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Effects of adsorbed water due to atmospheric humidity on ball-on-ball sliding contact

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ABSTRACT – This research aimed to elucidate how adsorbed water influences friction and wear in a ball-on-ball sliding test. Since the force due to Laplace pressure, $F_{Laplace}$ at the contact interface is the function of relative humidity and surface roughness, they were selected as the manipulated variables in this study. To analyze the role of Laplace pressure, friction and wear at different contact positions were investigated. The empirical tribological results correlate with the theoretical equation of $F_{Laplace}$ developed. Hence, it can be concluded that Laplace pressure is predominant to both friction and wear at low relative humidity and low surface roughness.

1. INTRODUCTION

It is widely recognized that Laplace pressure generated by the adsorbed water at the contact interface can influence the tribological performance of atomic to nanometer-level systems dominantly due to the high surface to body force ratio [1]. However, it has not yet been recognized if such effect is significant at micro to millimeter-level mechanical contacts which many industrial applications involve [2]. A previous research shows that the thickness of an adsorbed water layer on stainless steel can be up to 60nm at 90% RH [3]. This value is comparable to the surface roughness of a fine-finished sliding surface. This raises the question if the same mechanism for the atomic to nanometer-level systems influences the tribological phenomena of the micro to millimeter-level systems. Thus, a ball-on-ball sliding test was carried out [4]. Interesting phenomenon was found where friction is higher when the balls are away from each other than when they are approaching each other as shown in Figure 1 [4]. It was hypothesized that the friction surge is caused by Laplace pressure and it may be high enough in generating wear. This research aimed to elucidate the influence of adsorbed water on both friction and wear of a ball-on-ball sliding test.

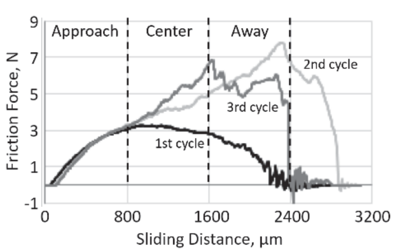

Figure 1 Friction force curve for JIS SUS316 at 8% RH in a ball-on-ball sliding test [4].

2. METHODOLOGY

The experiment was carried out utilizing a unidirectional ball-on-ball sliding tester as shown in Figure 2 [4]. The balls used were made of JIS SUS304 austenitic stainless steel with diameter of 8mm and were fixed in a humidity-controlled chamber. The relative humidity (RH) was adjusted to 5%, 50%, and 95% with an air flow rate of 5L/min. The surface roughness (Ra) was 0.04µm for polished balls and 0.16µm for unpolished balls. The overlap distance of the balls was 100µm and the sliding speed was 2000µm/s. The applied load was 10N. The calculated maximum Hertzian contact pressure was 1.74GPa which did not exceed the hardness of the JIS SUS304 balls (3GPa). Thus, the contact was under elastic deformation. The calculated maximum Hertzian contact diameter was 105µm. Before each experiment, the specimens were kept in the humidity chamber for 30 minutes so that the thickness of adsorbed water layer could achieve a steady state. Each experiment consisted of five unidirectional sliding cycles with 13 seconds interval per cycle. Each experiment condition was repeated thrice with newly prepared specimen pairs. All experiments were performed at room temperature at one atmospheric pressure. In terms of data acquisition, the friction was measured by load cells while the sliding contact status was checked by an electrical conductivity sensor. The wear behavior was characterized by the wear depth which was measured by an optical profilometer.

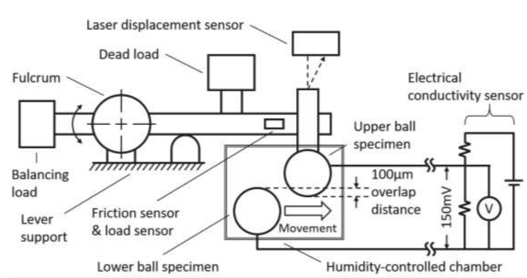

Figure 2 Schematic of a unidirectional ball-on-ball sliding tester [4].

