PARTICLE SIZE AND SURFACE TEXTURING EFFECTS ON FRICTION OF MAGNETORHEOLOGICAL FLUIDS

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ABSTRACT

MR fluids are produced by dispersing micron-sized ferrimagnetic particles in oil. Generally, the presence of foreign particles in a lubricant affects the sliding behavior of the lubricated surface. Accordingly, the dispersed particles in MR fluids should significantly affect the lubrication properties of the fluids. In this study, we investigated the lubrication properties of MR fluids through sliding tests and *in situ* observations, while focusing on the behavior of the dispersed particles. MR fluids containing dispersed particles of various diameters were tested. The results of the sliding tests suggested that the MR fluid with the smallest particles exhibited the best lubrication characteristics. Surface observations showed the presence of grooves on the lubricated surfaces after wear. It is assumed that the grooves are formed by the abrasive action of the dispersed particles and that they affect the behavior of the particles. *In situ* observations proved that, in the case of flat surfaces, the dispersed particles remained stationary during sliding. On the other hand, in case of grooved surfaces, they moved along the grooves. Given these results, it can be surmised that the grooves on the worn surface changed the behavior of the particles and improved the lubricity of MR fluids.

Keywords: Magnetorheological fluids, friction, wear, particle, *in situ* observation

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INTRODUCTION

Magnetorheological (MR) fluids are functional fluids produced by dispersing micron-sized ferrimagnetic (FM) particles in oil. One of the characteristics of MR fluids is that their viscosity can be controlled by applying a magnetic field. Hence, MR fluids are employed as hydraulic oils in dampers [1-3]. However, when MR fluids are used as hydraulic oils, the effects of the FM particles on the sliding surface is not negligible. These particles can lead to abrasive wear of the sliding surface or to oil starvation on it [4] [5]. On the other hand, including the particles in the fluids can help increase the thickness of the oil film and improve its characteristics under extreme pressure [5] [6]. Owing to these effects, it is essential to elucidate the lubrication properties of MR fluids, as this will help further their use in various applications. Previous studies on the lubrication properties of MR fluids reported that the aggregation of the FM particles, the deformation of these particles, and their size and type greatly affect the lubrication properties of the fluids [7] [8]. It was also reported that the presence of a magnetic field affected the lubrication properties of such fluids [9] [10]. However, the mechanical effects of the FM particles on the lubrication properties of MR fluids are still unknown.

In this study, we investigated the lubrication properties of MR fluids through sliding tests and *in situ* observations, while focusing on the behavior of the dispersed FM particles.

SLIDING TEST

Sliding test procedure

The sliding tests were performed using a cylinder on a disk-type reciprocating sliding tester (SRV, Optimol, Germany); the test conditions are listed in Table 1. The disk (diameter = 24 mm; thickness = 7.9 mm; *Rz* = 0.2 µm) and cylinder (diameter = 15 mm; length = 22 mm; *Rz* = 0.4 µm) were made of AISI 1010 and AISI 52100 steels, respectively. The disk and cylinder were cleaned ultrasonically in a mixed solution of petroleum, benzene, and acetone for 10 min before and after the tests. The wear tracks on the specimens were observed using optical microscopy (OM) and field-emission scanning electron microscopy (FE-SEM) (ZEISS, SUPRA40, Germany). The profiles of the wear scars were determined using a surface profilometer (SURFCOM 1500SD3-12, ACCRETECH, Japan).

Test MR fluids were produced by dispersing approximately 75 wt% pure iron particles in oil (Hydrocarbon base oil; Viscosity 3.014 mm^2/sec (80°C)). Three types of particles were used, resulting in three different MR fluids: Fine (average particle diameter = 2 µm), Medium (4 µm), and Coarse (8 µm).

Table 1. Conditions for the sliding tests.

Temperature	30 °C
Amplitude	1 mm
Frequency	50 Hz
Normal load	20 N
Test duration	3600 sec.

