A novel approach to tribological measurements at harsh conditions

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ABSTRACT

When dealing with high-tech equipment, accurate positioning is of the utmost importance to ensure durability and a productive lifetime. Unexpected high friction or wear of positioning mechanisms can lead to unnecessary down-time or products that are not up to specification.

To ensure a sufficient lifetime, it is necessary to know beforehand how the sliding and rolling contacts will behave over time. This demand becomes more stringent when the machine operates at extreme conditions, e.g. vacuum or extremely low temperatures. Traditional greases and mineral oil based lubricants do not perform adequately in such extreme environments, as they either contaminate the vacuum or do not provide sufficient film thickness. TNO recently developed a unique measuring application, the TNO cryotribometer, in order to measure friction and wear of position mechanisms at harsh conditions. Preliminary results show that the contact pressure and the sliding velocity influenced the friction level greatly. This set-up is currently used to find and analyze different material combinations, which demonstrate a constant friction level under cryogenic vacuum conditions.

Keywords: cryogenic, durability, material combinations, tribology, vacuum

1. INTRODUCTION

As far back as the 1930's one of the first books on vacuum compatible materials was published. The *Werkstoffkunde der Hochvakuumtechnik* by Espe and Knoll[1] was the first systematic and comprehensive presentation of high vacuum materials. It was emphasized that the selection and handling of vacuum compatible materials is based on a different viewpoint than the common industrial construction materials. This holds especially when dealing with dynamic constructions where accurate positioning is required. When choosing the construction materials for service under extreme conditions, one has to take into account the rate of outgassing, adequate strength at high and low temperatures, matching thermal expansion coefficients and the purity of the materials.

1.1 The influence of vacuum

Since vacuum is a space in which there is no matter or in which the pressure is so low that any particles in the space do not affect any processes being carried on there[2], it is often used in high-tech and accurate applications. But besides the advantages, e.g. no unwanted interaction and pollution, there is also a downside. Due to the low level of oxygen and water, interactions between different materials will be different from what is common in an ambient environment. For example, two metals that move, i.e. rolling or sliding, past each other in air, will both have a (hydr)oxide skin which will be damaged upon contact. The damage will be automatically repaired due to the abundance of water and air. However, when the same system is observed in a vacuum surrounding, the oxide skin will be present initially but it will not be repaired, therefore the damage that occurs in the end due to metal-metal contact is more extreme.

To mimic the protecting effect of the oxide skin and to decrease the friction and therefore increase the lifetime and accuracy of the system, a lubricant can be used. In high vacuum, however, traditional greases and mineral oil based lubricants do not perform adequately. They do not provide sufficient film thickness or contaminate the vacuum. Therefore a solid lubricant or special vacuum grease has to be used.

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1.2 Influence of temperature

Besides vacuum, temperature is of major influence on the material behavior as well, especially when going to extreme values. Since it is well known that the material properties of polymers are strongly temperature-dependent, this holds particularly for polymers. When a polymer is subjected to cryogenic temperatures, the plasticity, the mechanical strain, the coefficient of expansion, and the specific heat decrease, whereas the Young's modulus and the hardness are much higher at low temperatures. Some parameters, i.e. impact strength, adhesive shear strength, or thermal conductivity, may increase or decrease for different polymers[3]. The effect of temperature on metals is less severe, however present as well. When using metal in extreme cold environments, it is important to keep in mind that the conductivity of the material will change.

1.3 The importance of a well-defined tribological system

Tribology is the study that is concerned with friction, wear and lubrication. All three, either in combination or separately, influence the lifetime and accuracy of a system. In a tribological system two surfaces move past each other, as depicted in Figure 1. Without a proper functioning lubrication layer in-between, the friction cannot be controlled, leading to unwanted and uncontrollable wear. The different effects can also amplify each other. For example, due to wear the friction will increase leading to more damage and eventually to failure of the system.

