by 69 mm long and 4 mm thick, while the balls had a radius of 10 mm. All flats and balls were procured from their manufacturer (R&B Republic of Korea) and were polished using a lapping process to maintain a mirror finish and avoid unwanted surface imperfections. After the lapping process, the average roughness of the untested AISI 304 flat specimen was approximately Ra = 0.028 μm.

2-1-1. Preparation of test materials

Lubricants were prepared prior to the experiments to ensure proper lubrication settings. A bath sonication method was used to prepare the h-BN solution, while DI water was used as obtained. To select the appropriate concentration of h-BN for the experiments, several trials were conducted. Based on these trials, a 0.1 wt% h-BN solution in DI water was chosen, as it demonstrated even distribution of h-BN nanoparticles with minimal agglomeration and a good zeta potential and particle size. Additionally, this concentration of h-BN synthesized by bath sonication method is non-toxic as it does not involve any chemicals or surfactants for lubricant preparation and has been shown to be an excellent lubricant in our previous works[5,6].

To prepare the h-BN solution, the h-BN powder was manually mixed with DI water for 5 minutes before being bath sonicated for 3 hours at room temperature. The sonicated mixture was then centrifuged for approximately 5 minutes at 600 RCF to ensure

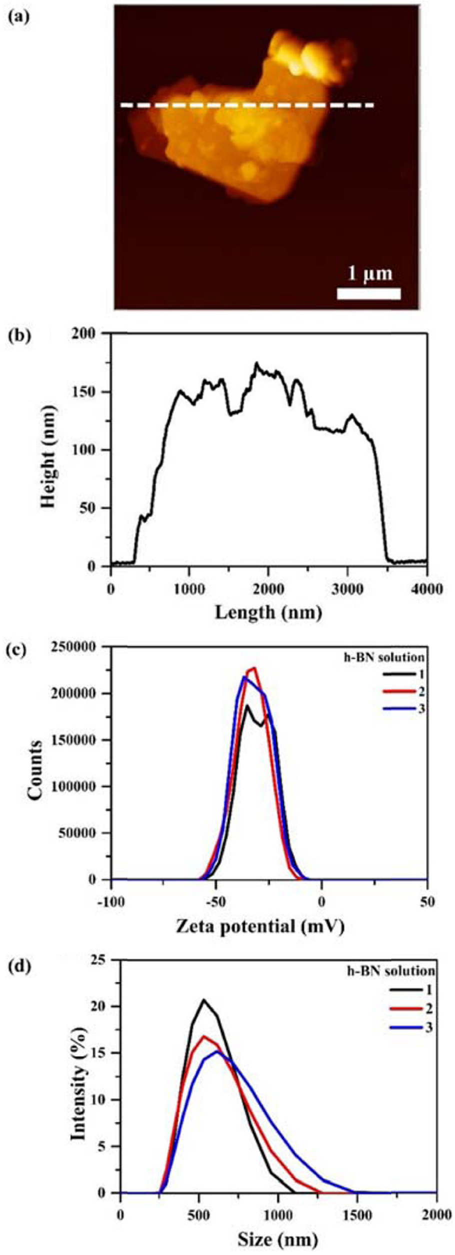

Fig. 1. h-BN nanoparticle measurement using AFM (a) Topography, (b) Width and height (along the white line of Fig. 1(a)) and measurements using particle analyzer, (c) Zeta potential (d) Size.

complete scattering of the h-BN nanoparticles throughout the DI water. Prior to inserting the h-BN solution into the sliding tester's lubricant bath, the centrifuged solution was sonicated for approximately 5 minutes to avoid h-BN particle aggregation and chilled for around 5 minutes to stabilize the solution temperature.

To measure the width and height of the dried h-BN particles, a 0.1wt% h-BN solution was spread on Si wafers and dried using a heating plate. The dried nanolubricants were then measured using AFM with an intermediate contact mode. Figure 1(a) shows a representative image of an h-BN nanolubricant scanned by atomic force microscopy (AFM, Hitachi 5100N). The width and height of the representative h-BN nanolubricant were measured to be approximately 3000 nm and 130 nm, respectively as shown in Fig. 1(b).

