Chemical Science International Journal

29(2): 1-10, 2020; Article no.CSIJ.54760
ISSN: 2456-706X
(Past name: American Chemical Science Journal, Past ISSN: 2249-0205)

Characterization of the Effect of Moisture on Tribology of Titanium Rubbed Against Different Pin Materials

Bodhi R. Manu[1], Adam M. Schroeder[1] and Ahalapitiya H. Jayatissa[1*]

[1]Department of Mechanical, Industrial and Manufacturing Engineering (MIME),
The University of Toledo, Toledo, OH 43606, USA.

Authors' contributions

This work was carried out in collaboration among all authors. Author BRM performed experimental work, data analysis and preparation of the first draft of the paper. Author AHJ designed the experiments and paper structure and also edit the manuscript. Author AMS edit the paper and analyses the content. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CSJI/2020/v29i230158
Editor(s):
(1) Dr. Gustaaf Schoukens, Ghent University, Belgium.
Reviewers:
(1) Kali Dass, National Agri-Food Biotechnology Institute, India.
(2) Kulwant Singh, Bhabha Atomic Research Centre, India.
Complete Peer review History: http://www.sdiarticle4.com/review-history/54760

Original Research Article

Received 12 December 2019
Accepted 21 February 2020
Published 02 March 2020

ABSTRACT

Tribology investigations were conducted to understand the effect of humidity and water adsorption at the interfacial surface on the friction coefficient of titanium. Pin-on-disk tribometer tests were conducted at different levels of humidity ranging from 0% to 71% RH using aluminum and steel pins on a titanium plate. The variation of the mean coefficient of friction was plotted as a function of relative humidity. The friction coefficient slightly decreased when the relative humidity was increased from 0% to 10% RH. However, it increased with a further increase in humidity. The maximum friction coefficients were observed at 55% and 65% RH for steel and aluminum, respectively. The thickness of the wear tracks also showed the same trend as the friction coefficient. Under high humidity conditions, water vapor can condense on the surface of the moving machine parts. To understand the influence of this water film, a pin-on-disk test was carried out on a sample where a thin film of water masks metal surfaces from contact. Although the coefficient of friction was similar for both the aluminum and steel pins' interaction with titanium (~0.36), the wear tracks were not formed for steel pin/titanium interaction even though this experiment was conducted for more cycles.

Keywords: Friction coefficient; tribology; humidity effect; steel pin; aluminum pin; pin-on-disk tribometer.

**Corresponding author: E-mail: ahalapitiya.jayatissa@utoledo.edu;*

1. INTRODUCTION

Titanium has received widespread attention in recent years because of its favorable properties such as high melting point, high specific strength, and low wear [1]. These properties make titanium attractive, especially for aerospace and automobile applications. Most current research on titanium focuses on improving the mechanical properties for applications involving highly corrosive environments [2,3] or extreme temperature conditions. However, little work has been conducted so far on the tribological behavior of pure titanium. In the present work, the effect of humidity on the friction coefficient of titanium was investigated.

The dependence of friction coefficient on humidity varies based on the nature of the interacting surfaces. Solid film lubricants are usually added as a coating on contacting surfaces to reduce friction. For solid lubricants such as graphene and graphite, the friction coefficient decreases with an increase in moisture content. On the other hand, for dichalcogenides, such as MoS_2, friction increases with moisture [4-6]. For diamond-like carbon, ultra-low friction can be obtained at dry conditions. However, the effect is lost even at low humidity [7]. Since most applications involving pure metal-metal contact use solid or liquid lubricants to reduce interfacial friction, [8-10], the tribological study of pure metal-metal interaction is studied less extensively [7]. Some research has been conducted to understand the effect of humidity on the friction of steel and aluminum [10-12]. Most publications in this regard have been focused on reducing the friction of metals like aluminum or steel against ceramic materials for their application in metal cutting [13,14]. Also, some research on internal friction at different temperatures has been conducted on ductile materials such as magnesium and copper to understand its effect on metal forming operations [15]. Based on these studies, different mechanisms were proposed to explain the friction at the microscopic level for metals and composite materials. They usually consider the laminar sliding between surfaces, tribo-chemical corrosion at the interface, and the adhesive property of particles [16,17].

In this study, a pin-on-disk tribometer was used to investigate the effect of various levels of relative humidity (RH) ranging from 0% RH (dry air) to 71% RH on the friction coefficient of the surface interaction between steel/titanium and aluminum/titanium. Also, the effect of a thin water film at the interfacial surface on the friction coefficient was investigated. This is the first detailed investigation conducted to understand the effect of humidity on the tribology of industrial grade titanium plate.