3. RESULTS AND DISCUSSION

Equation (1) is the force due to Laplace pressure, $F_{Laplace}$ derived based on Young-Laplace equation, Kelvin's radius, and Hertzian contact theory, where R_G is the molar gas constant, T is the absolute temperature, V is the molar volume of water, A_C is the constant related to Hertzian contact area, Ra is the surface roughness, and ρ/ρ0 is the RH. From the equation, $F_{Laplace}$ is the function of the reciprocal of Ra and the natural logarithm of RH.

$$F_{Laplace} = \frac{R_G T}{V A_C}\left(\frac{1}{Ra}\right)^{2/3} \ln\frac{p}{p_0} \quad (1)$$

Figure 3 shows the Pearson's skewness of friction force curve at the first sliding cycle. A positive skewness represents higher friction at the "approach" region as shown in Figure 1 due to the dominant mechanical slope effect while a negative skewness represents higher friction at the "away" region in Figure 1 due to the dominant negative Laplace pressure generated at the meniscus formed between adsorbed water layers on the surfaces. Figure 4 shows the Pearson's skewness of friction force curve against RH. The most negative skewness can be found at the point of low Ra and low RH. As RH increases from 5% to 50%, both polished and unpolished specimens show a significant change of skewness from negative to positive and with polished ones increase more drastically. This trend very much correlates with Equation (1). However, both specimens remain almost unchanged in skewness as RH increases from 50% to 95%. This may be due to the nearly saturated adsorbed water layer [3]. Hence, it can be concluded that the influence of the $F_{Laplace}$ is significant to friction generation at low Ra and low RH.

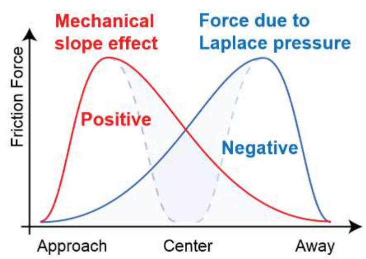

Figure 3 Pearson's skewness of friction force curve.

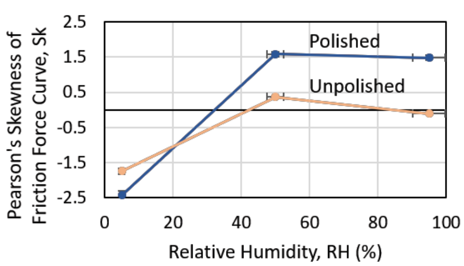

Figure 4 Pearson's skewness of friction force curve against RH.

Figure 5 and Figure 6 show the wear depth against contact position for polished and unpolished balls respectively. The wear depths for the approach and away positions were taken 500µm from the center of the wear track respectively. Overall, wear depth is higher when the balls are away from each other as compared to when they are approaching each other for the polished balls as shown in Figure 5. This is due to the negative Laplace pressure generated when the balls are away from each other. Looking at the "away" position specifically, the lower the RH, the higher the wear depth. This shows that the empirical results of both Ra and RH follow the theoretical equation of $F_{Laplace}$ as shown in Equation (1).

As for the unpolished balls, wear depth is higher at the "approach" position than that of "away". This is because higher Ra of the unpolished balls makes Laplace pressure less significant; hence, the mechanical slope effect is predominant due to the change in normal reaction.

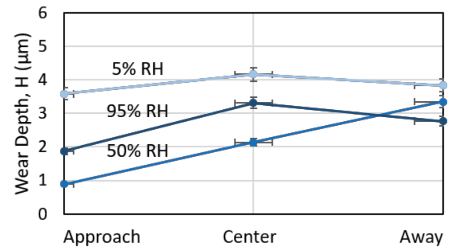

Figure 5 Wear depth against contact position (polished).

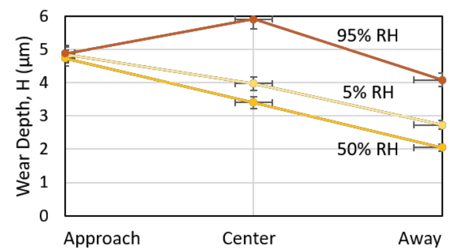

Figure 6 Wear depth against contact position (unpolished).

4. CONCLUSION

It is confirmed that the role of adsorbed water on the tribological performance of a ball-on-ball sliding test is significant at micro to millimeter levels. By interpreting friction and wear at different contact positions, the influence of Laplace pressure due to adsorbed water was elucidated. The empirical results of both friction and wear correlate with the theoretical equation of $F_{Laplace}$. Negative Laplace pressure is found predominant at low Ra and low RH.

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