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# Characterization of Isotropic Surface Texture in the Boundary Lubrication Regime and the Frictional Response

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Thesis Committee:

# Characterization of Isotropic Surface Texture in the Boundary Lubrication Regime and the Frictional Response

An Undergraduate Honors College Thesis

in the

Department of Mechanical Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

by

Edwin Hanks Bird

# Abstract

In the dynamic nature of today's engineering components the use of nanolubricants and the control of micron and sub-micron surface texture features can greatly aid in reducing frictional losses and thus reduce energy consumption. The primary purpose of this paper is to define texture and analyze the effects of an isotropic surface texture and lubrication on the frictional response of contacting surfaces in boundary lubrication. This experiment was carried out using a steel ball-on-disk tribometer set-up where the steel disk had a sandblasted surface texture using 40-60 grit glass beads to produce an average roughness, $S_a$, of 2.120 μm uniformly distributed as shown by an $S_{tr}$ value of 0.9. The disks were tested in the tribometer using three different lubrications: without the presence of a lubricant, with PAO base oil, and with $MoS_2$ nanoparticle lubricant. The $MoS_2$ nanolubricant frictional response showed the lowest amount of observable and quantifiable wear based on the areal surface texture parameters measured using a profilometer.

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*Characterization of Isotropic Surface Texture in the Boundary Lubrication Regime and the Frictional Response*

# Acknowledgments

The author would like to acknowledge Mr. Ben Fleming for his insightful supervision in the preparation of the steel disk samples. Many thanks to Salil Bapat for his help in providing resources, guidance throughout the entire process, running the tribometer experiments, and assistance in the writing of this report. The author would also like to thank Wenyang Zhang for his experience and profilometer data gathering. Also, a special thanks to my research advisor Dr. Malshe for his helpful guidance in the experimentation process, funding process, and the writing of this report.

# 1. Introduction

### *1.1 Introduction to Texture and Tribology*

The term ‘texture’ can have many different meanings depending on the methodology used to study a surface. In the field of materials science texture is defined as the preferred orientation of crystalline grains within a material [1]. Surface texture can also be defined as a repetitive arrangement of features or shapes and sizes over a surface in three dimensions [1]. In both machining science and surface metrology, texture refers to the roughness, waviness, and lay of surface features. In tribology the term texture refers to the form, dimensions, and patterning of a surface as well as the associated effects produced on the underlying material [1]. The definitions of texture in surface metrology, and tribology will be applied further in this paper.

Surface texture; as defined by surface metrology, has three components namely: lay, surface roughness, and waviness. Lay is the dominant direction of the surface pattern usually determined by the production process. The second and most familiar component of surface texture is surface roughness. This consists of the high frequency, fine irregularities resulting from the manufacturing process itself; for example, the grit size of abrasive particle utilized in grinding. Lastly, waviness is the lower frequency irregularities generally resulting from vibration in the machining process. The figure below illustrates simply these three components of surface texture along with showing the profile component which is a combination of the waviness and roughness profiles.

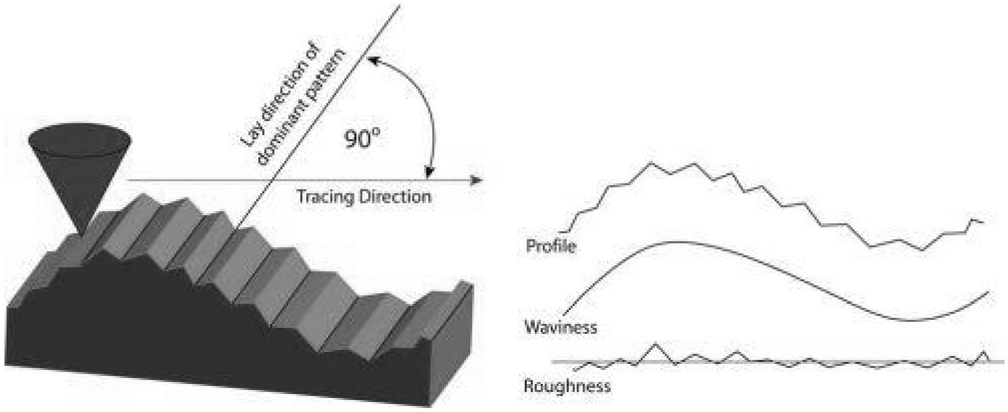

**Figure 1. Surface Texture Components [2]**

Lay and waviness will not be used further in this paper, but were introduced solely for completeness. When the surface feature size is considered along with the size of the contact area, the scale of concern for this experiment ranges from sub-micron to micron. The effects of waviness and lay on tribology are only present over larger contact areas.

For many years engineers have applied regular geometric features to lubricated surfaces with the goal of controlling friction and wear. More recently, with the advances in materials science and manufacturing techniques, the patterns of surfaces have evolved to micro and nano-scaled patterns. From the early 1990’s, with the advent of computer-based models, the effects of surface textures on contact stresses, lubricant film thickness, and friction have become easier to study with greater accuracy and realism.

The effect of surface texture has been studied on frictional characteristics (via tribological testing) of two surfaces in direct contact. Tribology is defined as the study of friction, lubrication, wear; or as the science of interacting surfaces in relative motion [3]. Friction is the force that resists an objects relative motion and is present whenever two contacting surfaces are moving with respect to each other. Friction is generally quantified by the coefficient of friction (COF). The COF is a dimensionless value that describes the ratio of the friction force to the normal force acting on an object. Accompanying friction over a time interval is surface wear. Wear is the removal of material from a surface due to surface shear.