2. SAMPLE PREPARATION

Industrial grade pure titanium plate was used as the test specimen whose composition is shown in Table 1. Two separate sets of titanium plates were used for testing with aluminum and steel pins. The specimen's surface was mechanically polished using an automatic grinding machine. An aluminum oxide abrasive grinding tool was used for this operation. The ground samples were again polished using a liquid suspension containing 0.25 µm silicon carbide particles to get a smoother appearance. The polished plates were then cleaned for 5 mins in an ultrasonic cleaner, rinsed with distilled water, sprayed with ethanol, and finally dried under a heat gun. The roughness of titanium plate was in the range of 0.130-0.150 microns. To investigate the effect of humidity on the friction coefficient, the pin-on-disk tribology test was then conducted.

Table 1. Chemical composition of titanium substrate

Weight %	Ti	C	Fe	N	O	H
Titanium TA2 Grade	Balance	0.10	0.30	0.03	0.25	0.015

In order to remove adsorbed water from the surface, the titanium plate was kept in a conventional oven at 130°C for 1 hour, and immediately after, it was installed in the tribometer where the humidity can be controlled. The humidity was controlled for the experiments by changing the dry air/water vapor ratio. The tribology testing was conducted at room temperature (26°C) in the range of 0% - 71% RH.

In high humidity conditions, water vapor condenses on the surface of moving machine elements. To investigate the effect of this water film, the titanium plate was rinsed with distilled water and the excess water was removed by blowing dry air at room temperature. For this sample, the test was conducted at a relative humidity of 55%. All the experiments were conducted using aluminum and steel pins against titanium plates.

3. PIN-ON-DISK TRIBOMETER

The tribology tests were conducted using a custom-made pin-on-disk tribometer. It consisted of a cantilever with a pin attached at the free end. The pin had the provision to add different weights so that data could be collected at various loads. Two strain gauges were attached to the lateral faces of the cantilever to measure the deflections. The test specimen was fixed to a rotating platform and rotated at a constant speed. Once the platform reached steady rotation, the pin, without any additional weight, was placed carefully so that the initial interaction between the pin and the titanium plate could be measured with the least amount of error. The entire setup is kept in a humidity-controlled environment so that data could be collected at various levels of humidity.

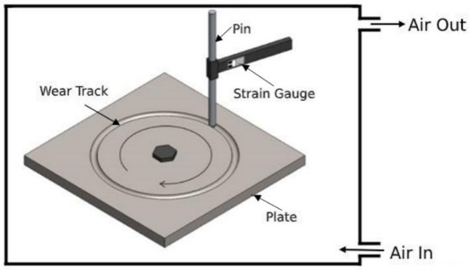


Fig. 1. Schematic of a pin-on-disk tribometer; The grades of aluminum and steel rods were respectively Al 6063 and SS 301 and the diameter of the pin 6 mm

A lateral force was exerted on the cantilever due to the friction, which caused deflection in the cantilever. The cantilever's inner strain gauge underwent compression, whereas the outer one was subjected to tension. The piezoelectric property of these strain gauges gave rise to a differential voltage, which was collected via a data acquisition system and was interfaced with a computer running custom LabVIEW software. Real-time deflection and frictional force data were collected and saved for further analysis. The schematic of the pin-on-disk tribometer is shown in Fig. 1 [18].

Two cylindrical pins made of aluminum and steel with a spherical tip were used for these experiments. The pressure exerted on the film by the pin was calculated by measuring the thickness of the wear tracks using an optical microscope. The tribology tests were conducted at 120 rpm speed and 1.285 N force. The coefficient of friction (COF) depends on the velocity. With increase in velocity, the COF also increases. If the experiment is done at a higher rpm, the effect of velocity on COF can dominate the effect of humidity levels. Therefore, it is difficult to capture the effect of humidity on friction coefficient at higher velocities. The maximum contact pressure ($P_{\max}$) between the pin and the titanium plate was calculated using Hertz's equation for the contact between a sphere and a plate, as shown in Equation (1) [19], where, w and F are the width of the wear track and applied normal load, respectively.

$$Pmax = \frac{3F}{2\pi w * w}. \tag{1}$$

P_{max} can be used to understand the wear phenomenon of a tribological surface: higher the P_{max} decreases wear of the contact surface.

