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Ambient and Nitrogen Environment Friction Data for Various Materials & Surface Treatments for Space Applications

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Abstract
Objectives:

A multivariate tribological evaluation of candidate materials, surface treatments and dry film lubricants is needed for design of moving mechanical components that function reliably in extreme conditions, including for long-duration space missions. In this study, linear reciprocating or unidirectional sliding friction data was collected using ball-on-flat tests. The balls were hardened 440C stainless steel (either uncoated or sputtered with MoS_2) and flat surfaces were 440C stainless steel, Nitronic 60 stainless steel or Ti6Al4V titanium alloy with various surface treatments and/or dry film lubricants. Surface treatments included anodizing, nitriding and electrical discharge machining. The dry film lubricants included Microseal 200-1, sputtered MoS_2 and a nano-composite coating i-Kote. The data contains applied normal load, measured friction force, calculated coefficient of friction, ball position, ambient temperature and relative humidity during testing. Tests were performed at different peak Hertzian contact pressure conditions ranging from 300 to 2000 MPa. Data is also available for flat surfaces that were vacuum baked at 150 °C after surface treatment and dry film coating as well as samples tested in inert gas (nitrogen) environment. This data can be used both to fundamentally understand the tribological properties of different material systems as well as to enable design of components for specific applications, conditions and duty cycles.

Keywords

Friction data, coefficient of friction, dry film lubricant, nitriding, anodizing, Ti alloy, MoS_2, microseal, i-Kote.

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Objective

Mechanical components are designed to perform reliably throughout their operational life. Design is guided, in part, by the tribological properties of the materials used to produce them. Often, these materials undergo surface treatments to improve their mechanical properties and they may be coated with dry film lubricants for efficient operation, particularly in extreme conditions where liquid lubricants are not feasible [1].

Efficient operation is particularly critical in space applications where service or replacement of parts is not possible. For such applications, the tribological performance of various candidate materials, surface treatments and dry film lubricants have to be evaluated to identify optimal design strategies [2, 3]. Tribological performance evaluation involves sliding between different materials with various surfaces of interest and measuring the friction force. The change in coefficient of friction (CoF) over time during sliding can help identify the best candidate for a given set of operating conditions and duty cycles. Such data can also provide fundamental insight into the tribological behavior of various materials [4].

In this study, we collected friction performance data for different substrate materials including 440C stainless steel, Nitronic 60 stainless steel and titanium alloy (Ti6Al4V), sliding against 440C stainless steel ball (uncoated or sputter coated with MoS_2). Substrates underwent different surface treatments, including anodizing (with or without PTFE impregnation) nitriding and electrical discharge machining. Some were coated with dry film lubricants, including Microseal 200-1, sputtered MoS_2 and i-Kote. Corresponding vendor information is shown in Table 1. Some friction tests were performed in inert gas environment (nitrogen) or after baking the samples in vacuum at 150 °C for one hour.

Table 1. Surface treatments and dry film lubricants with the corresponding vendors

	Surface Treatment	Dry Film Lubricant	Vendor
MS 200-1	-	Microseal 200-1	E/M Coating Services
i-Kote	-	i-Kote	Tribologix Inc
MoS_2	-	Sputtered MoS_2	Hohman Plating & Manufacturing Inc
Danco Type 2	Anodizing	-	Danco Anodizing
Tiodize Type II	Anodizing	-	Tiodize Co., Inc
Tiodize Type IV	Anodizing (with PTFE)	-	Tiodize Co., Inc

Data Uniqueness

The data reported here was collected to study the performance of different types of surface treatments and dry film lubricants on various substrates in both ambient and inert gas environments for space applications. An inert gas environment is typically used as a proxy for the vacuum of space in tribological studies. Testing in inert gas entailed designing and fabricating a custom enclosure that was retrofitted on to the tribometer instrument with sensors to monitor ambient temperature, humidity and oxygen concentration. Data collection also involved fabrication of custom test specimen that were processed using a variety of commercially available techniques provided by multiple different companies and performing tribological experiments across a range of operating parameters and environments. Running such experiments, particularly with the material and surface treatments studied here, is both expensive and labor-intensive. This data may be valuable to anyone considering corrosion resistant, anti-galling surface treatments and tribologically superior dry film lubricants in their mechanical components, particularly for space applications.

