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Ultrahigh vacuum system for advanced tribology studies: Design principles and applications

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ABSTRACT

The main difficulty in designing of an ultrahigh vacuum (UHV) tribometer combined with tribophysical and tribochemical characterization techniques is to find the critical compromise between the scientific requirements and technical or technological limitations from different subsystems and components. The principal conflicts, their possible solutions and the recommended tribometer configurations are analyzed. The developed methodological principles were applied for designing and construction of two UHV experimental tribological systems: TriDes-2 and Ca^3UHV. The advances in the design and development of the vacuum system as well as the UHV force sensor and sample holder are presented and discussed.

1. Introduction

In the 1960s, the space exploration needs prompted an increased research on problems related with friction, wear and lubrication in vacuum and controlled atmospheres [1]. That research was focused on the accelerated life testing of the mechanisms and components, as well as on developing and testing new lubricants and protective coatings. For this purpose a number of vacuum test equipment were developed covering a gas pressure range from low to ultrahigh vacuum [2]. By the early 1970's, when some of the problems had been resolved and the limitations of other had been defined, most of the research stopped.

However, recently tribological systems again have become the limiting factor in spacecraft reliability and performance since a number of new applications have arisen stimulating a renewed interest [1–3]. Advanced tribological materials should also comply with very strict requirements on the outgassing of volatiles [4] as well as on secondary electron emission both from free surfaces and during friction and mechanical deformation [5,6] in order to avoid contamination of lenses, sensors and other devices to prevent the multipactor effect. Therefore, vacuum test equipment should allow to study those phenomena. Similar problem exists in the modern semiconductor industry: the need to enhance yield of the semiconductor chips with ever-smaller elements challenges the engineers of manufacturing systems to reduce number of chip defects associated with gaseous and particulate contamination that in large part originates from mechanical elements [7,8].

On the other hand, there is a steadily growing interest in basic studies on the fundamental mechanisms of friction, wear, lubrication and related tribophysical processes and tribochemical reactions. Ultrahigh vacuum and/or controlled ambient atmosphere are the necessary conditions when studying gas-phase lubrication [9], mechanically stimulated gas emission (MSGE) [10–20], tribo-plasma [21–23], triboelectrification [24–26], triboluminescence [24,27,28], emission of charged particles [29–31], tribochemical reactions [23,32–34], etc. For these studies, conventional tribological test rigs should be combined with various physical, chemical and surface characterization techniques.

So far, various vacuum test equipment has been developed to address the needs of specific tribological characterization of materials in vacuum and under controlled atmosphere [2,15,30,35–46]. Some of these systems have optimal design, although "trial and error" has been the general approach. Development of a test equipment with controlled vacuum or gas environment aimed to answer to various scientific, technical and technological challenges associated with the tribological problems is not a trivial task since many, and often conflicting, requirements must be met. Lack of a methodological

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basis complicates the optimal development of vacuum test equipment making this task more art than science.

Bearing in mind that a vacuum tribometer for low vacuum can be developed by just placing a conventional tribometer inside a corresponding vacuum chamber the present work is focused on the designing of high and ultrahigh vacuum systems. We endeavor to suggest the ways of optimal designing of vacuum tribological test rigs finding a compromise between the requirements and limitations. This analysis was used by the authors for the development of two novel experimental systems in which tribological and tribo-physico-chemical characterization of materials and lubricants can be carried out. The authors believe that the developed approaches and lessons learnt in this work will underpin further development of these techniques.

2. Basic principles of design

2.1. General requirements and challenges

While tribological characterization is aimed at determining friction and wear properties of the materials under various experimental conditions and environment, tribo-physico-chemical (TPC) studies involve characterization of physical and chemical phenomena activated at the tribological contact. These phenomena can be studied using specific experimental techniques coupled to a conventional tribometer. As a result, an experimental system is much more sophisticated than just a vacuum tribometer that is quite complex per se.

Generally, an experimental system for combined tribological and physico-chemical characterization comprises the following seven subsystems: vacuum system, mechanical system, sensors, sample handling and manipulation, environment control, control of loading and kinematics, techniques for physico-chemical (TPC) characterization. Optimal designing of the experimental system implies finding a satisfactory compromise between the requirements set by these seven subsystems upon the environmental and operational conditions, relative position of the components and their compatibility, which problem can be called “Septilemma”. The schematic drawing of the subsystems and relations between them is shown in Fig. 1. Detail analysis of all relationships and conditions set by each of the subsystems is out of the scope of this work and can be consulted elsewhere [47]. Some relevant specific problems between the subsystems are discussed below.

