Tribology International 56 (2012) 81–88

Contents lists available at SciVerse ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

A compact reciprocating vacuum microtribometer

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ARTICLE INFO

Article history:
Received 25 September 2011
Received in revised form
31 May 2012
Accepted 27 June 2012
Available online 4 July 2012

Keywords:
Vacuum
Microtribometer
Friction force detection

ABSTRACT

This article reports on a newly developed reciprocating microtribometer for evaluating the tribological performance of materials and coatings in vacuum and controllable atmospheres on the micro- and milli-Newton scale. The microtribometer consists of a piezo driving table, an elastic force sensor and two laser interferometers to precisely detect normal and lateral deflections of the force sensor. Friction experiments involving Si–Si tribopairs were performed in ambient and vacuum conditions to validate the microtribometer. These measurements compare well with measurements performed on a commercial microtribometer under similar conditions as well as with values published in literature using other types of tribometers.

1. Introduction

In the past, investigations of the tribological performances of metal and non-metal material pairs in vacuum were closely related with space applications [1–5] as well as the development of vacuum mechanisms for technological equipment in areas such as surface studies and thin films. In recent years, the growing demands of precision and miniaturization in fields such as the semiconductor and MEMS/NEMS industries [6,7] are making tribological studies in vacuum important for these applications as well. An example of such an application is a vacuum-based nanopositioning and nanomeasuring machine (NMM-machine) being developed at the Ilmenau University of Technology [8]. Here the tribological challenge is to develop and investigate materials and surface modification methods that allow friction pairs of technological mechanisms, such as bearings, to function under vacuum condition in a highly stable and reproducible manner.

A review of several literature sources showed that, in most cases, tribometers are designed to fulfill a particular purpose. A small selection of the reviewed devices that are also relevant for vacuum applications can be divided into several classes according to the range of measuring forces:

– Nanotribometers – tribometers based on AFM and similar techniques [9–13];
– MEMS tribometers or "on-chip" tribometers – tribometers entirely manufactured by MEMS technology and specified for friction measurements for MEMS applications [7,14,15];
– Microtribometers – tribometers operating in air [16–19] or vacuum [20–26] conditions in micro- and milli-Newton range;
– "Macro" tribometers and scratch testers – tribometers which work in the range of Newtons [27–29].

A first version of a vacuum microtribometer in the Microtribology group of the Ilmenau University of Technology was developed over a decade ago [20,30]. It was dedicated mainly for MEMS-related researches and had a rather small stroke (20–25 μm) which was limited by the extension of the piezo module, and a construction which gave no capability of direct normal load measurements. The tribological demands of the NPM-machine necessitated a vacuum tribometer with a wider normal load and friciton force range as well as accurate normal force detection. This is the motivation behind the reciprocating vacuum microtribometer reported in this article. The newly developed microtribometer was developed with the following design principles: (1) direct and independent normal load and friction force measurements; (2) force measuring range extended to milli-Newtons and (3) modular construction with a possibility to readily incorporate the device into a complex vacuum analytical setup with minimal modifications.

A typical microtribometer usually consists of three main parts: (1) an actuator system that brings the samples in contact with a particular normal load and applies a relative motion between the sample and the counterbody; (2) a force transducer or sensor that results in a measurable response when subjected to friction and

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http://dx.doi.org/10.1016/j.triboint.2012.06.019

normal load and (3) a system for measuring and registering the friction and normal forces. The two main configurations of the relative motion usually applied in tribometers are: a rotational motion provided by a rotational actuator resulting in the historically established ''pin-on-disk'' or ''ball-on-disk'' type setup and a reciprocating motion made possible by an oscillating actuator. Since the latter setup most closely simulates the operation of the nanopositioning stage of the NPM-machine, this was chosen for the microtribometer configuration reported in this paper.

There are two distinct methods of introducing relative reciprocating motion of samples in vacuum: to place the actuator outside the vacuum chamber and transmit the motion via appropriate feedthroughs [24,27,31] or to mount the entire actuator inside the vacuum chamber. The main merit of installing the actuator outside the vacuum system is that the actuator does not influence the experiments being conducted in vacuum and detrimental effects such as outgassing, lubricant evaporation or the generation of microparticles, can be avoided. One of the first setups following this method was reported by Bowden and Tabor [32]. A disadvantage of such an approach, however, is that it is necessary to include an additional transmission module between the actuator and sample to introduce motion in vacuum. A possible configuration in form of a vacuum feedthrough with ''flexible walls'' or vacuum bellows can be used. However, in this case the actuator needs to overcome significant additional force due to the atmospheric pressure as well as the resistance of the feedthrough mechanism. For the case of vacuum feedthroughs that mediate motion through the solid steel wall of the chamber through a magnetic coupling it could be difficult to control the position of the sample precisely. These reasons make it challenging to perform tribological measurements at low normal loads and slow sliding speeds with such a configuration. Such setups are more suited to perform macrotribological [27,28] or scratch [29] tests in vacuum at high normal loads (several Newtons or more) and fast sliding speeds. In the second scheme with the actuator situated inside the vacuum chamber, the main problem is the material compatibility of this mechanism with the vacuum environment as well as the influence that such an actuator may have on the chamber vacuum while it is in operation. These problems have largely been overcome with the development of piezo modules.

