Solid lubricating coatings tribological test rig development

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Abstract. Solid lubricant coatings are commonly used under difficult operating conditions. Compositions containing graphite and molybdenum disulphide are the most used worldwide. Friction and wear tests are carried out to evaluate solid lubricant quality. Tribological properties are characterised by friction coefficient. The following paper presents the design of a ball-on-disc scheme testing rig. The normal load is applied by weights and remains constant during the entire testing time. The sliding speed is controlled by computer and changes smoothly. A strain gauge is installed to friction force determination. The sensor provides direct measurement of the bending strain and also the torque. The latter to be reduced for higher accuracy. To evaluate the design stiffness and contact point displacement the finite element analysis was done. The test rig is developed in accordance with ASTM G99.

1. Introduction

Lubrication in dry conditions is achieved by the means of solid lubricants. The same as liquid lubricants or greases solid lubricants decrease friction and wear. These materials are best in high or extremely low temperatures, vacuum, high contact pressure or other specific environmental conditions [1].

Solid lubricants are highly efficient at high loads, close to the yield strength of contacting materials, at low sliding speeds when oils cannot form a hydrodynamic wedge [2].

Solid lubricants are added in oils, greases and self-lubricating composites. Various materials are used as solid lubricants, but the most common are molybdenum disulfide, graphite and polytetrafluoroethylene (PTFE) [1-3].

There are various methods of applying solid lubricants on the friction surface: from the simplest staining with a suspension containing a solid lubricant to the formation of thin films by chemical and physical vapor deposition [2].

Staining with a suspension is the most common way to obtain a coating with a solid lubricant on a product surface. Solid lubricating coating is a composition of antifriction filler, solvent and film-forming substances. Antifriction filler provides a low coefficient of friction, a solvent is necessary to maintain a suspension in a liquid form suitable for application, and film-forming substances, which are polymer binders, are responsible for the coating high adhesion to the surface and bind solid lubricant particles into a continuous film [1].

The combination of solid lubricants makes the special properties of the coating. Compositions of MoS₂ with graphite or silver are corrosion resistant. MoS₂ combined with PTFE increases the service life of the antifriction coating [1-2].
Various compositions of solid lubricating coatings produced by different manufacturers are widely represented on the market. At the same time, despite the attention paid by researchers to this issue [1-2, 4-6], the composition of the coating is selected mainly experimentally [2].

The solid lubricating coating operates in different conditions. Hence its quality is assessed according to various criteria: the ability to withstand high contact pressure, high or low temperatures, work in a vacuum, etc. However, it is possible to evaluate the performance of the coating in general by the friction coefficient. It should represent the certain low values throughout the entire period of operation under specified conditions.

Tribological tests are necessary both for evaluation the coating quality and for composition developing, and therefore are in demand by manufacturers and consumers of solid lubricating coatings. However, the equipment for friction tests available on the market are too expensive. Thus, researchers are forced to develop their own tribological test rigs [1, 7-8].

It is important to use standard test designs so that results obtained by researchers can be compared. Not all types of test installations are equally suitable for modeling the operation of friction units, since the different nature of the relative motion can cause differences in experimental results [9].

The self-lubricating composites low friction coefficient depends on test conditions: load and relative velocity. Therefore, when studying the tribological properties of solid lubricating coatings, it is necessary to ensure the same experimental conditions [2].

Pin-on-Disk or Ball-on-Disk test scheme corresponding to the ASTM G99 is widespread all over the world. The Ball-on-Disk kinematic scheme is preferable for studying friction at high contact loads. The ball-shaped indenter is capable of self-centering, in contrast to the cylindrical or square shape pin. This ensures good reproducibility of results [8, 10].

The purpose of this work is to develop a tribological test rig for materials and coatings in accordance with international standards.

The equipment being developed must meet the following requirements. Test scheme - Ball-on-Disk in accordance with ASTM G99. Friction coefficient measurement data are displayed on a computer screen and recorded in digital form for further processing.