Methodology

Test Conditions

Tribological testing to measure friction and wear was performed using an Rtec Instruments Multifunction tribometer, modified to include a custom enclosure that enabled testing in inert gas environments. Linear reciprocating and unidirectional sliding tests were performed to measure CoF with ball-on-flat and ball-on-disk set-ups using modified ASTM G-133 and ASTM G99-17 standard procedures, shown schematically in Fig. 1a and b, respectively. Most tests were performed at room temperature (22 °C) and ambient air conditions with relative humidity between 30 and 50% and some tests were performed in dry nitrogen environment at room temperature and relative humidity < 5% and oxygen concentration < 0.4%. The test parameters in the reciprocating tests were 10 mm stroke length, 0.5 mms^{-1} sliding speed and applied loads corresponding to calculated peak Hertzian contact pressures of 300, 500, 800, 1100 and 2000 MPa. In the unidirectional tests, the sliding speed was 1000 mms^{-1} at 300 MPa and 100 mms^{-1} at 1100 MPa contact pressure.

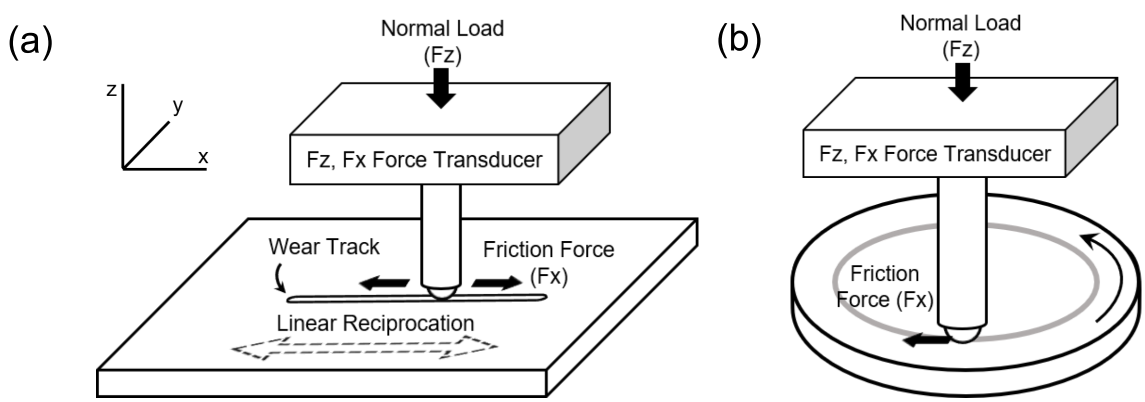

Figure 1. Schematics of the (a) ball-on-flat linear reciprocating test and (b) ball-on-disk unidirectional test.

Materials

Flat or disk specimens with different substrate materials and surface treatments were tested. The substrate was stainless steel (440C or Nitronic 60) or titanium alloy Ti6Al4V. The Ti6Al4V alloy was either machine cut (referred to as 'Ti6Al4V') or electrical discharge machining (EDM) cut (referred to as 'EDM Ti6Al4V'). Some surface and mechanical properties of these substrates are shown in Table 2. The surface roughness of the substrates before treatment or DFL coating was measured to be ~130 nm using contact mode profilometry and the roughness of the tested surfaces (reported in the Overview spreadsheet) was measured using interferometry. The surface treatments included in this study were nitriding and anodizing, and the dry film lubricants tested were sputtered MoS_2, Microseal 200-1 or i-Kote. The anodized surfaces were fabricated by two different vendors Danco (Type 2 anodizing) or Tiodize (Type II and Type IV anodizing). Representative images of these samples are shown in Fig. 2.440C stainless steel balls of diameter 4.76 mm (3/16 inch) or 9.53 mm (3/8 inch) and Rockwell C60 hardness (with and without sputtered MoS_2) were used as the counter-body.

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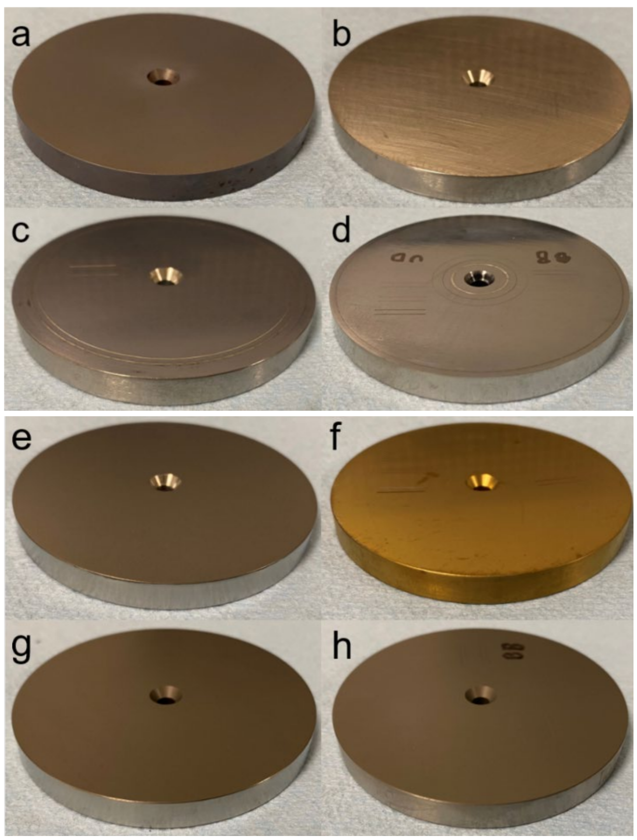
Table 2. Substrate material and surface properties.