Results of sliding tests

The variation in friction coefficient behavior as a function of sliding time are shown in Fig. 1. In the case of Base oil, the friction coefficient was stable at a value of 0.2. However, for all the MR fluids, the friction coefficient started varying at a sliding time of 2000 second. Focusing on the values at the first 2000 second, the average friction coefficient in the cases of Fine was about 0.18. Thus, Fine exhibited the lowest friction coefficient of all the lubricants.

Figure 2 shows OM image of the wear tracks formed on the disk after the test. Focusing on the border of the wear tracks, plowed wear was observed for all the MR fluids. It was found that the plowed wear occurred partially in the cases of Fine and Medium. On the other hand, plowed wear was evident across the entire border of the wear tracks in the case of Coarse.

Figure 3 shows the maximum disk wear depth for each lubricant. The maximum wear depth is the lowest point in the cross-section profile (The cross-section profiles were measured 9 times); the plowed wear tracks were excluded from the measurements. The maximum wear depth for all the MR fluids was smaller than that for Base oil. Furthermore, of all the MR fluids, Fine resulted in the smallest wear depth, which was about 0.8 µm. These results indicated that MR fluids should result in an increase in the wear resistance of materials subjected to friction.

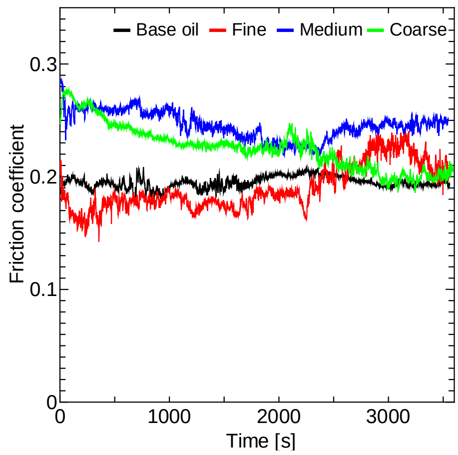

Figure 1. Variation in friction coefficient behavior as a function of sliding time.

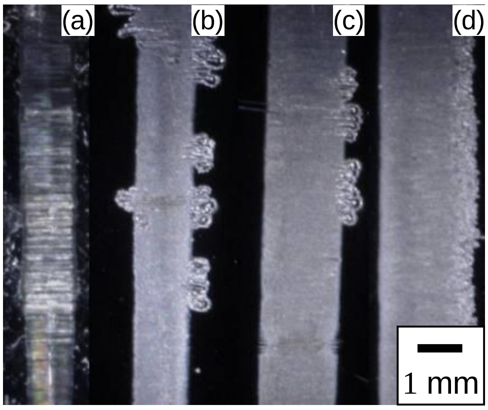

Figure 2. OM images of wear tracks: (a) Base oil (b) Fine (c) Medium, and (d) Coarse.

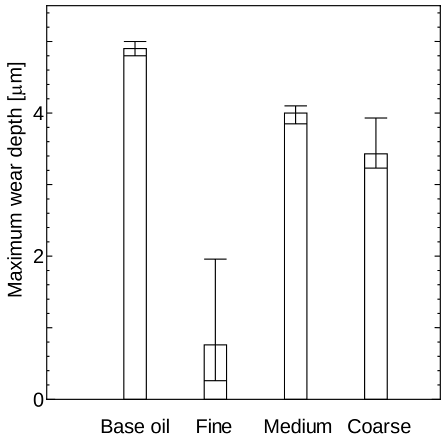

Figure 3. Maximum wear depth.

<u>Results of surface observations</u>

Figure 4 shows FE-SEM images of the wear tracks corresponding to the various lubricants. It can be seen that the wear characteristics related to Base oil and those corresponding to the MR fluids were different. In the case of Base oil (Fig. 4 (a)), no characteristic patterns were noticed. On the other hand, in the case of the MR fluids (Figs. 4 (b-d)), groovy patterns were detected on the entire wear track.