Friction can either be beneficial or harmful depending on the application. An example of a benefit of friction is tire traction on an icy road when applying the brakes to stop the car. Just the opposite on and internal to all industrial equipment, friction translates to heat which means there is energy being transferred, or lost, from the system to the surroundings. This energy loss leads to inefficiencies which in internal combustion engines can be equal to 33% of the fuel energy input [4]. Knowing that the friction losses can be so high, the importance of considering all friction control options when designing two mating surfaces is magnified greatly. These control options can include: improved lubricants, improved part design of mating surfaces, utilization of coatings and surface treatments, and texturing of surfaces [1]. The latter, texturing of lubricated surfaces, will be considered in this paper.

### *1.2 Importance and Functionality of Texture*

Surface texture is prevalent both in nature and in manufacturing. Generally it is the analysis of natural textures that leads to the conception of manufactured textures. One interesting example of a natural texture is shark skin. The texture of shark skin has been shown to perform two important functions: reduce friction drag, and greatly reduce biofouling. Water craft manufacturers have begun designing the hulls of ships to have similar surface texture features to the grooves and patterns found on shark skin [5].

A more specific manufacturing application of texture is found direct metal to metal contacts in the presence of a lubricant. The texture of the two metal surfaces sliding with respect to each other both creates friction due to contacting peaks, and traps the lubricant in the valleys between asperities.

Another function of the surface texture is to allow the debris from the contacting asperities to be trapped in the valleys. Without this trapping the debris particles would act as abrasives on the surface and contribute to wear. It is widely accepted that surface texture aids lubrication via the following four mechanisms [1,6]:

1. Altering the flow and film thickness of lubricating fluids both locally and across the contact region as a whole.
2. Serving as channels for lubricant supply to the surfaces in contact.
3. Trapping wear debris that could otherwise be abrasive to the contacting surfaces.
4. Altering the bearing pressure distribution.

For example, in bearing applications, the surface texture desired consists of deep valleys with relatively flat peaks. This can be seen in **Figure 2** where a bearing surface prepared by grinding is on the right and an ideal "superfinished" surface is on the left.

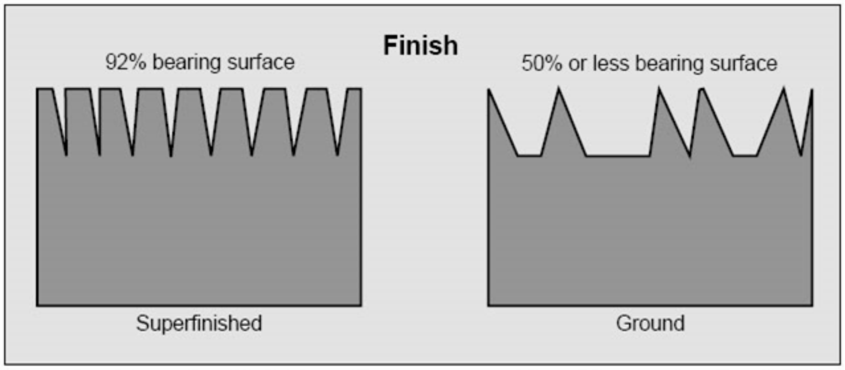

**Figure 2.** Bearing surface Finish [7]

### *1.3 Introduction to Boundary Lubrication*

In boundary lubrication the surfaces in contact carry the load and the friction is reduced by molecularly thin layers of lubricant adhering to these solid surfaces. The mechanisms of friction and wear are influenced by the texture, surface hardness, lubricant, and wear products. These mechanisms make the analysis complex; however, this experiment will be primarily focused on the effects of texture. The effect of surface texturing in the boundary lubrication regime is an unexplored area of study [8].

In boundary lubrication the heat generated by the high local pressure causes some asperities to break off due to adhesion, ploughing, and peeling off the asperities; namely, wear. Tribofilms form as a result of boundary lubrication and form a protective layer against this wear. A tribofilm is defined as a molecularly thin solid film generated as a result of contacting surfaces, which is adherent on the parent surface, yet has different chemical composition, structure, and tribological behavior [9]. Tribofilms are a third body acting to greatly affect the magnitude of friction, and consequently wear. Tribofilms can be classified into four types [9]:

1. Tribofilms generated from the wear of the major constituents of the sliding couple surfaces
2. Tribofilms generated from the preferential wear of the soft or lubricious constituents of a multi-phase or composite material
3. Tribofilms being different from the parent worn surfaces in chemical composition and or crystalline structure as a result of sliding contact
4. Tribofilms generated as a result of tribo-chemical reactions between the wear products (i.e. wear debris and worn surfaces) and the environmental species

### *1.4 Overview of Texturing Parameters*

As previously introduced surface metrology deals with quantifying surface texture with the goal of producing standards dealing with surface form, surface waviness, and surface roughness. This goal is accomplished by the standardization and proper application of surface texture parameters. Surface texture parameters are important for three reasons: (a) simplifying the description of a surface's texture, (b) allowing comparisons with other parts, and (c) to form a suitable measure for a quality system. There are two types of techniques for characterizing surface texture, those measured along a straight line; profile methods, and those measured over an area; raster area methods. Profile surface texture characterization has now been standardized for some time and areal standards have recently been drafted. Initially areal surface texture was characterized by the 'Birmingham-14' parameters; however, more recently ISO began working on the standardization of areal surface texture. A project by the name of SURFSTAND was carried out from 1998 to 2001 which culminated with the publication of the Green Book, as well as generating the basic documents for upcoming specification standards [10]. Now that a brief history has been developed, profile parameters will be introduced followed by areal parameters, and lastly a discussion of the importance of each set of parameters.

Surface profile measurement is the measurement of a line across the surface that can be represented as a height function with respect to the displacement in the lateral direction, z(x). Per ISO standard 4287 the direction for assessment when utilizing a stylus measuring instrument is perpendicular to the direction of the lay. Once the form has been removed from the measured data, each respective parameter can be calculated. The first capital letter in the parameter symbol designates the type of profile being measured after the other profiles have been filtered out. The capital letter *R* is calculated from the roughness profile, *W* from the waviness profile, *P* from the primary profile.