4. RESULTS

4.1 Tribology Test under Dry Air (0% RH)

Figs. 2 and 3 show the variation of the friction coefficient at 55% RH and dry air (0% RH)

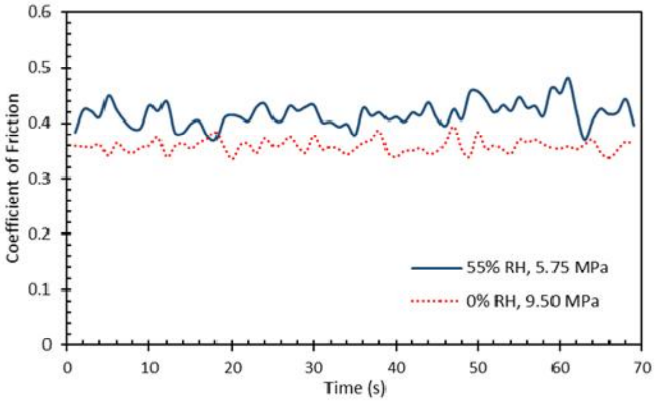


Fig. 2. Coefficient of friction values for aluminum/titanium interactions at 55% RH and dry air (0% RH) condition

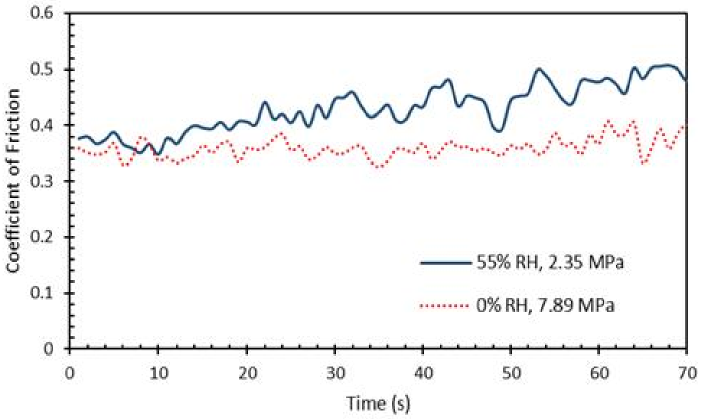


Fig. 3. Coefficient of friction values for steel/titanium interactions at 55% RH and dry air (0% RH) condition

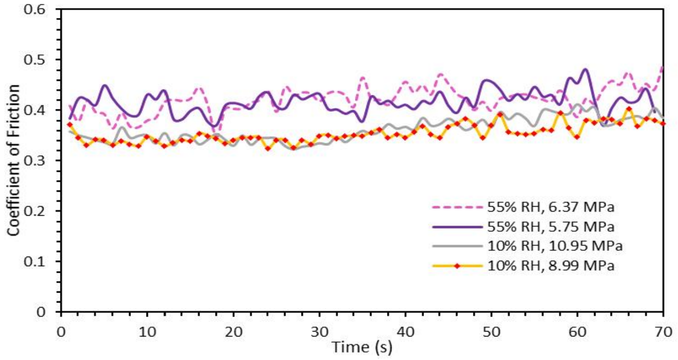


Fig. 4. Coefficient of friction values for aluminum/titanium interactions at 55% RH and 10% RH

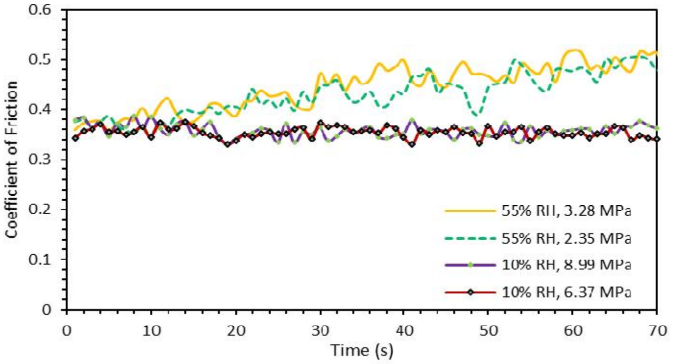


Fig. 5. Coefficient of friction values for steel/titanium interactions at 55% RH and 10% RH

conditions for the aluminum and steel pins, respectively. The friction coefficient values were lower for dry air than at 55% RH for both aluminum and steel pins rubbed against titanium.