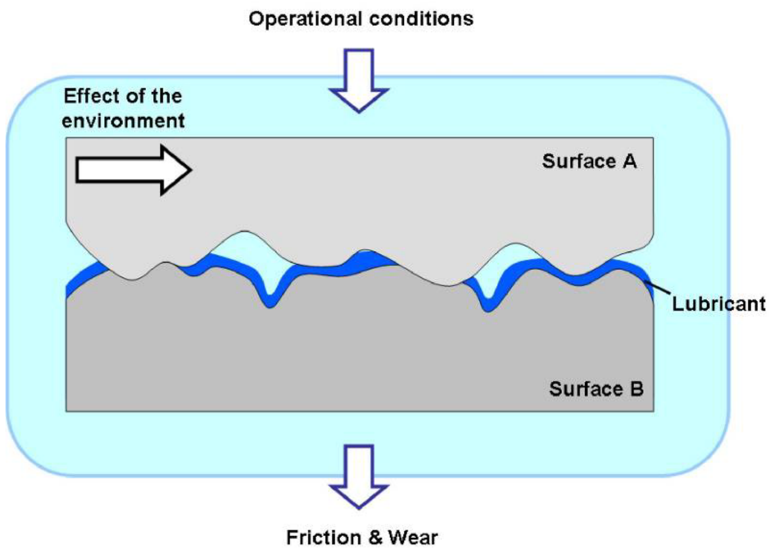

Figure 1: A schematical representation of a tribological system.

For a proper tribological analysis it is therefore important to consider the entire system, meaning two moving surfaces in contact with each other and the surroundings. The type and amount of damage is partly determined by the materials and the surface roughness used in the system, but also by the intermediate layers like lubricants and the prescribed conditions. Eventually multiple causes can induce wear.

This study describes guidelines to determine the proper materials for accurate and robust positioning mechanisms under extreme conditions. First the experimental set-up used to qualify the tribological system is described, followed by the experimental results and finalized with the overall conclusions and recommendations.

2. EXPERIMENTAL SET-UP

To analyze and simulate the contact between materials in industrial systems, a tribometer is used. A tribometer consists of a rotating and a static part. Using a dead load, the materials are pressed together mimicking the pressure applied in the application. E.g. to simulate a point load a ball can be used, another option can be to use a pin-on-disk set-up to imitate plane on plane. The two different set-ups are depicted in Figure 2.

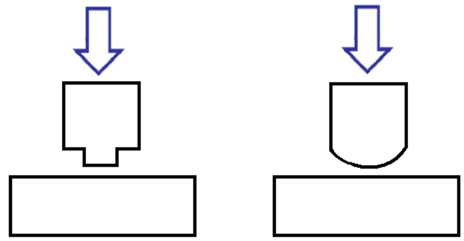

Figure 2: Schematic representation of a plane-on-plane set-up and ball-on-disk set-up.

Since a regular tribometer is not able to apply the condition required for space applications, TNO developed a unique measuring application, the TNO cryotribometer, in order to measure friction and wear of position mechanisms at harsh conditions. Using this device, experiments can be conducted using extreme low temperatures as well as high ones in vacuum. The cryotribometer has a temperature range of 120 K to 420 K. Due to the fact that the disk is cooled and heated via a gas flow, a sample can be easily subjected to a temperature cycle during an experiment.

The centre of the tribometer consists of a rotating disk, which can be actuated by means of a stepper motor using a feedthrough. Because of the temperature (120 K to 420 K) and the pressure (1 bar to 10^{-8} mbar) in the vacuum chamber, the feedthrough had to be isolated to ensure a proper measurement. An overview of the specifications is given in Table 1.

Table 1: Specifications of the TNO cryotribometer.

p	10^{-8}mbar to 1 bar
T	120 K to 420 K
v	1.5 mm/s to 150 mm/s
$\mathbf{F_n}$	Up to 1.5N
θ	90º to 360º

In Figure 3 the TNO cryotribometer is depicted, showing the vacuum chamber with different feedthroughs in the front.

Figure 3: The TNO Cryotribometer.

Using these feedthroughs different analyses can be conducted, e.g. one can use a mass spectrometer to determine the quality of the vacuum during a test. Behind the vacuum vessel the cryostat is visible, which consists of a liquid nitrogen vessel with a heat exchanger and a pump.