The first difference to note when transitioning the discussion from profile to areal characterization is that there is no need for three profile symbols, but rather only the letter *S* is used to symbolize areal parameters. Another difference to note is that since the following parameters are based on areal measurement instead of profile, there is no requirement for the coordinate system to be related to the lay.

There are two main classifications of areal parameters; field parameters and feature parameters. Field parameters are defined from all the points on a scale-limited surface; whereas, feature parameters are defined from a subset of predefined topological features from the selected surface [10]. The following table only contains the parameters that are of interest to this initial experiment. Complete list of parameters and their descriptions can be found in ISO 25178: Part 2.

| **Spatial and Amplitude Information** | | |
|---|---|---|
| **Height** | Sq: Rms height | Sa: Arithmetic mean height |
| | Ssk: Skewness | Sp: Max peak height |
| | Sku: Kurtosis | Sv: Max pit height |
| | Sz: Max surface height | |
| **Spatial** | Sal: Auto-correlation length | |
| | Str: Texture aspect ratio | |
| **Hybrid** | Sdq: Root mean square gradient | |
| | Sdr: Developed interfacial area ratio | |
| **Misc.** | Std: Texture direction | |

**Table 1.** Areal Parameters [10]; ISO 25178-2

The importance of these parameters has been previously introduced; however, in regards to this paper a few of the parameters will be selected and further used to measure and compare the surface textures of multiple steel disks. When comparing areal parameters to profile parameters there are inherent limitations to be noticed in the 2D profile method. The fundamental problem with profile measurement is that the profile does not necessarily indicate the functional aspects of the surface. An example to illustrate this limitation can be seen in **Figure 4**. When using a profile measuring technique the two profiles below would report the same Ra value but clearly have different height distributions. Due to having different height distributions the surfaces would have very different functional properties [10].

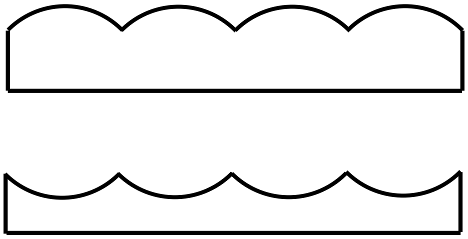

**Figure 4.** Profiles with Equivalent Ra Values [10]

Another example showing the problems with 2D measurement techniques is when a pit is observed on a 2D profile and this same sample is examined with a 3D method the pit that was observed could actually be shown to be a valley spanning a relatively long length on the sample. The above limitations or profile parameters exemplify to the fact that when two surfaces are in contact there is a certain area that is in contact on each surface, not a linear path [10].

### *1.5 Experimental Objectives*

This paper will attempt to answer the following scientific questions: What is the meaning of texture and its relation to tribology? What is the effect of surface texturing on the frictional response of two sliding surfaces in the boundary lubrication regime? How does surface texturing aid in lubrication? How does texture evolve as a function of time and lubrication?

# 2. Experimental Methods

## *2.1 Tribometer*

Tribology in this experiment is studied by employing a tribometer set-up with ball-on-disk contacting surfaces (CSM Instruments, Model No. TRB, Serial No. 01-02326). A tribometer fundamentally consists of an arm that constrains the ball tangent to the disk surface, a motor to rotate the disk (not pictured), and a strain gauge to measure the arm deflection; **Figure 5**. The particular set-up of this experiment used a device to convert the rotational motion of the motor to linear motion so that the disk would only move linearly between two points set by the ½ amplitude parameter described later. The tribometer sends the strain gauge data to a computer which with the benefit of a TriboX 2.10.C program allows the user to meaningfully analyze the information. The program displays the information as a graph of the coefficient of friction (μ) versus time.

**Figure 5.** Pin-on-Disk Tribometer [11]

## *2.2 Material Selection*

The ball-on-disk set-up consisted of 52100 hardened steel balls (Hardness: HRC 60), 10mm in diameter, and 4140 steel disks (Hardness: HRC 29), 30mm in diameter, both purchased from McMaster-Carr. The 52100 steel balls were chosen based on prior experiments performed on the tribometer. The steel disk alloy was chosen based on having a lower hardness value than the steel balls in order to ensure that majority of the surface texture evolution is limited to the disk.

One of the objectives of this experiment was to determine the important texture design selection criteria. The surface texture design selection criteria that were chosen are as follows: periodicity, feature size (average roughness $S_a$, $S_q$), particle size of sandblasting media. It was decided, after considering the periodicity of features on the surface that this experiment should first begin with the manufacturing of a uniform texture on the surface of the 4140 steel disks. This uniform surface texture would need to be produced without having major directionality. The manufacturing process that was chosen for this purpose was to cut the steel rod to disks, polish the disks to remove artifacts from cutting, and sandblast the surface with glass beads. The glass beads that were used were 40-60 grit (250-420 microns). These beads were chosen due to several factors: the moisture content in the machine shop airlines prevented the use of aluminum oxide media, the glass beads were available at the machine shop, and the filtration system for the sandblast machine could not filter media smaller than the 250 micron glass beads. As mentioned, aluminum oxide blasting media with an average particle size of 3 micron was considered, but due to the limitations listed above could not be utilized.