Vacuum system against mechanical, loading and kinematics subsystems (link i in Fig. 1). Optimal mechanical design of a system implies the right selection of constructional materials. The mechanical structure must have sufficiently high stiffness in order to increase the eigenfrequency and reduce the effect of low frequency oscillations on the stability of loading, relative position of the pin and the sample, motion and friction force measurements. The Mechanical system has to ensure also the required level of the vibroinsulation from the basement and from mechanical and turbomolecular pumps. Furthermore, these materials must fulfill the requirements of an ultrahigh vacuum system such as low outgassing rate, low adsorption capacity, resistance to outgassing baking temperature in the range between 100 °C and 400 °C. The effectiveness of the pumping out has to be considered: blind tapped openings should be avoided, internal cavities must be connected with the vacuum chamber or the pumping line by the ducts of sufficient conductance for rapid evacuation of the gases, the configuration of the internal elements should be optimized in order to reduce nonuniformity of pressure due to dynamic processes, etc. When very high stability of gas pressure is required, such as for the measuring of MSGE, pressure variation due to contraction and expansion of the bellows in the loading and kinematics subsystems must be taken into account.

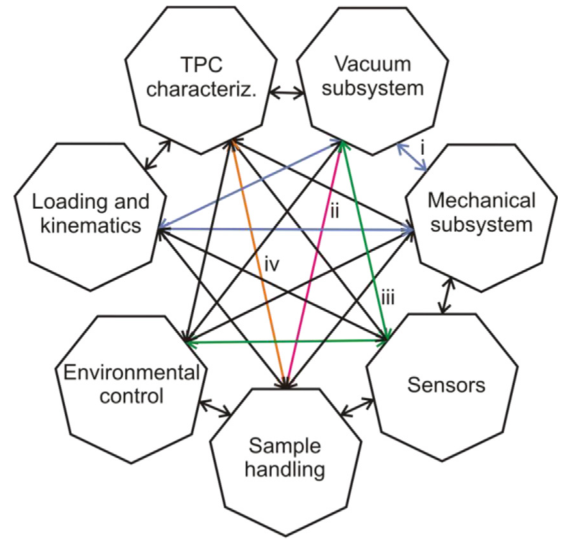

Fig. 1. Subsystems of a vacuum test rig for complex tribological and tribo-physico-chemical (TPC) characterization of materials. Some of the critical relationships and constrictions between the subsystems are shown by arrows: i (blue) – limitations between "Vacuum", "Mechanical" and "Loading and Kinematics" subsystems; ii (red) – limitations between "Vacuum" and "Sample handling" subsystems; iii (green) – limitations between "Sensors", "Environmental control" and "Vacuum" subsystems; and iv (orange) – limitations between "Sample handling" and "TPC" subsystems. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Vacuum system against sample handling (link ii in Fig. 1). For high and ultrahigh vacuum systems the time required to achieve gas pressure below 10^{-7} hPa after venting can be significantly reduced by using a load-lock system (LLS). However, sample handling in a system with LLS is much more complicated and requires using of special long-travel manipulators with various degrees of freedom, devices for locking and unlocking the sample holder, etc.

Furthermore, the components of the sample handling system must meet the requirements and limitations of the environmental control subsystem (sample temperature control) and TPC characterization (bias electric potential, tribocurrent, etc.). The sample holder must fulfill at least the following requirements: good thermal contact with the base surface (for the sample heating and cooling), good wear resistance and low friction (to make easier sample manipulation), be insulated from the ground and should be electrically biased (for tribocurrent, tribopotential and triboemission characterization). Also, it can be necessary to plug into the sample holder a temperature sensor using a special connector suitable for vacuum. Higher and lower temperatures of the sample require special setups in order to cut off the undesired infrared emission from the environment to a cold sample or from the hot sample to the environment. Cooling to cryogenic temperatures may require also special measures to reduce vibrations produced by the cooler and cooling agent flows.

Sensor against vacuum and TPC subsystems. The force sensors are used to measure and control the normal and friction forces. An additional displacement sensor can be used for indentation. All the sensors must be vacuum-compatible with low desorption rate and suitable for moderate outgassing baking temperature. Furthermore, the force and displacement sensors must not interfere with TPC devices. For example, strain gauges, capacitive and inductive displacement sensors can produce electromagnetic interference on charge detectors, electron multipliers, antennas and other sensitive devices. Therefore, optical sensors can be a good