Substrate	Rockwell Hardness	Surface Roughness, Ra (nm)	Elastic Modulus (GPa)	Poisson's Ratio
440C	C45-50	130	200	0.28
Nitronic 60	B85	130	180	0.30
Ti6Al4V	C35	130	110	0.31
EDM Ti6Al4V	C35	130	110	0.31



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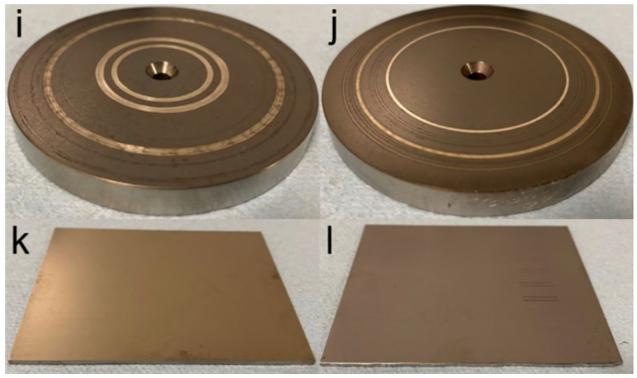

Figure 2. Photos of the samples tested in this study: (a) 440C with MS 200-1, (b) Nitronic 60, (c) Nitronic 60 with MS 200-1, (d) EDM Ti6Al4V with MoS_2, (e) Anodized Ti6Al4V (Danco Type 2), (f) Nitrided Ti6Al4V, (g) Anodized Ti6Al4V (Tiodize Type II), (h) Anodized Ti6Al4V (Tiodize Type IV), (i) Ti6Al4V with i-Kote (j) 440C with i-Kote (k) Ti6Al4V, and (l) Ti6Al4V with MS 200-1.

Friction Data Processing

The available files contain raw (reciprocating and unidirectional tests) and post-processed (reciprocating tests) data. Post-processing was done in the case of reciprocating tests to correct for friction force bias that occurs due to misalignment between the force transducer and the sample surface. This misalignment is typically a result of changes in surface topography during sliding or machining imperfections. Misalignment induced friction force measurement uncertainties can be minimized by averaging the absolute friction force from the forward and backward motion of the ball on the sample [5]. Averaging and data smoothing was accomplished using a moving mean and Bartlett window [6] size of ~ 8000 data points with a boundary handler. Although the Bartlett window function can result in discontinuities at the beginning and end of the data, the general CoF trend is not affected, as shown in the example in Fig. 3.

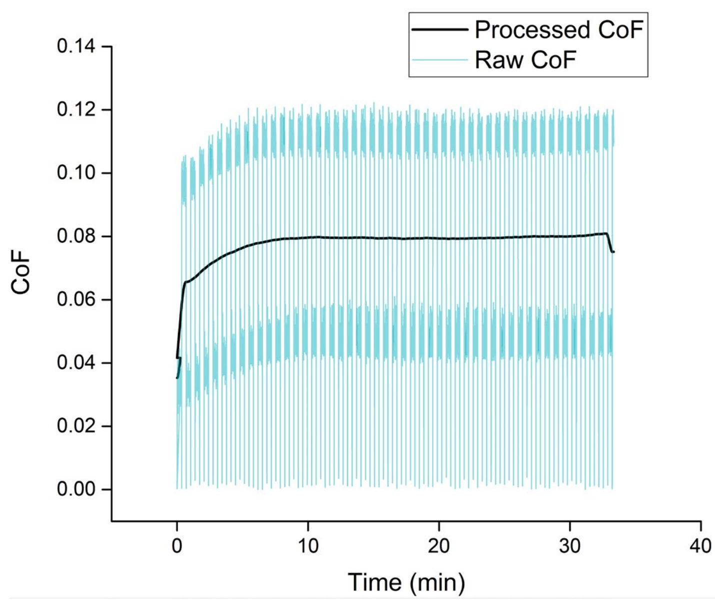

Figure 3. CoF plot from a linear reciprocating test showing raw and processed data.