There are two lubricants used in this experiment. One is the commercially available base oil, polyalphaolefin (PAO 10), and the other is Molybdenum Disulfide ($MoS_2$). PAO is referred to as the base oil as it is the primary lubricant constituent in the $MoS_2$ lubricant formulation. The composition of the Molybdenum Disulfide lubricant formulation by weight is: 1% $MoS_2$ particles, 1.5% canola oil, 0.5% lecithin, and 97% base oil. Micron sized $MoS_2$ particles are purchased from Alfa Aeser and are first dry milled for 48 hours, followed by wet milling with canola oil for 48 hours. The resultant $MoS_2$ nanoparticles have to an average particle size of around 80-100 nm. These nanoparticles are capped with organic ligands (canola oil) facilitating easy suspension in base PAO oil. The lecithin is a phospholipid that is added for its anti-wear properties. [12,6]

### *2.3 Sample Preparation Procedure*

1. 1 ft steel rod sectioned using a horizontal band saw to disks approximately 5mm thick
2. Disks were polished on a belt sander with 80 grit paper
3. Disks were hand polished with 120 grit then 180 grit, rotating the sample 90 degrees after sanding each direction for 10 seconds
4. Once all cut marks have been removed the sanding process is complete
5. The samples were then sandblasted on one side with glass beads

The times shown in the procedure below for the tribometer tests, 30 seconds, 120 seconds, 30 minutes, 1 hour, and 3 hours were chosen based on the events observed from a friction curve with $MoS_2$ as the lubricant. The 30 second experiment corresponds with the start point on the $MoS_2$ friction curve where the coefficient begins to increase. The 120 second duration was chosen due to the fact that the maximum COF is observed at this time. For the 30 minute test the friction curve should begin to drop off, followed by steady state in the 1 hour and 3 hour tests.

### *2.4 Tribometer Testing Procedure*

1. Sample disk, five balls, tribometer ball mount are placed in a beaker with an acetone solution, this beaker is then placed in a sonicator for 10 minutes
2. Disk, one ball, and mount are taken out of the acetone and allowed to air dry
3. The $MoS_2$ lubricant is also sonicated to ensure a uniform suspension
4. The sample disk and each ball is mounted following standard operating procedures as outlined by CSM Instruments
5. Tribometer arm is calibrated by adjusting counterweights until, when the machine is tapped with two fingers the arm will fall to its vertical resting position
6. Lubricant if necessary is dropped onto the disk surface with a pipette (2-3 drops to fully cover the contact area)

7. The 10N load is applied manually with a gasket for a vibration dampener
8. Open TriboX 2.10.C and input parameters found in **Table 2**, the program will prompt user to follow certain steps
9. Between tests the tribometer arm is advanced approximately 2 mm to the right and more lubricant can be added if necessary
10. Steps 3-11 are repeated for tests 2-5

| **Test** | **Approx. Duration (sec)** | **Total Distance (m)** | **Max Speed (cm/s)** | **Acquisition rate (Hz)** | **Load (N)** | **1/2 Amplitude (mm)** |
|---|---|---|---|---|---|---|
| **1** | 30 | 0.36 | 2.000 | 2.00 | 10 | 18.000 |
| **2** | 120 | 1.44 | 2.000 | 2.00 | 10 | 18.000 |
| **3** | 1800 | 23.00 | 2.000 | 2.00 | 10 | 18.000 |
| **4** | 3600 | 46.00 | 2.000 | 2.00 | 10 | 18.000 |
| **5** | 10800 | 138.00 | 2.000 | 2.00 | 10 | 18.000 |
| | **Note:** All tests performed at ambient conditions | | | | | |

**Table 2**. Tribometer Parameters

### *2.5 Characterization Methods*

Scanning white light interferometry (SWLI) is a noncontact method of measuring 3D surface roughness [13]. A SWLI can also be known as a profilometer and is effectively combines the technology of interferometry and microscopy. A profilometer works by passing a white light beam through filter as well as a microscope objective lens to the sample surface. A portion of the white light is reflected back from a reference mirror while the rest of the light is reflected off the sample surface. The combination of the reference beam and the reflected light creates light and dark bands known as fringes. These fringes combine to form the interferogram which shows the surfaces topography or texture. The different intensities of light are measured on the interferogram and via a computer algorithm are converted to surface height information. The particular profilometer used to gather data for this experiment was purchased from Zygo for use at NanoMech.

# 3. Results and Discussion

## *3.1 Tribometer Results*

The following charts were prepared using Microsoft Excel with data exported from TriboX 2.10.C using the procedure outlined in the previous chapter.