4.2 Tribology Test at 10% RH

The pin-on-disk tribology test was conducted at 10% RH. The variation of the coefficient of friction with time for both aluminum and steel pins against titanium is shown in Figs. 4 and 5 respectively, along with the data obtained at 55% RH for comparison. The mean coefficient of friction values slightly decreased compared with the experiment conducted at dry air (0% RH).

For both the aluminum and steel pin interaction with titanium, the coefficient of friction was smaller than the one obtained at 55% relative humidity. This gave evidence that dehumidification decreased the coefficient of friction. The wear track analysis of the experiment with dry air showed that the wear rate was also higher for the atmospheric condition. Fewer grooves were formed with a decrease in contact pressure. Wear between aluminum pin and titanium plate was more as aluminum is much softer than steel. Figs. 6 and 7 show the optical microscopic photograph of the wear track at 750 x magnification for both aluminum/ titanium and steel/titanium interaction.

Liu et al. [20] reported the effect of trace amounts of moisture on a silicon surface. The molecular dynamics simulation at the interfacial surface of water and silicon showed that since oxygen is highly electronegative, the hydroxyl ion formed by dissociation of the water molecules formed a hydrogen bond with hydrogen ions, which increased the surface energy. Since friction is determined by the surface energy interaction between the sliding surfaces, this increased the friction coefficient. Our experiment also showed that a trace amount of moisture increased the friction coefficient.

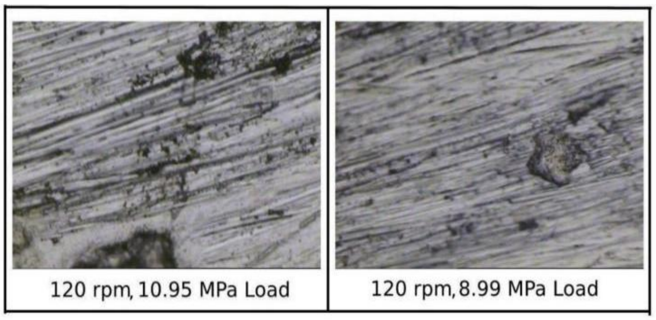

120 rpm, 10.95 MPa Load
120 rpm, 8.99 MPa Load

Fig. 6. Optical microscope photograph (750x magnification) of the wear track for aluminum/titanium interaction at 10% RH

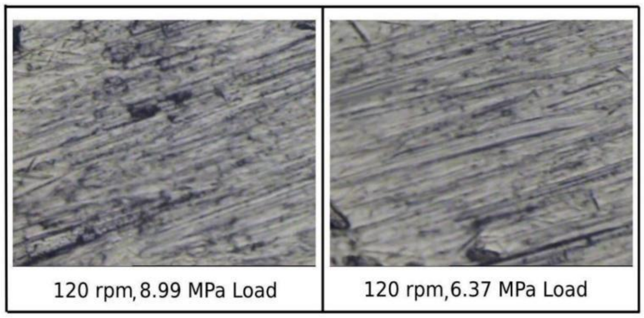

120 rpm, 8.99 MPa Load
120 rpm, 6.37 MPa Load

Fig. 7. Optical microscope photograph (750x magnification) of the wear track of steel/titanium interaction at 10% RH

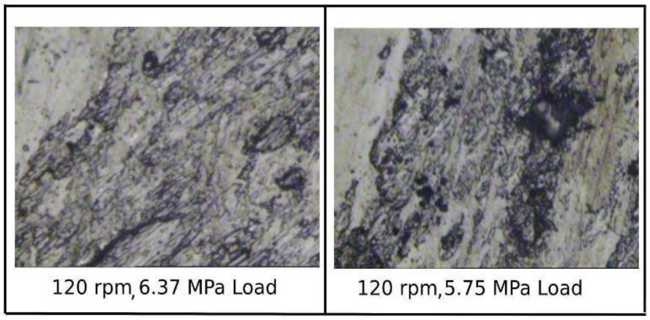
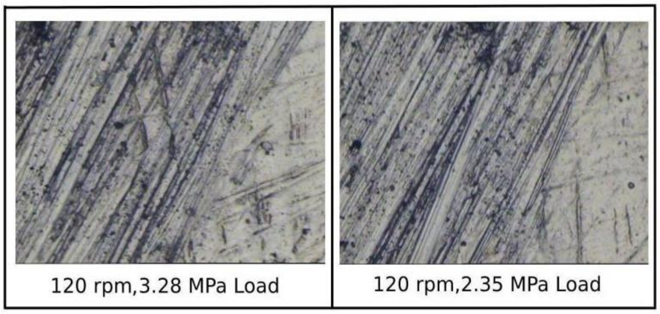