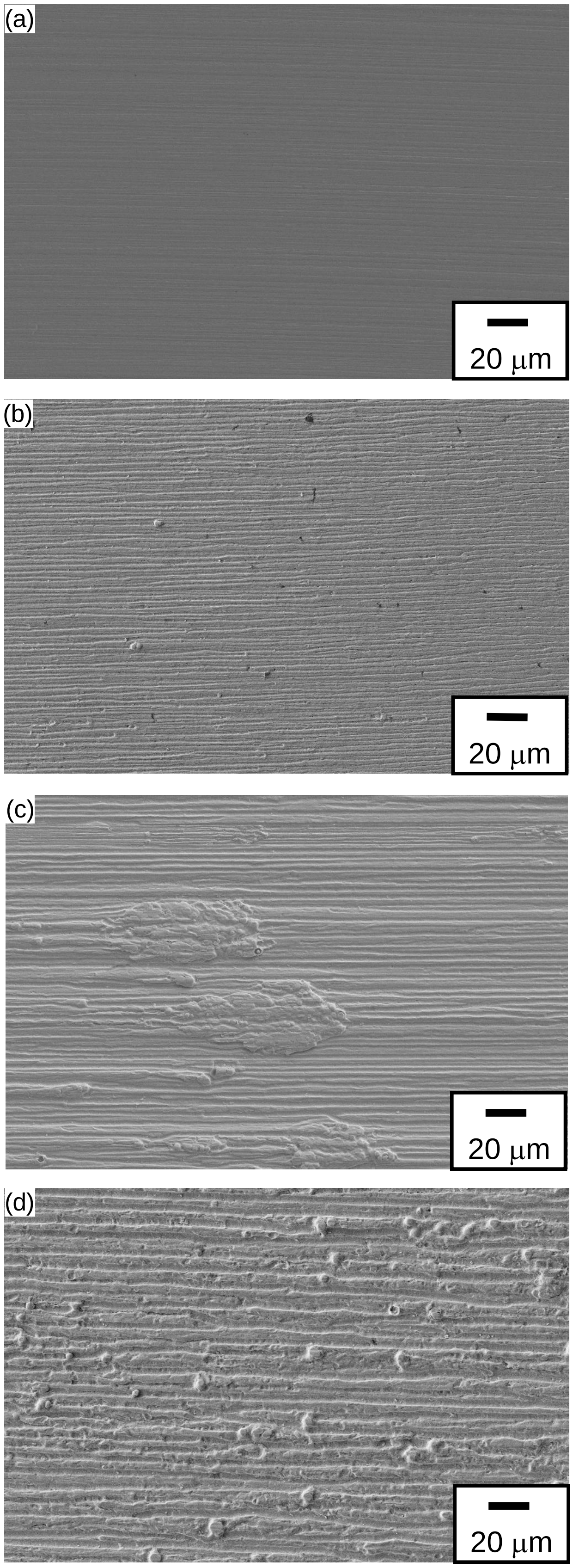

Figure 4. FE-SEM images of wear tracks: (a) Base oil (b) Fine (c) Medium, and (d) Coarse.

Figures 4 (b-d) show that the FM particles in the MR fluids adhered to the wear tracks. In the case of Fine (Fig. 4 (b)), the particles that adhered to the track had a diameter greater than the average diameter. Further, they adhered to the wear tracks individually. In contrast, in the case of Medium (Fig. 4 (c)), the particles adhered to the wear tracks in the form of aggregates. Further, in the case of Coarse (Fig. 4(d)), the adhered particles had a diameter almost similar to the average particle diameter; these particles also did not form aggregates. These results suggested that, in the cases of Medium and Coarse, the particles disrupted the groovy patterns on the wear tracks significantly. However, this was not true for Fine, that is, significant pattern disruption was not observed.