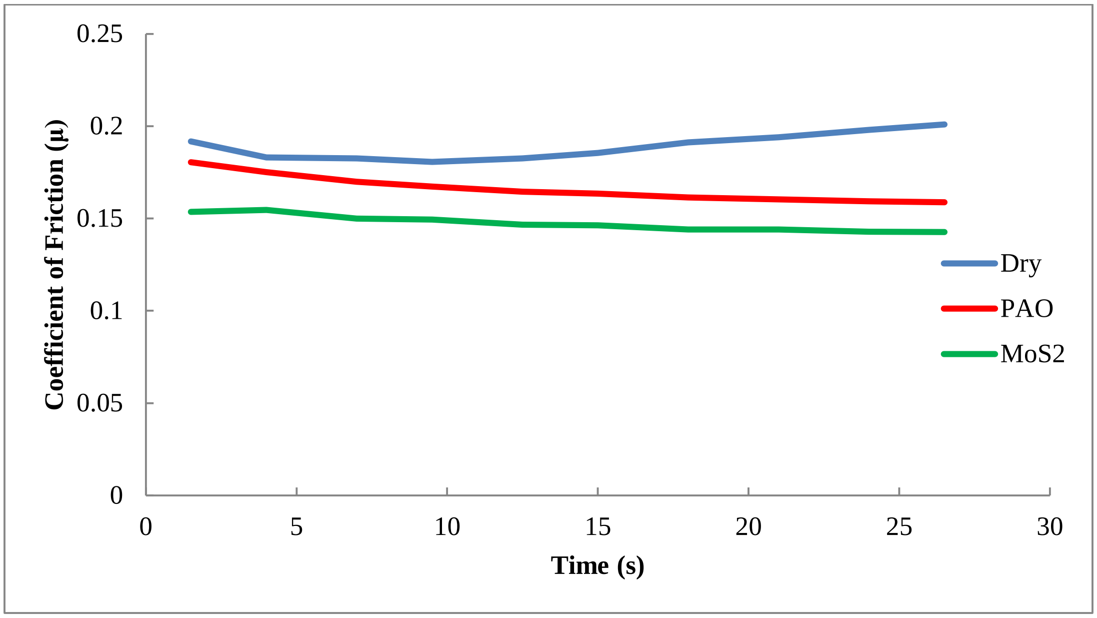

**Figure 6**. 30 Second Tribometer Test Results

**Figure 6** shows the graph of COF as a function of time on each disk surface.  From **Figure 6** it is observed that the general trend in coefficient of friction versus time was consistent over time for both lubricants; whereas, for the dry sample the coefficient of friction began to increase by the end of the test.

The trend to note in **Figure 6** is that in all tribometer tests from dry to base lubricant to $MoS_2$ lubricant each surface's coefficient of friction began at its respective value and decreased initially in the first few seconds.  This is believed to be due to the texture transformation as a result of the initial contact of asperities. After the initial few seconds the coefficient decreases due to the wear and flattening of asperities.

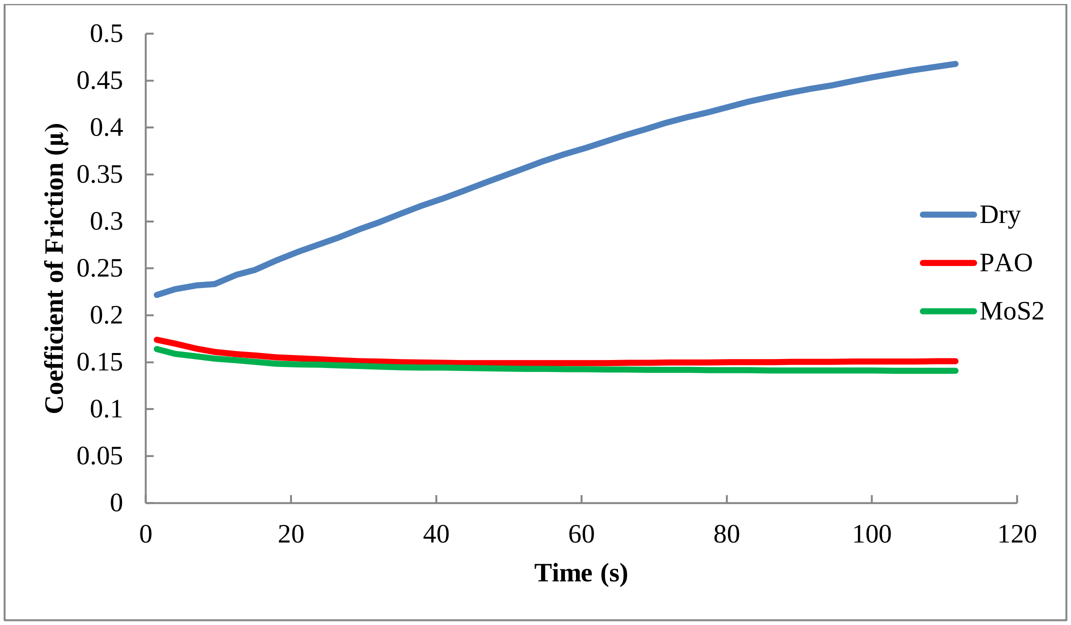

**Figure 7**. 120 Second Tribometer Test Results

For the 120 second test the base lubricant (PAO) and Molybdenum Disulfide disks performed produced nearly the same friction curves, with the PAO coefficient being slightly greater. This is contrasted by the dry sample as a general increase in coefficient of friction was observed over the entire time interval.

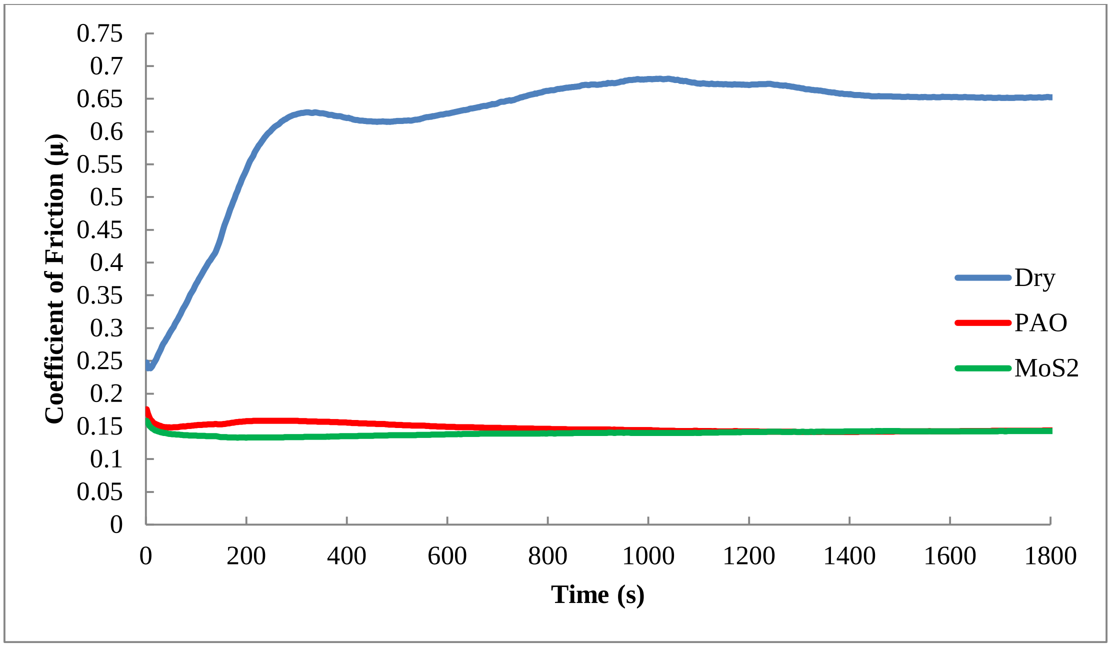

**Figure 8**. 30 Minute Tribometer Test Results

When the 30 minute test was performed again both lubricated disks performed nearly the same. From zero to 300 seconds the dry disk coefficient of friction increased greatly to a value of over 4 times the magnitude of both lubricated disks. From around 300 seconds onward the dry disk coefficient began to level off at an approximated value of 0.65.