120 rpm, 6.37 MPa Load
120 rpm, 5.75 MPa Load

Fig. 8. Optical microscope photograph (750x magnification) of the wear track of aluminum/titanium interaction at 55% RH


120 rpm,3.28 MPa Load

120 rpm,2.35 MPa Load

Fig. 9. Optical microscope photograph (750x magnification) of the wear track of steel/titanium interaction at 55% RH

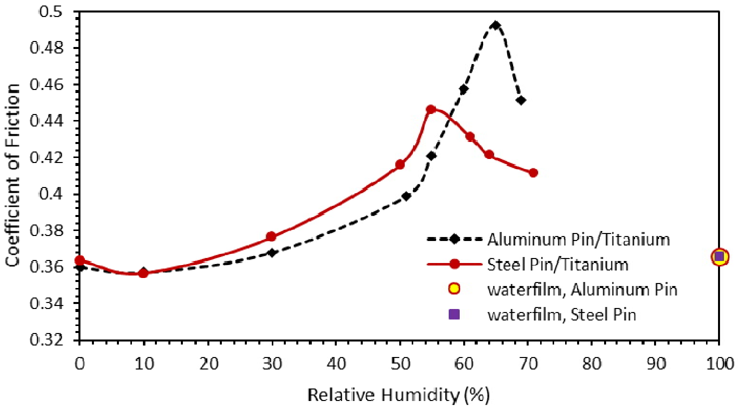


Fig. 10. Variation of the coefficient of friction with relative humidity for both aluminum and steel pins against titanium; ○ / ■ represent friction coefficient values for aluminum and steel with the presence of a water film

4.3 Tribology Test at 55% RH

The pin-on-disk tribology test was conducted at atmospheric conditions to calculate the friction coefficient for aluminum/titanium and steel/titanium interfaces. A humidity level of 55% was maintained during this test. A mean coefficient of friction of 0.36 for aluminum/titanium interaction and 0.41 for steel/titanium was observed during the tests at atmospheric conditions. These data were comparable (± 5%) to the data already published [21,22]. The wear tracks for aluminum/titanium and steel/titanium are shown in Figs. 8 and 9, respectively.

Similar to the case of 10% relative humidity, the wear tracks appeared to be smooth with a gradual decrease in pressure for both the aluminum and steel pins' interaction with titanium. The reduction in pressure was due to the increase in the contact area between the plate and the pin. This increase in contact area caused additional wear. The grooves were flattened with time, creating a smooth wear track.

4.4 Variation of the Coefficient of Friction with Relative Humidity

The pin on disk tribology test was conducted at different humidity levels from dry air (0% RH) to 71% RH. Fig. 10 shows the mean coefficient of friction as a function of relative humidity for both the aluminum and steel pins interacting with the titanium plate.

For the aluminum and steel pins, the coefficient of friction increased with an increase in humidity at low humidity levels, reached a maximum value, and then decreased. The maximum coefficient of friction of 0.49 was recorded at a relative humidity of 65% for aluminum/titanium and a maximum coefficient of friction of 0.45 at 55% relative humidity for steel/titanium. The coefficient of friction was slightly higher at 0% RH than 10% RH.

4.5 Effect of Water Film

At high humidity conditions, water vapor can condense on the surface of interacting machine elements. An experiment was conducted to understand the effect of water layers on the friction coefficient. To mimic this interaction, the samples were dipped in distilled water for 30 min followed by blowing dry air at a room temperature of 26°C. The experiment was conducted at 55% RH. The graphs for these test results are shown in Figs. 11 and 12.

For steel/titanium interaction in the presence of a water film at 55% RH, the wear tracks were not visible through the microscope. For both aluminum and steel pins' interaction at this condition, the coefficient of friction decreased. In the case of steel, the wear tracks were not formed though the test was conducted for more cycles. Chen et al. [7] reported that the friction coefficient and wear decreased for steel and brass as humidity was increased [2]. In our study also, the friction decreased for both aluminum/titanium and steel/titanium interactions at very high humidity levels. A possible explanation for this behavior is that the water molecules adhere to the interface of the interacting surfaces and restrict the formation of a metal-metal contact tribo-film. This would lead to reduced friction and wear. The mean coefficient of friction of 0.36 was observed for both aluminum and steel pin experiments. This gives more credibility for the above explanation.