IN SITU OBSERVATIONS

Observation procedure

A schematic view of the device used for the *in situ* observations is shown in Fig. 5; the test conditions are listed in Table 2. This device allowed the behavior of the FM particles on the sliding surface to be observed using a high-speed camera attached to an OM system. The observations were performed using the pin-on-plate method. The edge of the pin used was made of MC Nylon®, and the plate was made of glass. During the observations, an MR fluids was used as the lubricant.

The shape of the pin edge is shown in Fig. 6. A Type 1 pin (Fig. 6 (a)) was flattened through polishing with 1200 grit paper. Then, in order to investigate particle behavior in a grooved surface, a Type 2 pin was prepared; this pin is shown in Fig. 6 (b). The groove shape is shown in Fig. 6 (c).

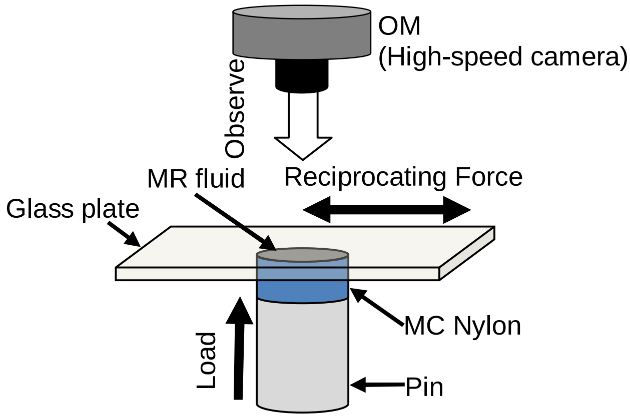

Figure 5. Schematic of device used for in situ observations.

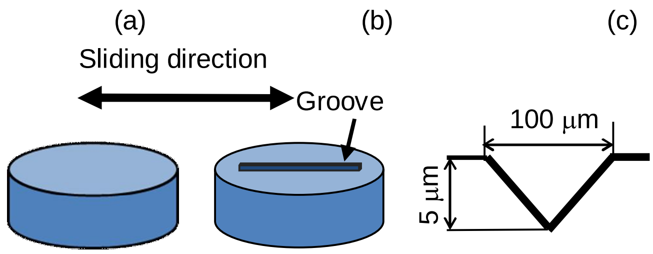

Figure 6. Pins used: (a) Type 1 and (b) Type 2. (c) Shape of groove.

Table 2. Conditions for in situ observations

Temperature	Room temperature
Amplitude	1 mm
Frequency	1 Hz
Load	20 N

Observation results

Figures 7 and 8 show images of the particles in motion, taken during the *in situ* observations. It was found that the positions of the particles remained unchanged throughout the sliding process. Hence, it can be surmised that the FM particles remained motionless in the case of Type 1 pin (Fig. 7).

In the case of Type 2 pin (Fig. 8), the particles underwent displacement. It was found that the particles moved along the groove, which was prepared prior to the experiment. These results indicate that the motion behavior of the particles was greatly affected by the presence of the groove on the tip surface.