During the 30 minute test with no lubricant the friction began to reach a high enough value such that the disk and ball were starting to create noise as the tribometer ran. After the test was completed there was a large amount of wear debris present, and for these two reasons this was the longest experiment run using a disk without lubrication.

Using **Figure 8** the dry disk friction curve can be examined in great detail. The friction increases greatly in the beginning due to the initial flattening of peaks which eventually results in a steady state with more uniform distribution of the applied load. From this point onward the coefficient of friction undergoes minor fluctuations believed to be due to third body wear debris.

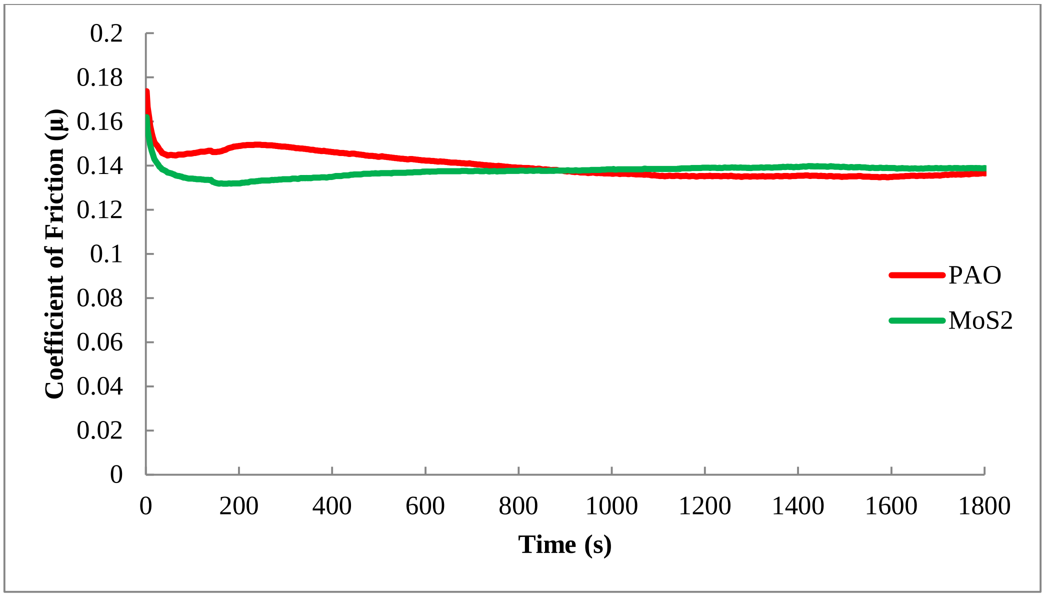

**Figure 9**. 1 Hour Tribometer Test Results

**Figure 9** depicts the variation in COF from tribological testing over a 1 hour duration for both the $MoS_2$ and the base oil lubricated disks. Initially for the PAO lubricated disk the friction was greater than the $MoS_2$ lubricated disk. The values then became very close with the PAO value for friction being slightly less than the Molybdenum Disulfide disk.

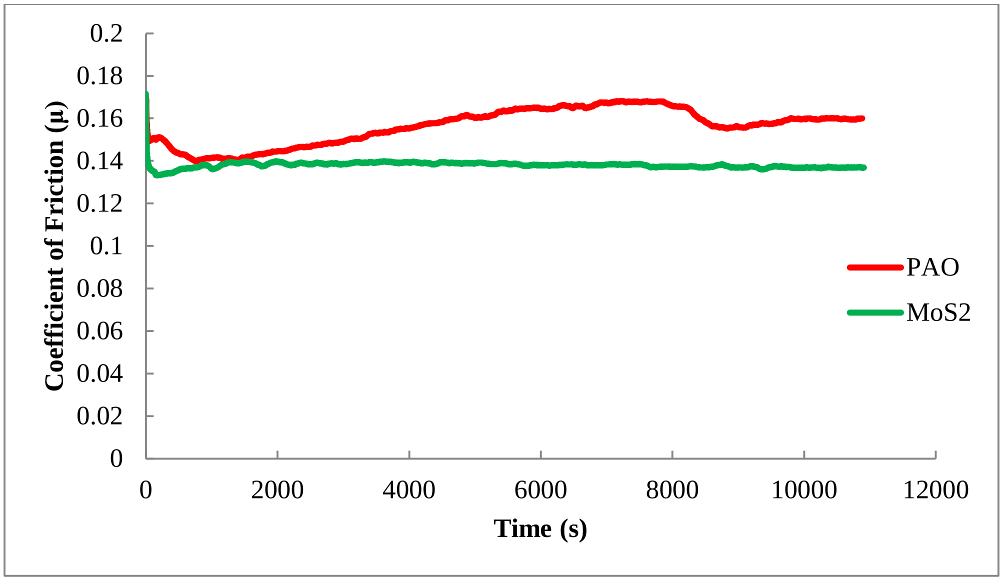

**Figure 10**. 3 Hour Tribometer Test Results

Over the duration of the three hour test the value for friction for the disk lubricated with $MoS_2$ maintained a constant value of 0.14. This is contrasted by the graph for the disk lubricated with the base oil. The coefficient of friction both increased and decreased over the 3 hour time interval concentrating around 0.16, slightly higher than the $MoS_2$ lubricated disk.