An optical micrograph of the wear track for aluminum/titanium interaction is shown in Fig. 13. With a decrease in contact pressure, the wear tracks became less grooved as the contact area increased.

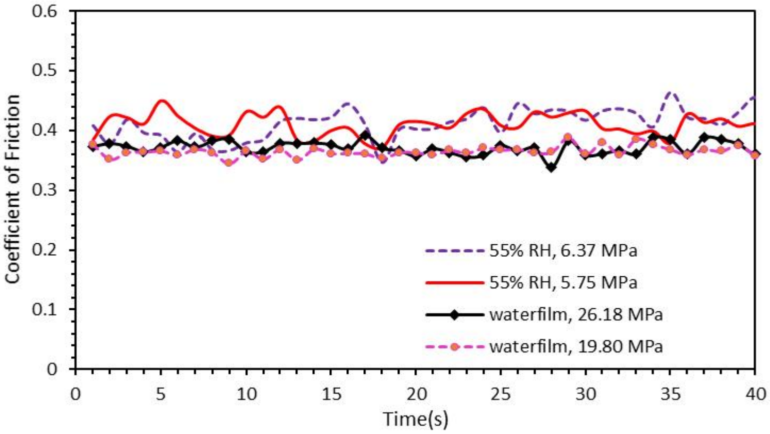


Fig. 11. Coefficient of friction for aluminum/titanium interactions at atmospheric and humid air conditions

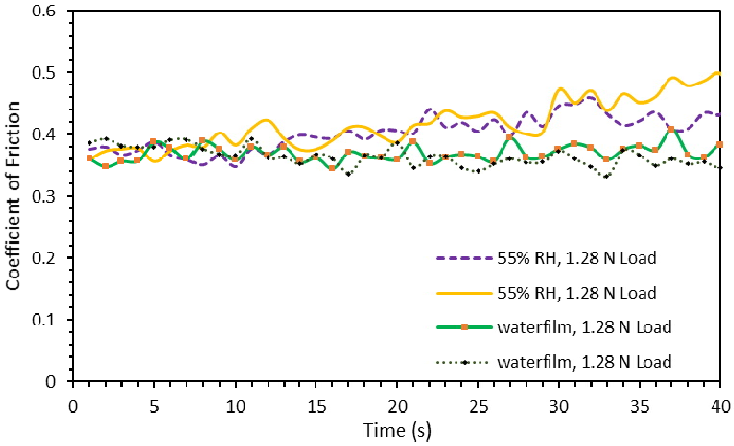


Fig. 12. Coefficient of friction for steel/titanium interactions at 55% RH and with a water film

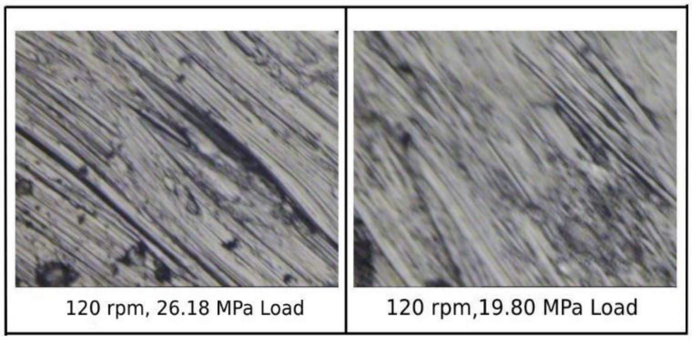


Fig. 13. Optical microscope photograph of the wear track of the aluminum/titanium interaction in the presence of water film at 55% RH

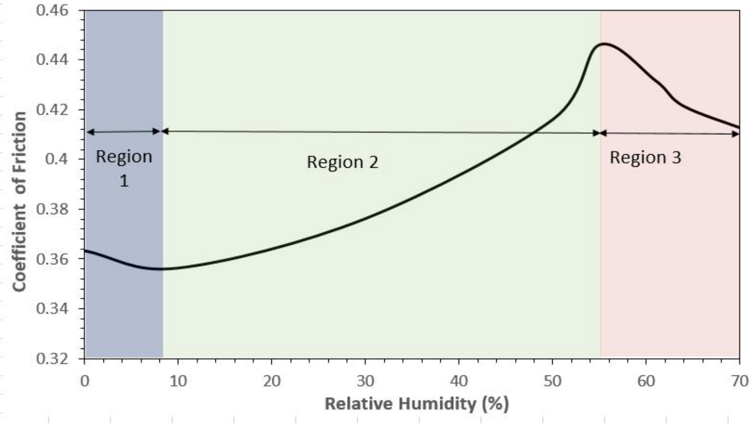


Fig. 14. Dependence of friction coefficient on humidity: Three regions were marked in different colors to explain the effect better