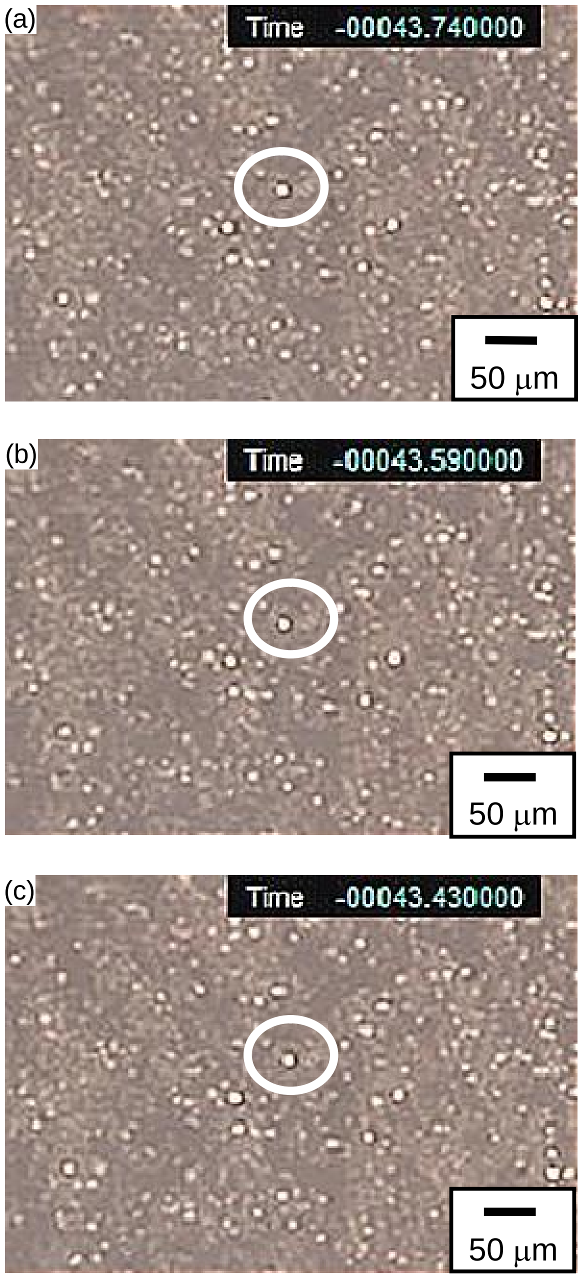

Figure 7. Results of in situ observations in the case of Type 1 pin: (a) 0.00 s, (b) 0.15 s, and (c) 0.31 s.

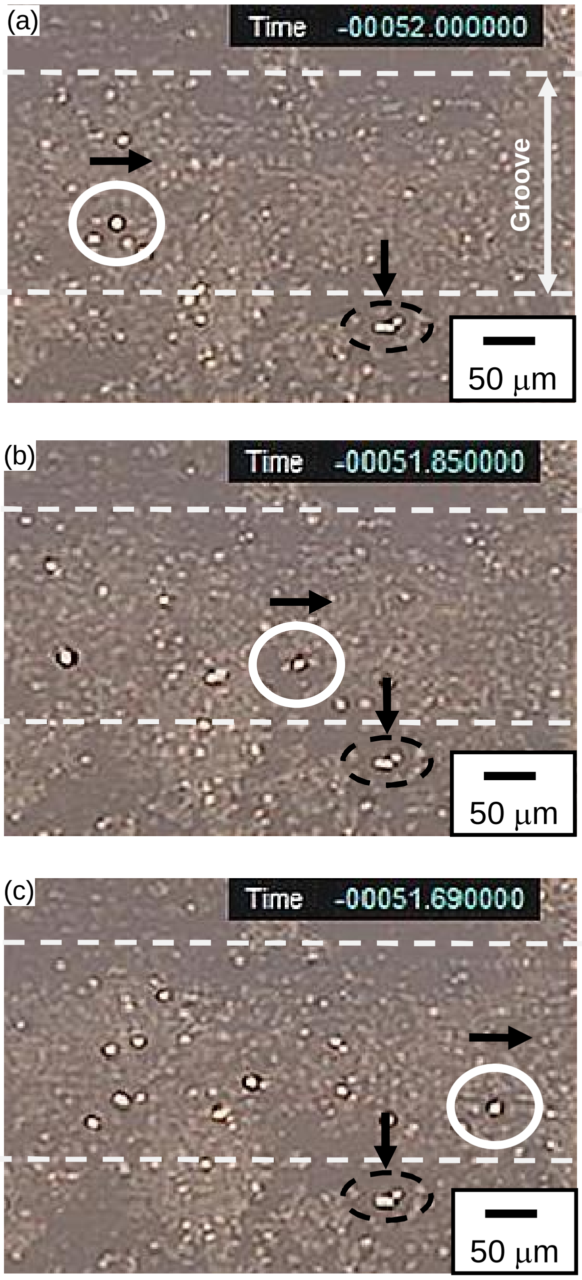

Figure 8. Results of in situ observations in the case of Type 2 pin: (a) 0.00 s, (b) 0.15 s, and (c) 0.31 s.