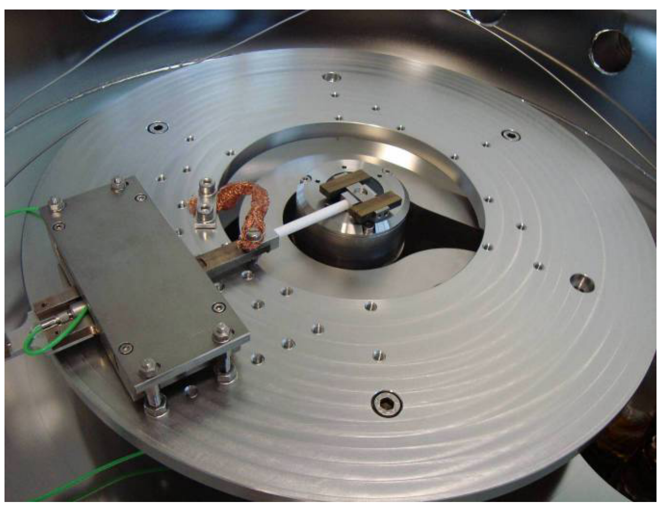

Figure 4: The measuring device inside the vacuum chamber of the TNO cryotribometer.

Within the vacuum vessel the measuring device is positioned as depicted in Figure 4. The white axle in the center is used to guide the friction force from the originating point on the right, to the sensor on the left of the white axle. On the right one can see the dead weights, used to apply the pressure on the sample. Underneath the weights the rotating shaft is visible.

Measurements were conducted using a spherical shaped surface which was placed against the test disk by means of deadweights (ball-on-disk set-up).

3. EXPERIMENTAL RESULTS

In order to determine the influence of load, surface roughness and material combinations, multiple experiments have been performed on the TNO cryotribometer. The test conditions and materials of a selection of combinations are stated in Table 1. In this study the emphasis is on the influence of MoST^{TM} coating, a solid lubricant which is applied via Physical Vapor Deposition (PVD) process. All experiments are conducted at a temperature of 120 K and in vacuum surroundings (<10^{-5} mbar); the rotation speed of the disk is 50 mm/s over an angle of 320º.

Table 2: Material combinations and conditions used in experiments on the TNO cryotribometer.

	Material disk	Surface roughness [µm]	Material ball	Surface roughness [nm]	Load [N]
1	AISI 420 with MoST^{TM} coating	0.6	Copper	90	1
2	AISI 420 with MoST^{TM} coating	0.1	Copper	90	1
3	AISI 420 with MoST^{TM} coating	0.1	Copper	90	0.05
4	AISI 420 with MoST^{TM} coating	0.1	AISI 420	25	1
5	AISI 420	0.1	Copper	90	1

Before starting the measurement, the tribological system was defined. Hereto the average surface roughness, i.e. Ra, of all the specimens was measured. Also the hardness of the different materials was determined. Finally a surface analysis by means of optical microscopy was conducted before and after the experiment. This way a proper comparison of the different tribological systems and their boundary conditions can be made.

Figures 5 to 9 show the friction coefficient as a function of testing time of the different material combinations. The depicted results show the signal after the run-in time. In all the figures the reciprocal movement is clearly visible, i.e. the vertical line in the graphs. Here the rotational direction changes. In Figure 5 the results of the combination AISI 420 with MoST^{TM} and a surface roughness of 0.6µm versus copper is shown for a load of 1N. When these results are compared with the friction coefficients given in Figure 6 and Figure 7 it is clear that there is a discrepancy between the three. Although the same material combination is tested, the influence of surface roughness and applied load is significant. Decreasing the surface roughness decreases the friction and increases the lifetime. Decreasing the load, on the other hand shows little improvement on the friction level. The friction level is hard to control; there are significant spikes on the signal. Due to this irregular friction level, the lifetime of the system decreases.

When Figure 5 is compared with Figure 8, one can see that balancing the hardness of the materials can have a positive influence on the friction coefficient. It is clear that the friction level for AISI 420 with MoST^{TM} coating versus AISI 420 is much lower than for AISI 420 with MoST^{TM} coating versus copper. Copper has a hardness of 250 HVN while AISI 420 measures a hardness of 650 HVN. This means that the hardness of AISI 420 is much closer to the hardness of the MoST^{TM} coating. The hardness of the MoST^{TM} coating is supplied by the manufacturer, being 700 HVN to 1300 HVN depending on application and test conditions[4]. And even though friction values are machine dependent, the aforementioned friction values compare well with the values provided by the manufacturer of the MoST^{TM} coating, being between 0.02 and 0.15 depending on application and test conditions [4].