5. DISCUSSION

Titanium and its alloys have gained a great deal of attention in the spacecraft, marine and automobile industries as a substitute for steel and aluminum for machine elements operating under a variety of conditions. Most of these applications require titanium to work under different humidity levels ranging from dry air to high humidity and water lubrications [23-26]. The effect of humidity on thin solid lubricant coatings such as molybdenum disulfide, graphene, and DNC were investigated in the past [5,7,27], however, detailed investigations were not reported on the effect of humidity on the tribological performance of titanium and its alloys.

The variation of the friction coefficient as a function of relative humidity for steel and aluminum pins against titanium is shown in Fig. 10. Also, Fig. 14 shows that dependence of friction coefficient on humidity with marked regions in different colors to explain the effect better. Under dry conditions (0% RH), the coefficient of friction was higher, and it decreased as the humidity was increased (region-1) Beyond a relative humidity of 10%, the friction coefficient increased with relative humidity and reached a maximum value (region-2). Once the humidity level reached this critical value where the friction coefficient was maximum (region-3), further increases in relative humidity decreased the coefficient of friction. Iwabuchi et al. [28] conducted experiments on the effect of atmospheric pressure on friction and wear of carbon steel. Under vacuum pressure the coefficient of friction increased as the adsorbed gas molecules evaporated. This removal of surface molecules increased the friction due to an increase in adhesive forces between the interacting surfaces. In our experiment, initially dry air caused the evaporation of adsorbed water molecules which increased the surface energy and hence the friction coefficient. As the humidity was increased from a dry atmospheric condition, the surface energy decreased for the titanium plate due to adsorption of water molecules at lower humidity levels. The coefficient of friction decreased from a dry air condition to 10% RH. Increasing the humidity beyond this point increased the coefficient of friction. This is because as the humidity levels are increased, the thickness of the adsorbed water molecular layer increases. Liquid films in the order of 5-10 molecular diameters exhibit unusual properties such as having a critical shear stress and stick-slip motion which cannot be explained by the concept of fluid friction. Hence, this liquid film acts as an induced solid film which increases the surface energy of the metal surface during motion [29]. The formation of a hydrogen bond between the H and OH molecules of the adsorbed water molecules also increases the surface energy and, therefore, friction [30]. The coefficient of friction increased until 56% RH for steel/titanium and 63% RH for aluminum/titanium interactions. With further increases in humidity levels, the thickness of the adsorbed water level also increases. After a critical thickness of the water film, the solid like behavior of the water film breaks and acts as a boundary lubricant which reduces the friction coefficient [20].

6. CONCLUSION

Pin-on-disk tribology tests were conducted from dry air (0% RH) to 71% RH. The experiments show that the friction of titanium/metal-pin interactions depends on the levels of humidity. A trace amount of moisture decreased the friction compared to dry air (0% RH) but increases in humidity of more than 10% resulted in an increase of friction to a maximum value. Further increases in humidity reduced the friction coefficient due to the reduced interaction between metals from a water interface layer. A maximum coefficient of friction of 0.49 at 65% RH for aluminum/titanium and of 0.45 for steel/titanium at 55% RH were recorded. The width of wear track also followed the same trend as the coefficient of friction with a change in humidity levels. An optical micrograph of the wear tracks showed that with a decrease in contact pressure, the wear tracks became flattened because of an increase in the metal-metal contact area. However, when the experiment was conducted in the presence of a water film on the surface, for steel/titanium interaction, the wear track was not visible, even under an optical microscope. The authors expect this research is very useful in designing of moving mechanical components in aerospace vehicles such as NASA and the Indian Space Research Organization (ISRO). The research is underway to improve the rotating and sliding devices that operate outdoor conditions utilizing these findings.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Mansuri AK, Medhane SL, Gunjal SU. Comparative study of aluminum lithium alloy and composites. Int. J. of Science, Technology & Management. 2015;4: 234.
2. Nuruzzaman DM, Chowdhury MA. Effect of load and sliding velocity on friction coefficient of aluminum sliding against different pin materials. J. Material Science. 2012;2:26.
3. Okazaki Y, Ito Y, Kyo K, Tateishi T. Corrosion resistance and corrosion fatigue strength of new titanium alloys for medical implants without V and Al. Materials Science and Engineering. 1996;213: 138.
4. Berman D, Erdemir A, Sumant AV. Few layers graphene to reduce wear and friction on sliding steel surfaces. Carbon. 2013; 54:454.
5. Berman D, Erdemir A, Sumant AV. Graphene: A new emerging lubricant. Materials Today. 2014;17:31.
6. Furlan KP, de Mello JDB, Klein AN. Self-lubricating composites containing MoS_2: A review. Tribology International. 2018;120: 280.
7. Chen Z, He X, Xiao C, Kim S. Effect of humidity on friction and wear — A critical review. Lubricants. 2018;6:74.
8. Liew WYH. Effect of relative humidity on the unlubricated wear of metals. Wear. 2006;260:720.
9. Bregliozzi G, Di Schino A, Kenny JM, Haefke H. The influence of atmospheric humidity and grain size on the friction and wear of AISI 304 austenitic stainless steel. Materials Letters. 2003;57:4505.
10. Oh HK, Yeon KH, Kim HY. Influence of atmospheric humidity on the friction and wear of carbon steels. J. Mater. Process. Technol. 1999;95:10.