**Figure 9** and **Figure 10** show the same trends in comparing the tribological responses of $MoS_2$ and PAO base oil. From **Figures 9** and **10** a comparison can be made between the lubricant properties affecting the coefficient of friction. The differentiation between these two lubricants can be seen at around 2000 seconds into the experiment. At this point the effects of adding the $MoS_2$ nanoparticles along with the canola and lecithin oils to the base oil can be seen in the formation of the tribofilm and the consequent constancy in friction. The durability of the tribofilm can ultimately be seen in comparison with the base lubricated disk. When the time is over 1 hour it can be seen that the base oil loses its effectiveness which could be due to wear particles on the wear track, or could also be that the base oil had been removed from the surface due to the long testing duration.

Surface texture was shown to aid in lubrication when nanolubricant was present due to the steady state COF value when the 3 hour experiment was run. When the steady state value was reached the tribofilm has formed on the surface. This shows that the texture was conducive to the formation of a tribofilm and the resulting steady state COF exemplifies the effect of a tribofilm.

### *3.2 Profilometer Results*

The following table and charts were prepared using Microsoft Excel with data measured at the edge of the wear track from a Zygo profilometer located at NanoMech. The control data column is profilometer data before the tribometer tests were run on the sample; in other words it is data for areal surface texture not located on the wear track.

| Parameters | Dry | PAO | MoS2 | Control |
|---|---|---|---|---|
| **Sa-µm** | 1.050 | 1.534 | 1.924 | 2.120 |
| **Sq-µm** | 1.444 | 1.876 | 2.359 | 2.674 |
| **Sku** | 138.51 | 30.59 | 14.04 | 3.57 |
| **Ssk** | 3.69 | 1.07 | 0.78 | 0.53 |
| **Sp-µm** | 72.603 | 51.366 | 50.377 | 14.189 |
| **Sv-µm** | -10.549 | -19.175 | -38.572 | -10.011 |
| **Str** | 0.21 | 0.69 | 0.75 | 0.90 |

**Table 3**. 30 minute Wear Track Profilometer Data (Edge of Track)

**Table 3** tabulates data for the areal parameters of each lubrication set-up as well as the control measurement which was performed using the original sandblasted disk surface.

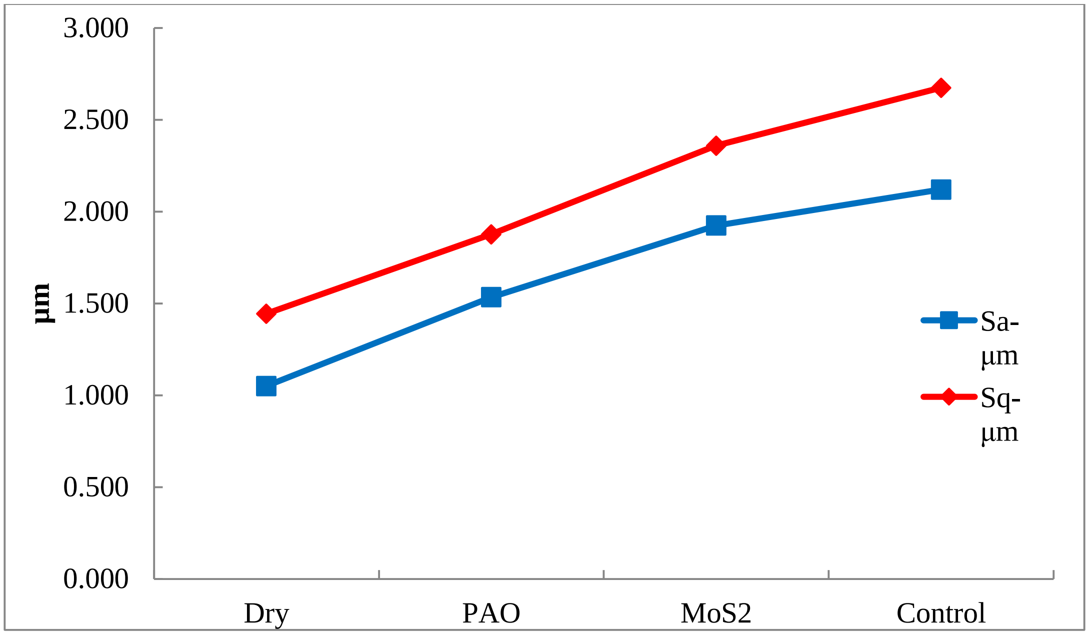

**Figure 11**. Height Parameters (Sa and Sq)

**Figure 11** shows a comparison of the areal height roughness parameters for different testing conditions.

The sandblasted surface texture produced had an average roughness, $S_a$, of 2.120 µm. Surface texture evolves over time as a result of friction between the two contacting surfaces. With a greater magnitude of friction comes a greater change in $S_a$ on the wear track. Knowing this wear can be quantified by the changes in $S_a$ and $S_q$. The disk with the greatest change in $S_a$ and $S_q$ was shown to be the dry disk (**Figure 11**), followed by the base lubricated disk and lastly showing the least amount of change is the disk lubricated with the nanolubricant. This was expected from the experiment's hypothesis, knowing that the purpose of a tribofilm is to reduce the effects of friction and wear.