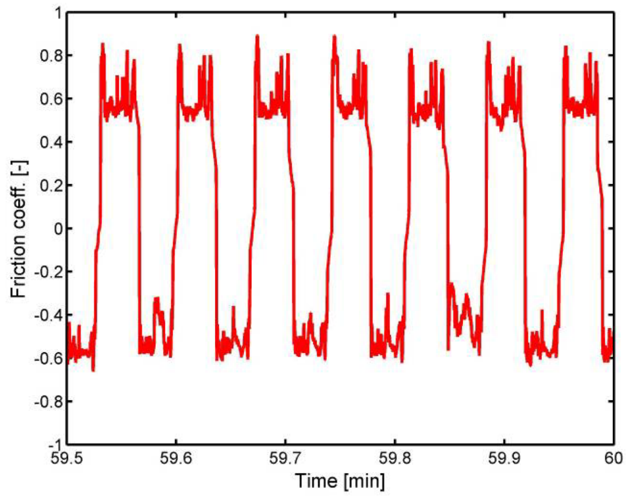

Figure 5: Friction coefficient of MoST^{TM} coating vs. copper with a load of 1N (#1).

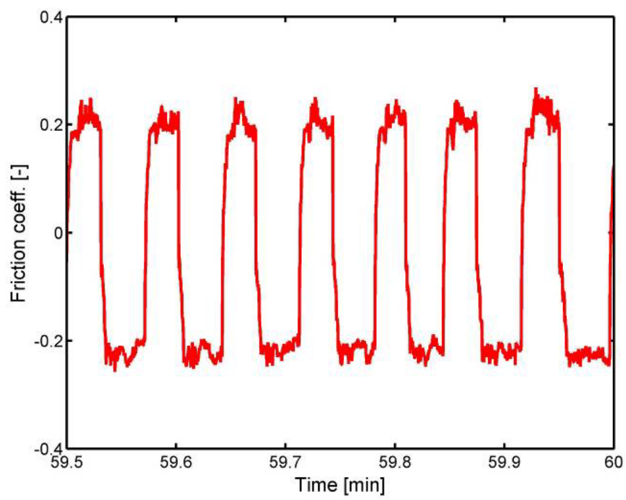

Figure 6: Friction coefficient of MoST^{TM} coating vs. copper with a load of 1N (#2).

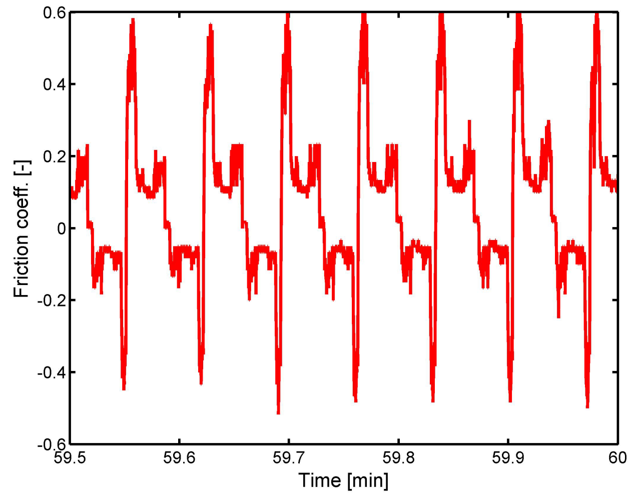

Figure 7: Friction coefficient of MoST^{TM} coating vs. copper with a load of 0.05N (#3).

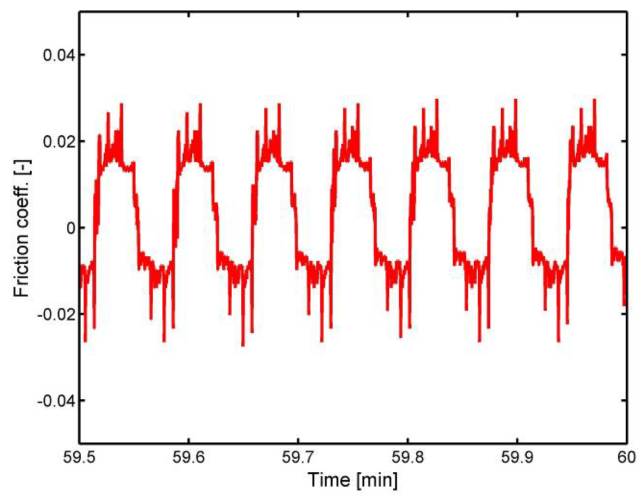

Figure 8: Friction coefficient of MoST^{TM} coating vs. AISI 420 with a load of 1N (#4).