DISCUSSION

Lubrication properties

On the basis of the results obtained in the case of Type 1 pin (Fig. 7), it can be assumed that the stagnant particles on the sliding surface cause abrasion, producing grooves on the surface. The results obtained in the case of Type 2 pin (Fig. 8), which showed that the particles moved along the groove, suggested that presence of the grooves ought to have a significant effect on the lubrication properties of MR fluids. Grooves can help improve the lubrication properties of MR fluids in two ways. Firstly, the formation of a groovy pattern on the underlying surface by the FM particles results in a decrease in the number of particles that remain stagnant and thus cause abrasion. Therefore, the abrasive effect can largely be eliminated, resulting in a reduction in the wear of the lubricated specimen. Secondly, grooves channel the MR fluid used to lubricate the sliding surface. This improves the lubricity of the surface. These improvements in lubricity and antiwear properties suggest that the grooves formed by the FM particles enhance the lubrication properties of MR fluids.

An analysis of the sliding test results revealed that the groove-related effect was the most prominent in the case of Fine. That is to say, the improvement in its lubrication properties was much more significant than that in the properties of the other lubricants. To analyze this phenomenon, we investigated the conditions that induce this groove-related effect. To begin with, on the basis of the SEM images of the wear tracks, it was found that the adhered FM particles caused disruptions in the grooves in the cases of Medium and Coarse. In contrast, in the case of Fine, the groovy pattern was not disrupted. Further, Fig. 9 shows the relationship between the diameter of the FM particles and the groove width. In the case of Fine, the groove width was almost similar to the particle diameter. Thus, it can be assumed that particles with diameters similar to the groove width enhance the groove-related effect, as does the presence of undisrupted groovy patterns.

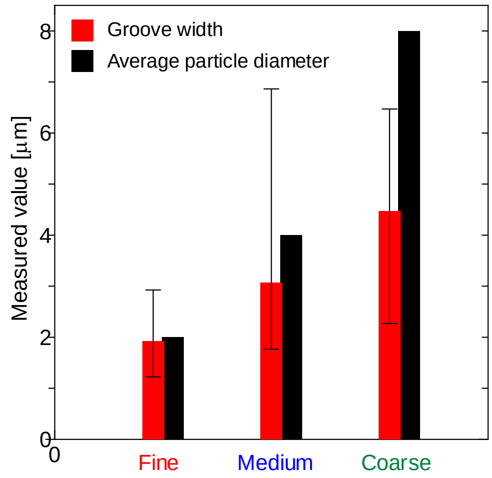

Figure 9. Relationship between FM particle diameter and groove width.

Surface texturing

Because the groove-related effect leads to improvements in the lubrication properties of MR fluids, we investigated the effects that the texturing of the surface of the lubricated specimen would have on these properties. The surfaces of the disk specimens were textured using a laser beam, and sliding tests were performed on the textured disks. Figure 10 shows the textured pattern. The sliding direction is also shown in the figure. Table 3 lists the dimentions of the texture.

Table 3. Dimentions of the formed texture.

Width	25 µm
Pitch	100 µm
Depth	10 µm

Figure 11 shows the variation in friction coefficient behavior as a function of sliding time in the case of the textured surface. The friction coefficient of all the MR fluids decreased. Hence, it can be considered that the groove-related effect was enhanced by the surface texturing, resulting in further improvements in the lubrication properties of the MR fluids.