2. Design

2.1. Concept

The schematic of a reciprocating ball-on-flat tribometer is presented in Fig. 1(a). In this design, a flat sample (1) with linear dimensions and height ranging from 5–15 mm to 0.5–3 mm, respectively is mounted on the 2D actuator (2) that provides the horizontal and vertical motion. A ball (3) with a diameter in the range 1–3 mm is attached to the force sensor (4). The sensor itself is fixed onto the base unit of the tribometer (7). In this configuration, the microtribometer operates similar to atomic force microscope (AFM) setups, where a cantilever with an attached tip is fixed and a sample performing relative motion by a piezo-actuator. The force sensor of the tribometer (4) consists of a couple of springs, which deforms in the horizontal and the vertical direction. These deflections are monitored by an optical detection system consisting of small square aluminum coated silicon mirrors (5, 6), which are diced from the Si(100) wafers, along with a couple of commercial miniature laser interferometers (SIOS GmbH, Germany) mounted outside the vacuum chamber.

The photo of the developed vacuum microtribometer is presented in Fig. 1(b). Numbers on this photo are corresponded to ones in the schematic Fig. 1(a).

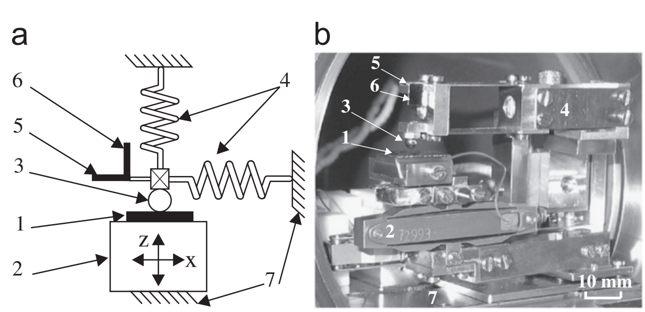

Fig. 1. Concept of the microtribometer: (a) Schematic (1) flat sample; (2) 2D actuator; (3) ball (counterbody); (4) force sensor; (5,6) mirrors for optical measurements for determining force sensor deflections; and (7) base. (b) Photo. Numbers in the photo correspondto ones in the schematic.

2.2. Actuator

The actuator (Fig. 2) is based on piezo-modules (PX-500, Piezo-System Jena GmbH, Germany). These modules can readily operate in vacuum and provide a stroke of about 560 μm as well as support normal and lateral forces up to 1.5 N. The horizontal piezo (1) is fixed on the actuator base (2) while the vertical piezo (3) is fixed on the horizontal piezo through the frame (4). This construction allows the actuator to move the sample in two directions simultaneously. A spring support (5) was utilized to prevent the actuator from tilting under the normal load as well as to avoid the piezo-module frame from bending. This spring support consists of two plates made from beryllium bronze with a thickness of 0.12 mm, which were fixed between the frame (4) and an adjustable platform on the actuator base (6). This platform has three adjustable screws to set its position on the actuator base and the platform is itself fixed onto the base (2) using three fixed screws. This configuration results in a structure with a high stiffness in the normal direction and a relatively low stiffness in lateral direction. The stiffness in lateral direction can be estimated by the following[33]:

$$k = \frac{E\,b\,t^3}{l^3} \tag{1}$$

where E is the Young's modulus, b is the spring plate width, t is the spring plate thickness and l is the length of the spring plate. Substituting the size parameters of the developed flexure into the above equation gives a lateral spring constant k of 221.2 N/m. The stiffness measurement of this flexure performed by using precision weights yielded a lateral spring constant k of 241 ± 1 N/m. Such a flexure can support the applied normal loads envisaged for this microtribometer, which ranges from milli-Newtons down to nano-Newtons. Another advantage of such a support is the

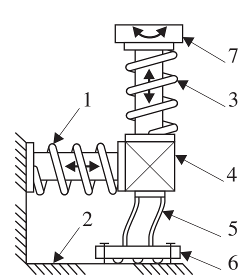

Fig. 2. Piezo actuator: (1) horizontal piezo; (2) actuator base; (3) vertical piezo; (4) frame; (5) spring support; (6) adjustable platform; and (7) rotatable sample-holder.