Three different h-BN sample solutions were used for zeta potential and size measurements using a nanoparticle analyzer (Malvern Panalytical, ZEN3600) as shown in Fig. 1(c and d). The solutions were found to be negatively charged in the range of about −42.0 to −46.0 mV, indicating good stability and proper suspension of the h-BN particles in DI water. The average h-BN nanoparticle size measured using the nanoparticle analyzer was approximately 1280 nm (Fig. 1(d)).

2-2. Reciprocating sliding test

We used a ball-on-flat reciprocating sliding tester RB 104 FW, manufactured by R&B, Republic of Korea as displayed in Fig. 2. The sliding tester has a reciprocating stroke ranging between 10 and 90 μm, a maximum operating frequency of 30 Hz, and a maximum applicable normal load of 300 N. Before each experiment, the AISI 304 flats and balls were cleaned with DI water for 10 minutes in a bath sonicator. They were then cleaned for 10 minutes in a bath sonicator with 99.5% pure acetone and 70% purity ethanol.

The flat was assembled in the base test fixture, and the ball was mounted to the actuator. The ball was set to reciprocating motion on the flat counterpart. After attaching the ball to the actuator on the flat, we applied a normal load of 58.8 N using steel metal plates on the loading area provided on top of the machine. This loading arrangement will be made to be placed on the actuator connected with the ball specimen. Then, the nanolubricant was added to the test bath. The lubricant level was set to be enough to include the sliding surfaces.

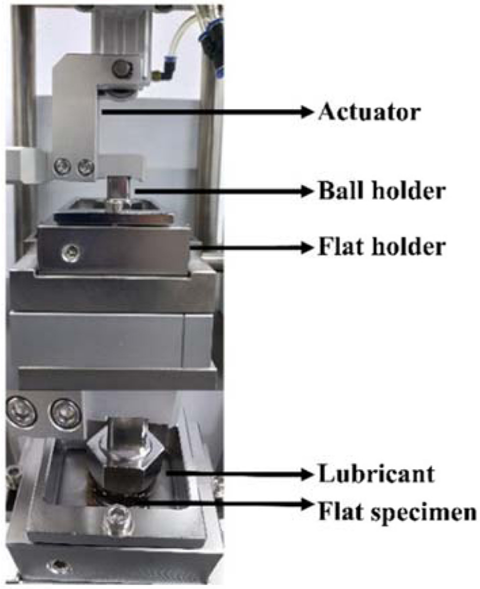

Fig. 2. Photograph of the reciprocating sliding wear tester along with ball and flat specimens immersed in lubricant bath.

Friction data were acquired during the sliding tests every 1 ms. We carried out the experiments for a reciprocating stroke of 50 μm for 84 minutes at a frequency of 2 Hz. The coefficient of friction (COF) was acquired by computing the mean absolute value of each reciprocating cycle. We conducted all the reciprocating sliding tests at 23°C, and after each test, we carried out ex-situ experimental characterizations.

2-3. Ex-situ characterizations

After each sliding test, we obtained optical photographs of the worn surfaces using a Nikon Eclipse LV100ND optical microscope. We measured the wear depth and roughness of the flats using a Bruker DektaxXT stylus profilometer. To visualize the micro wear debris, oxidation level of worn surfaces, and deposited nanolubricant on the wear scar, we employed a field emission SEM (ThermoFisher Scientific Apreo2). We also used the same equipment for EDS analysis to confirm the elemental weight percent and atomic percent of the specimens, wear debris, and nanolubricant on the wear scar.