Figure 12 shows SEM images of the wear tracks formed on the textured surface in the case of Medium. It can be seen from the image that the FM particles were trapped within the grooves. It can be inferred that the grooves protect the abrasive groovy pattern on the wear tracks from adhering particles (Fig. 6). The decrease in the friction coefficient was particularly large in the case of Medium. Thus, the trapping of the FM particles was much more significant in the case of Medium, as the particle-disrupting abrasion-related groovy pattern was not as extensive; this was owing to the aggregation of the particles. Hence, it can be assumed that, in order to maximize the groove-related effect, it is important to reduce the amount of particles, which cause the disruption of the abrasion-caused groovy pattern on the sliding surface, so that efficient trapping can take place.

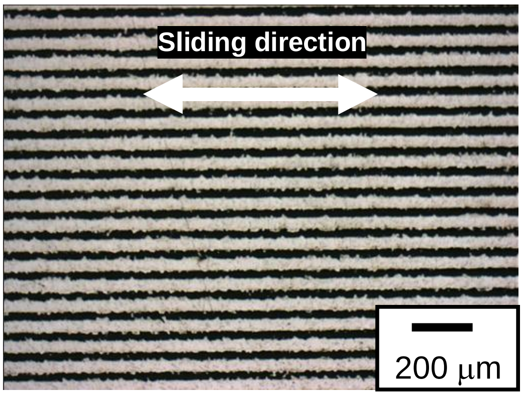

Figure 10. Surface texture of the disk specimens.

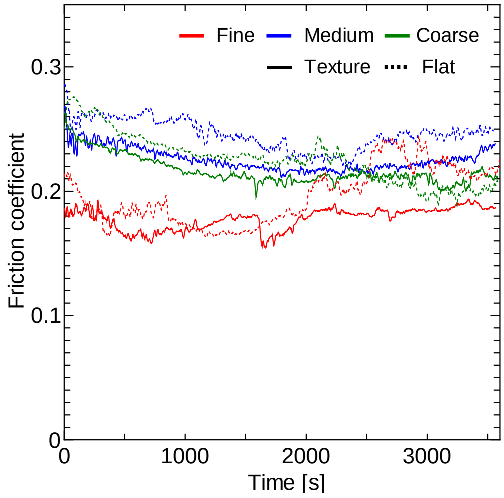

Figure 11. Variation in friction coefficient behavior as a function of sliding time in the case of the textured surface.

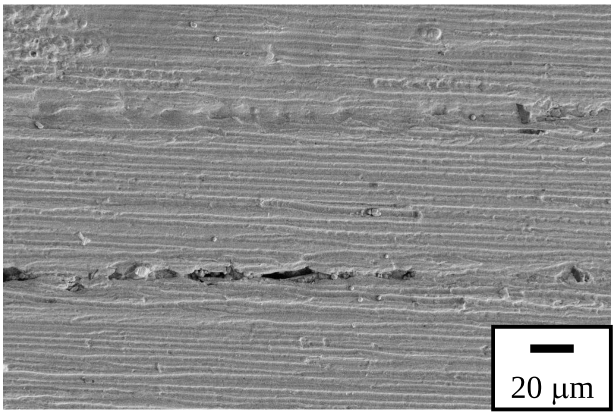

Figure 12. SEM images of wear tracks on the textured surface in the case of Medium.

CONCLUSIONS

- The presence of a groovy pattern and adhered particles on the wear tracks was confirmed. It can be assumed that stagnant particles cause abrasive wear and induce the formation of grooves on the wear tracks. In the cases of Medium and Coarse, the adhered particles disrupted the groovy pattern significantly. In contrast, Fine particles with an average diameter of 2 µm did not disrupt the

- pattern and resulted in significant reductions in friction and wear.

- The presence of particles with diameters similar to the groove width and wear scar consisting of an undisrupted groovy pattern was found to be necessary for maximizing the groove-related effect. A decrease in the friction coefficient was observed for all the MR fluids when entire surface of the disk was textured with grooves.

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