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Data description

The data contains applied normal load, measured friction force, calculated CoF, position of the ball, ambient temperature and relative humidity during testing. The column headers corresponding to each parameter are listed below in the order of appearance in the data file.

1. Step – Tribometer program step
2. Timestamp – Time of recording of data
3. RecipeStep – Tribometer program step
4. DAQ.Fz (N) – Normal load in N
5. DAQ.Fx (N) – Friction force in N
6. DAQ.COF () – Coefficient of friction
7. XYZ.X Position (mm) or Rotary.Position (rev) – Absolute position of ball along the wear track in mm (for reciprocating tests) or absolute angular displacement of the flat disk in terms of number of revolutions (for unidirectional tests)
8. RTC.Temperature (Â°C) – Ambient temperature in degrees Celsius
9. RTC.RH (%) – Relative humidity of ambient air

Headers 'Step' and 'RecipeStep' (1 and 3) both refer to the programming step the tribometer is operating at the time of recording. For example, the reciprocating sliding tests were performed by the tribometer in two steps. In the 1st step, the ball was moved towards the substrate until the desired normal load was attained. In the 2nd step, sliding was performed, and the friction force was measured. So, the COF data in the Step/RecipeStep 1 is to be disregarded for sliding friction performance. Similarly, the unidirectional tests were performed in two steps: Step 1 was rotating the disk at set RPM and Step 2 was loading the ball. However, note that only Step 2 data was recorded in unidirectional tests. Header `Timestamp' starts from zero in each step and represents the time in seconds at which the data was recorded. Headers with `DAQ' prefix (4,5 and 6) correspond to normal force (Fz), friction force (Fx) and CoF measured and calculated from the force sensors. Header `XYZ.X' (7), only present in case of linear reciprocating tests, refers to the absolute position of ball along the wear track at any given time. The difference between the minimum and maximum values of the absolute position is the stroke length. The rate of change of the ball position can be used to calculate the instantaneous sliding speed. Header 'Rotary.Position (rev)' (7), only present in case of unidirectional sliding tests, refers to the absolute angular displacement of the test specimen (disk) in terms of number of revolutions. Note that XYZ.X Position and Rotary.Position do not always start at zero. Lastly, headers `RTC.Temperature' and `RTC.RH' refer to temperature (in degrees Celsius) and relative humidity (%) of the testing environment, respectively.

The sampling frequency of the force sensor was approximately 1000 Hz; however, every 10 points were averaged resulting in an effective sampling frequency of 100 Hz. The raw unfiltered data along with the processed data is stored as comma delimited data in CSV format files. Data files corresponding to different substrate materials and surface treatments are combined into datasets as shown in Table 3.

Table 3: Overview of data files grouped by substrate material.

Label	Name of Data File/Data Set	File extension	Data repository and identifier (DOI or accession number)
File 1	Overview.xlsx	.xlsx	https://doi.org/10.6071/M33M4Q
Data Set 1	Nitronic60.zip	.zip	https://doi.org/10.6071/M33M4Q
Data Set 2	440C.zip	.zip	https://doi.org/10.6071/M33M4Q
Data Set 3	Ti6Al4V.zip	.zip	https://doi.org/10.6071/M33M4Q
Data Set 4	EDM Ti6Al4V.zip	.zip	https://doi.org/10.6071/M33M4Q

Limitations

- In most cases, there are only two test repetitions and, in few cases, three.
- Not all pressure conditions were tested for all material/surface treatment/dry film lubricant cases.
- In a few tests, temperature data was not collected, and the temperature is shown as `-999'.
- Wear data was not captured in this study.

Vendor contact information pertaining to dry film lubricants and surface treatments

1. Tiodize Co., Inc.
   5858 Engineer Drive, Huntington Beach, California, USA 92649
   Tel: +17148984377 Website: www.tiodize.com
2. Danco Anodizing
   44 LA Porte St., Arcadia, California, USA 91006
   Tel: +16264453303 Website: www.danco.net
3. E/M Coating Services (Parent company: Curtiss-Wright Surface Technologies)
   20751 Superior Street, Chatsworth, California, USA 91311
   Tel: +18184076280 Website: https://cwst.com
4. Hohman Plating & Manufacturing Inc.
   814 Hillrose Ave, Dayton, Ohio, USA 45404
   Tel: +19372282191 Website: https://hohmanplating.com
5. Tribologix Inc
   1440 Brickyard Road, Unit 4, Golden, Colorado, USA 80403
   Tel: +13032782211 Website: https://tribologix.com

Availability of data material

The data described in this data note can be freely and openly accessed on DRYAD (https://datadryad.org). Please see Table 3 for details and links to the data.

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