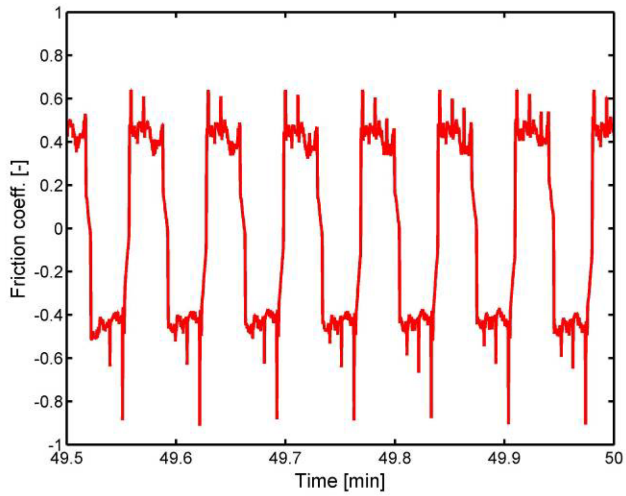

Figure 9: Friction coefficient of AISI 420 vs. copper with a load of 1N (#5).

When comparing Figure 5 to Figure 9, one can see that adding a coating or solid lubricant will not improve the friction level if the surface where the coating is applied to has not a sufficiently low surface roughness.

A surface analysis of the MoST^{TM} coated disk, Ra = 0.6, is given in Figure 10 after it has been run in by a copper ball. It shows that the copper is smeared out over the MoST^{TM} surface, while hardly any particles of the AISI 420 ball were found on the MoST^{TM} surface after run in by the AISI 420 ball.

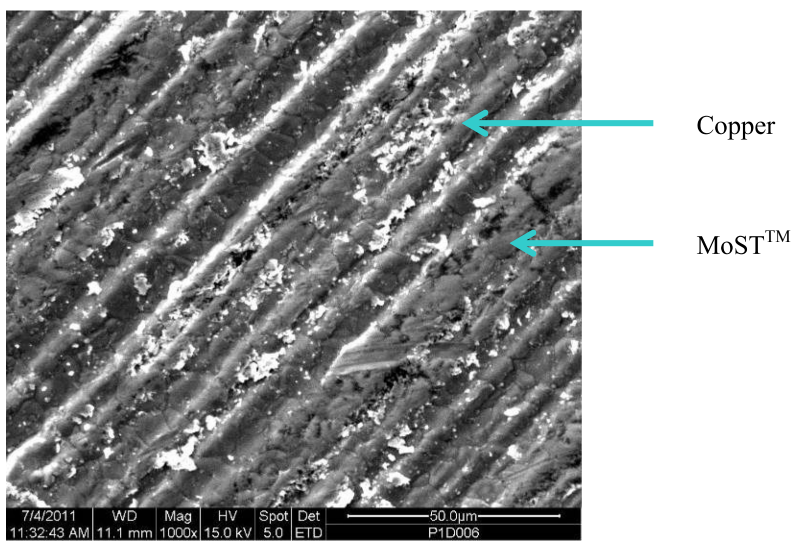

Figure 10: SEM picture of tested MoST^{TM} coating.

4. CONCLUSION

A tribometer capable of applying extreme conditions has been devised. The TNO tribometer is able to distinguish between different material combinations with respect to friction and wear and shows friction results comparable to ones provided by the manufacturer of the MoST^{TM}, being between 0.02 and 0.15 depending on application and test conditions[4].

The results shown in this paper illustrate the influence of a solid lubricant, the surface roughness and material hardness on the friction level in a cryogenic vacuum environment.

By adding a solid lubricant the friction can be reduced. However, adding a solid lubricant is not always the solution. If beforehand the surface is very rough, applying a solid lubricant will not improve the tribological system significantly. On the other hand, if the material combination is not optimal it can induce limitations on the system as well.

Therefore, to ensure durability and a productive lifetime of the application, it is important to evaluate the tribological system during the design stage. The TNO tribometer can help to find and analyze the different material combinations which have the desired properties for the application.

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