2. Test rig design
According to solid lubricating coatings properties and friction test equipment analysis technical characteristics of installation developed are determined (table 1).

| Parameter                      | Value                        |
|--------------------------------|------------------------------|
| Kinematic scheme               | Ball-on-Disk                 |
| Measurement data               | Friction coefficient         |
| Friction coefficient range     | 0.05…1 (±1.5%)               |
| Sliding speed (m·s⁻¹)          | 0.1…1                       |
| Maximum normal load (N)        | 25                           |
| Ball diameter (mm)             | 6                            |
| Disk diameter (mm)             | 40                           |
| Maximum torque (Nm)            | 1                            |
| Engine power (kW)              | 0.3                          |
| Size (mm)                      | 360x220x600                  |
| Operating environment          | Air                          |
| Operating temperature (°C)     | 20…25                        |
The test rig consists of the following functional parts (figure 1).

The electric motor 1 is installed on the frame 2. The rotation of the motor shaft is transmitted by means of the coupling 3 to the cartridge 4, which is installed in the support 5. The support, which is a housing with an angular contact bearing and radial bearing, perceives the axial load and ensures the sample rotation axis is vertical. A sample 6 is fixed with a clamping washer 7 in the cartridge. A metal ball 8 is set at the end of the indenter 9. The ball contacts with the sample and its rolling is limited by a screw 10. The indenter is installed in the strain gauge mounting hole 11. The indenter ability to move vertically allows to test different height samples. It is fixed with a screw 12 in the working position. Normal force is applied to the sample by means of weight 13. Supports 14 allow the load cell to move freely in the vertical plane, bending stresses caused by the weight do not act on the sensor, and thus all normal load is transferred to the sample. To ensure that the weight of the sensor and the indenter does not affect the sample during the test, a balancing weight 15 is provided. All units are mounted on plate 16 to provide the exact mutual position of the indenter and the sample.

The test rig developed 3D model is shown in the figure 2.
The installation is equipped with a strain gauge for continuous friction coefficient measurement during testing. The signals from the strain gauge are processed by the data acquisition system, displayed on the computer screen and written to a file. The test rig launch, the sliding speed and initial test conditions are set using the control system. Sample speed smooth control is achieved by using a frequency converter. The data acquisition and test rig control system is implemented through the National Instruments controller and LabView software (figure 3).

![Figure 3. Tribological test LabView program window.](image)

The friction force is measured by the deformation of a single point beam-type strain gauge. For the correct operation, it is necessary that the force measured is directed perpendicular to the sensor. Sensor deformation is caused by the combined action of bending moment and torque. To reduce the measurement error, the sensor is installed as close as possible to the sample surface in order to reduce the shoulder of the friction force.

3. Stress and strain simulation
To evaluate the design performance under operating loads the finite element method analysis of the stresses and strains in the test rig was done (figures 4 and 5). The SolidWorks Simulation software was used. The supports lower surface was fixed in the simulation. The force was applied to the ball and disk contact point. Disk surface was supposed to be flat and perpendicular to the indenter axis. The force 25 N is equivalent to the friction force arising at the maximum normal load and the coefficient of friction (table 1).

![Figure 4. Finite element test rig model.](image)
The deformations and stresses caused are concentrated mainly on the sensor, and the support system has sufficient stiffness. The maximum stresses turn up in places where the geometry of the sensor changes. The middle sensor area, where the strain gauge is situated, has even stress distribution. At a frictional force of 25 N the maximum stress generated is 30 MPa which is lower than the yield stress of sensor material.

The contact point displacement due to system deformation was also measured. Ball offset leads to wear track cross section area increasing. The warn face shape obtained by profile measurement tends to be more elliptical than spherical. The maximum displacement calculated value seems to be less than 0.13 mm. We expect friction coefficient range obtained in vast majority of studies 0.05…0.2. Then friction force is 1.25…5 N and the real contact point is set 0.008…0.032 mm from theoretical place. This is necessary to consider while wear rate is calculated by the mean of profiling.

4. Conclusion
Lubrication in extreme operating conditions such as high contact loads is usually solid lubricant field. Solid lubricating coatings development and quality evaluation requires friction and wear tests. The Ball-on-Disk configuration is used for high contact loads friction studying.

The Ball-on-Disk tribological test rig model has been developed. The installation developed is suitable for tribological tests according to international standard ASTM G99. Friction coefficient measurement and writing in digital form is available. The design finite element analysis shows the measurement accuracy.

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