3. Results and Discussion

Figures 3(a and b) show that the COF remains

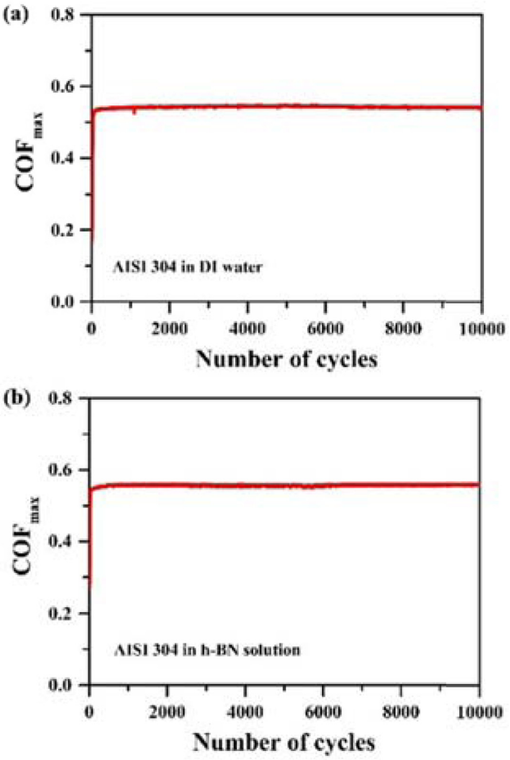

Fig. 3. Variation of COF of AISI 304 flat specimens under the lubrication of (a) DI water and (b) h-BN water dispersions at 50 μm reciprocating stroke and 58.8 N normal load.

nearly constant throughout the test for both lubricant conditions. The COFs recorded from the AISI 304 pairs under the lubrication of DI water and h-BN water dispersions do not show a significant difference, revealing that the h-BN lubricants do not have an influence on the friction behavior.

The COF value for the DI water tests were about 0.53-0.54 and the h-BN tests show a COF of about 0.55. These values are almost constant for the whole reciprocating sliding tests and their reproducibility was confirmed by performing the tests for two to three times.

Optical micrographs were taken to determine the severity of the damage caused by the ball counterpart's reciprocating sliding motion. As shown in Fig. 4, the tests with DI water result in more severe damage than the h-BN cases. It can be speculated that h-BN nanolubricants prevent tribopairs from making direct metal-metal contact while sliding, as reported in previous studies[7,8].

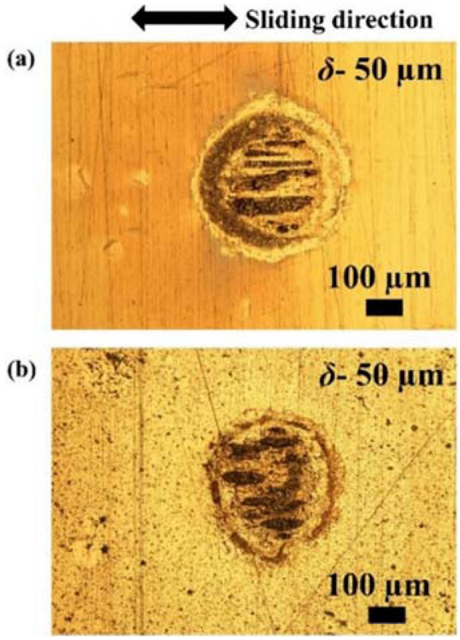

Fig. 4. Optical morphologies of AISI 304 studied under (a) DI water and (b) h-BN water dispersions at a reciprocating stroke of δ = 50 μm and a normal load of 58.8 N.

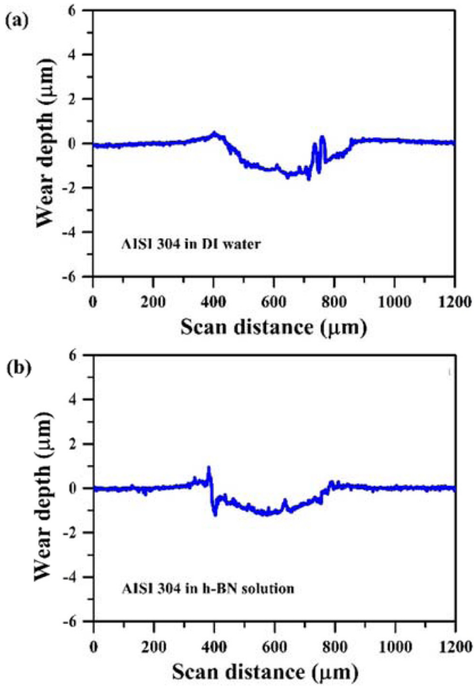

Fig. 5. Wear morphologies of AISI 304 tested with (a) DI water, (b) h-BN with 50 μm reciprocating stroke and at a normal load of 58.8 N.