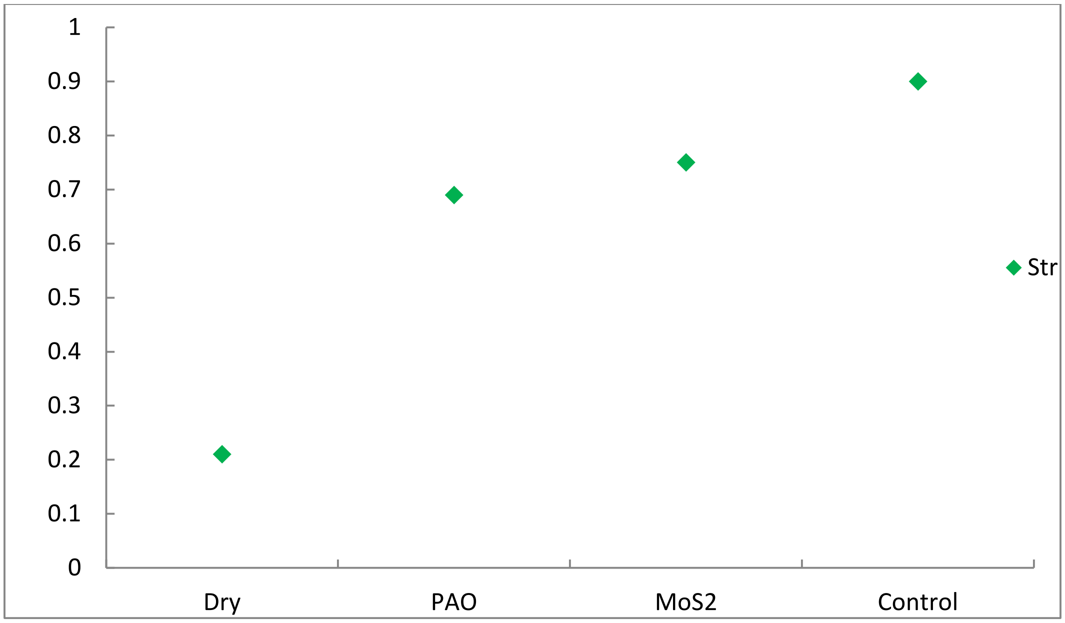

**Figure 12**. Spatial Parameter Str

**Figures 12** shows the variations in the texture aspect ratio parameter for different testing conditions. The control sample denotes measurement on the original sandblasted disk surface without any tribological testing.

The goal of this experiment was to produce a uniform surface texture and observe the effects of different lubrication situations on this uniform surface texture. A uniform surface texture means that there is limited directionality in the machining or polishing process. In this experiment the texture was controlled by polishing the disks with 180 grit sandpaper and following this up by using 40-60 grit sandblasting media. By using a larger grit sandblasting medium after polishing, the directionality of surface texture was shown to be minimized. The directionality of surface texture is examined by a parameter $S_{tr}$ (surface texture ratio) from ISO 25178 parameter set. Typically, $S_{tr}$ varies in between 0 and 1, with values closer to 1 suggest isotropic features without any lay and values close to 0 suggest directionality of the surface texture [10]. Experts agree that a value greater than 0.5 means a surface has an isotropic texture whereas a value below 0.3 shows a high amount of directionality. As seen in

**Figure 12**, value of $S_{tr}$ of the controlled surface is 0.90 suggesting highly isotropic texture. The dry disk on the other hand had an $S_{tr}$ value of 0.21 after the 30 minute experiment. This value shows that the texture was highly directional which again points to a high amount of wear on the surface. The values of $S_{tr}$ for the base oil and nanolubricant fall in between the dry experiment and the control with the nanolubricant being the most isotropic of all 3 lubrication set-ups.

As mentioned previously in the introduction, surface texture can have several positive effects to the frictional response of contacting surfaces [6,14]. These effects include facilitating the supply of lubricant; the valleys serve as storage space for both lubricant and wear debris particles. While texture has positive effects for lubrication, it also has negative effects on a surfaces frictional response. Prior to performing this experiment it was hypothesized that in order to achieve a low coefficient of friction the contacting surfaces need to have a relatively smooth surface texture. This was found to only be partially true. In order for a surface to have ideal frictional characteristics in boundary lubrication the texture needs to have surface features of similar size to the lubricant particles. For the Molybdenum Disulfide lubricant used the particle size is around 80-100 nm. As mentioned in the introduction the effect of friction over time is wear. When the coefficient of friction is high between the ball and disk, the amount of wear will subsequently be high. Although when a surface has a high value for roughness, $S_a$, the friction will be higher, it is this roughness that is used to store lubricant and physically activate the chemical reaction that results in a tribofilm. With this being said there is a balance that needs to be found between surface roughness and friction.

# 4. Conclusions

Isotropic surface texture with an $S_{tr}$ value of 0.9 was produced using the sample preparation procedure as outlined in the experimental methods chapter. The formation of a tribofilm when the disk was lubricated with $MoS_2$ nanolubricant was evident by the steady state frictional response during the 3 hour test shown in **Figure 10**. The evidence of a tribofilm proves that the surface texture produced by sandblasting, having an $S_a$ value of 2.120 μm, effectively aided in lubrication by having a feature size comparable to the lubricant particle size. While tribofilms can form with other values for surface roughness this simply shows that this surface texture is particularly conducive with the formation of tribofilms.

The presence of wear debris due to a high COF in the dry disk experiment proves that texture evolves greatly without the presence of lubrication. In contrast, the tribofilm produced in the presence of a nanolubricant protected the surface in such a way that the surface texture transformation was minimized as shown by the areal parameter data in **Table 3**. The positive effect of the nanoparticles suspended in the base oil was evident from the friction response plots showing that the coefficient of friction was reduced in the presence of the additives found in the nanolubricant.

Furthermore, this research shows that the implementation of nanoparticles to the base oil described in this paper can significantly enhance the tribological performance that results in better durability. This combination of better durability and enhanced frictional performance can lead to energy savings in many industrial applications.

Future work will further investigate the tribological effects of a directional surface texture and also systematically study the evolution of surface texture as a function of tribological testing parameters.

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