11. Rusin NM, Kolubaev EA. Dry friction of pure aluminum against steel. J. Friction and Wear. 2016;37:86.
12. Fukuda K, Masaaki H, Joichi S. Friction and wear of ferrous materials in a hydrogen gas environment. Tribology. 2011;6(2):142.
13. Chen X, Han Z, Li X, Lu K. Lowering coefficient of friction in Cu alloys with stable gradient nanostructures. Science Advances. 2016;2:e1601942.
14. Hiratsuka K, Enomoto A, Sasada T. Friction and wear of Al_2O_3, ZrO_2, and SiO_2 rubbed against pure metals. Wear. 1992; 153(1992):361.
15. Routbort JL, Sack HS. Background internal friction of some pure metals at low frequencies. J. Applied Physics. 1996;3: 4803.
16. Carlos R, Alhafez I, Urbassek H. Atomistic studies of nanoindentation — A review of recent advances. Crystals. 2017;7:293.
17. Landman U, Luedtke WD, Burnham NA, Colton RJ. Atomistic mechanisms and dynamics of adhesion, nanoindentation, and fracture. Science. 1990;248:454.
18. Manu BR, Jayatissa AH. Tribological properties at the interface of the aluminum and aluminum oxide. J. Multidisciplinary Engineering Science Studies (JMESS). 2019;5:2594.
19. Ahmed O, Jayatissa AH. Tribological properties of multilayer TiN and MoS_2 thin films. Colloid and Surface Science. 2017;2: 137.
20. Szlufarska I, Liu Y. Effect of trace moisture on friction. Appl. Phys. Lett. 2010;96: 101902.
21. Qu J, Blau PJ, Watkins TR, Cavin OB, Kulkarni NS. Friction and wear of titanium alloys sliding against metal, polymer and ceramic counterfaces. Wear. 2005;258: 1348.
22. Obaidi HA, Al-Mukhatr AM. The frictional coefficient comparison between stainless steel and beta-titanium archwires ligatured to the stainless-steel bracket via different ligatures. Al-Rafidain Dent J. 2008;8: 79.
23. Gorynin IV. Titanium alloys for marine application. Material Science and Engineering. 1999;263:112.
24. Davim JP, Loureiro AJR, Veiga C. Properties and Applications of Titanium Alloys: A Brief Review. Adv. Mater. Sci. 2012;32:133.
25. Kumpfert J, Ward CH, Leyens C, Peters M. Titanium alloys for aerospace applications. Advanced Engineering Materials. 2003;5:419.
26. Yamada M. An overview on the development of titanium alloys for non-aerospace application in Japan. Material Science and Engineering. 1996;213:8.
27. Arif T, Colas G, Filleter T. Effect of humidity and water intercalation on the tribological behavior of graphene and graphene oxide. Appl Mater Interfaces. 2018;10:22537.
28. Iwabuchi A, Kayaba T, Kato K. Effect of atmospheric pressure on friction and wear of 0.45 steel in fretting. Wear. 1983;91: 289.
29. Yoshizawa H, Israelachvili J. Relation between adhesion and friction forces across thin films. Thin Solid Films.1994; 246:71.
30. Kane M, Cerezo V, Do M. Effect of thin water film on tire/road friction. Young researchers Seminar. Denmark: Res. Gate; 2011.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/54760