The wear morphologies of flat specimens were measured using a stylus profilometer. All the wear scars were measured parallel to the sliding motion, as shown in Fig. 5. The measured wear depth was about 1.4 μm (Fig. 5(a)) with DI water and 1.0 μm (Fig. 5(b)) in h-BN tests. This reduced wear depth with h-BN tests is another significant evidence for the inhibition behavior of h-BN nanolubricants against direct metal-metal contacts.

During sliding motion, metal to metal contact at the interface is prominent with DI water tests. But with h-BN tests, even though there is an initial contact between surfaces at the interface, h-BN nanoparticles may fill up the interface contact area, trapping on the sliding interfaces and compensating for the loss of material, thus reducing wear damage[7,8]. To check this idea, SEM and EDS micrographs were acquired (Fig. 6).

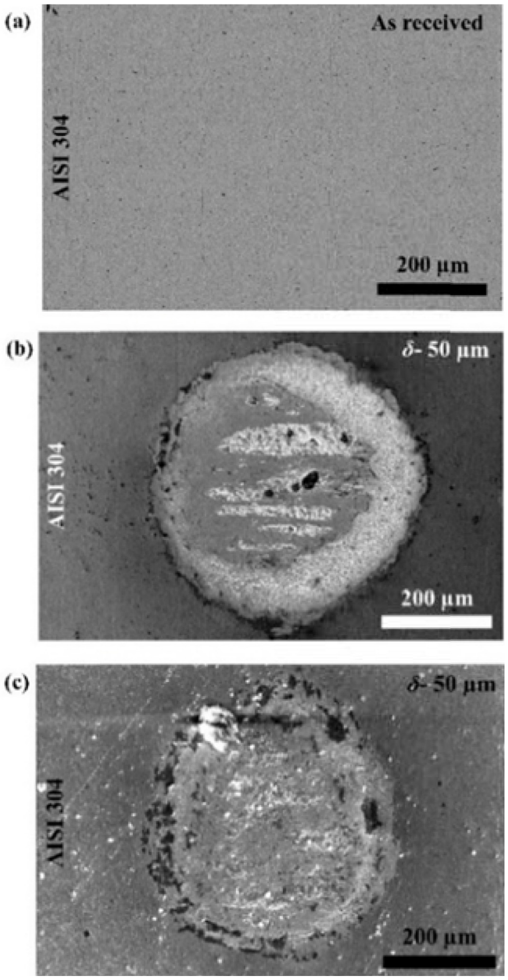

Fig. 6. SEM micrographs of AISI 304 (a) Pristine and tested with (b) DI water, (c) h-BN at a reciprocating stroke of δ= 50 μm with a normal load of 58.8 N.

Figure 6(a) shows SEM and EDS images representing the oxygen signal of the pristine surface. DI water tests (Fig. 6(b)) show significant material removal when compared to h-BN (Fig. 6(c)). This can also be attributed to the h-BN trapping between sliding interfaces, where the trapped lubricants can distribute the contact pressure, so that the severe wear was not dominant when h-BN was used as nanolubricant[5,7,8].

To conclude, the h-BN nanolubricants do not have significant effect on the friction behavior but can reduce wear due to their trapping effect between the sliding interfaces.

4. Conclusion

In this study, the tribological behavior of AISI 304 stainless steel pairs under DI water and h-BN water dispersion lubrication was investigated. The results showed that h-BN nanolubricants did not have a significant effect on the friction behavior but reduced wear due to their trapping effect between the sliding interfaces. The wear depth of the specimens under h-BN lubrication was found to be smaller than that under DI water lubrication, indicating the inhibition behavior of h-BN nanolubricants towards direct metal-metal contacts. SEM and EDS results further support the idea that h-BN nanoparticles fill up the sliding interfaces and reduce wear damage. However, further research is necessary to obtain direct evidence of the inhibition behavior of h-BN nanolubricants towards direct metal-metal contacts.

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