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How to measure the real contact area? A simple marker and relocation foot-printing approach

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ABSTRACT

A marker layer (Au80Pd20) combined with four different techniques was used in order to estimate the real contact area between static steel–steel contact pairing (substrate: AISI304 and ball: AISI 52100). The experiments were done with polished references (substrate and ball) and with substrates having a laser-patterned line-like surface topography using two loads (1 and 5 N) and two pattern periodicities (9 and 15 μm). Irrespective of the normal load, all techniques led to the same results within the standard deviation for the polished surfaces. For the laser-patterns, only the combination of foot-printing, scanning electron microscopy and image segmentation is capable to provide meaningful results, since the other techniques significantly overestimate the real contact area.

1. Introduction

The control of friction are of utmost importance in many technical applications [1]. In bearings or cylinder liner surfaces, friction is intended to be reduced [2]. In contrast to that, in brakes or clutch linings, friction should be increased and remain constant over the life time of the component [3]. It is important to note, that friction is in general not only dependent on inherent material properties but is rather a system response influenced by many factors.

About 300 years ago, Amontons stated that the friction force opposing a movement only depends on the normal load but not on the macroscopic contact area. The ratio of the friction force and normal load defines the coefficient of friction (COF). Since Bowden and Tabor, it is known that friction only occurs at asperity peaks that adhere to each other before being again separated by shearing. Therefore, the friction force is proportional to the shear modulus and the real contact area [4]. Hence, one way to influence friction is to manipulate the number and size of the asperity peaks of the bodies being in contact by controlling their surface geometry. It is however difficult to measure the number and size of asperity peaks which constitute the real contact area because the two bodies generally do not allow for a direct observation of the contact zone. This is particularly important in technical systems that are usually not optically transparent.

The challenge of measuring the real contact area was approached using a variety of methods. Those were summarized by Woo and Thomas in 1980 [5] and by Bhushan in 1985 [6] and can be categorized in in- and ex-situ methods. The first group includes optical, thermal, electrical, and acoustic methods. The other group mainly comprises methods that rely on relocating the real contact area after the experiment in order to analyze this area by means of different microscopes or profilometers.

Recent work focused on the development of in-situ methods that employ optical or acoustic waves. Kendall and Tabor first employed ultrasonic waves to investigate the tribological contact zone [7]. Ultrasonic methods have the advantage that they do not need optically transparent or electrically conductive materials. However, their main drawback is the relatively large wavelength thus resulting in a lateral resolution less 100 μm [8]. Ovcharenko et al. made use of the interference of optical waves and developed an experimental test rig that enables a direct observation of the contact zone [9,10]. In order to evaluate the images, interference patterns of Newton's rings were analyzed and image intensity distributions were thresholded. The test rig is suitable to determine the evolution of the contact area with different loads. Furthermore, the real contact area, the relative displacement of the bodies, and the friction force could be measured simultaneously and related to each other. By doing so, the lateral resolution was limited by the optical system and was in the range of 1.2 to 3.6 μm [9]. In general, the optical methods are limited to tribological systems with at least one body being optically semitransparent [11].

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Marker and relocation (foot-print) methods were refined by Nitta [12] and Selvadurai and Glaser [13]. Nitta inserted a PET film of a thickness of 0.9 μm between the contact pairing and analyzed the plastic deformation of the PET film to estimate the real contact area. The results were in good agreement with optical measurements. Surfaces with roughnesses smaller than the film thickness could not be measured [12]. Selvadurai and Glaser used a pressure sensitive film with a thickness of 5 μm to measure both the stresses in the contact zone as well as the size of the real contact area in the static case. A spatial resolution of down to 5 μm was reported [13]. The real contact area is determined by summing over all pixels that are loaded similarly. This requires a threshold to be set in the color coded image of the pressure sensitive film. However, it remains questionable how a threshold can be set with a high replicability.

The goal of this research work is to develop a simple marker and relocation (foot-print) method that is not dependent on transparent materials and that is capable to measure the real contact area with both lateral and height resolution on the nano-scale. In contrast to the presented optical methods, such a technique will allow to measure the real contact area in technical systems with non-transparent materials. In this research work, a marker layer of Au80Pd20 with a thickness of roughly 10 nm is sputtered onto stainless steel samples (AISI 304) having either a polished stochastic surface roughness (roughness on the nano scale) or a deterministic surface (laser-patterned by direct laser interference patterning DLIP). The samples are loaded with different dead weights using a tribological set-up and the contact zone is then imaged by means of scanning electron microscopy, white light interferometry, and differential interference contrasting, and finally analyzed by measuring the diameter and by image segmentation by thresholding. The results of those methods are compared to each other and conclusions on the best suitable method are drawn.

2. Experimental procedure

2.1. Samples

Commercially available stainless steel samples (AISI 304) with a mirror-like surface finish ($R_q \sim 30$ nm) and dimensions of 20 mm × 20 mm × 1 mm were used as substrates as well as steel balls (AISI 52100) with a diameter of 6 mm as tribological counter bodies. The chemical composition of both materials is given in Table 1. The Young's modulus and Poisson´s ratio of the materials are given in Table 2.

2.2. Direct laser interference patterning (DLIP)

A high power, pulsed solid-state Nd: YAG laser (*Quanta Ray Pro 290, Newport Spectra Physics*) with a wavelength of 355 nm (third harmonic), a pulse duration of 10 ns and a repetition rate of 10 Hz was used for the laser patterning. First, the primary beam travels through an optical set-up consisting of a lens, a shutter and an attenuator in order to adjust the energy density and to control the number of pulses used for the surface patterning. Afterwards, the primary beam is split into two sub-beams by means of a suitable beam splitter. These sub-beams are guided to the surface of the sample by two mirrors in order interfere with each other, with constructive and destructive interferences occurring periodically. At the positions where constructive interference occurs the surface temperature rises quickly, the steel is molten and a temperature gradient between the laser interference maxima (constructive interference) and minima positions (destructive interference) is established. This temperature gradient induces a gradient in the surface tension thus leading to the formation of the respective surface pattern while the molten material resolidifies. In the case of two beam interference, this results in a line-like surface pattern having a characteristic periodicity P, defined by the laser wavelength λ and the angle between the interfering sub-beams [16–18]. The laser fluence was kept constant at 29 J/cm^2 for all patterned samples in order to produce well-defined and homogeneous surface patterns. The DLIP was carried out under ambient conditions at room temperature and atmospheric pressure using one single laser pulse.

Table 1
Chemical composition of the substrate and counter body in wt%.

Part	Short name	Fe	Cr	Ni	Mn	Si	C	Mo
Substrate	AISI 304	68.9	18	10	2	1	0.1	/
Ball	AISI 52100	96.7	1.5	/	0.4	0.3	1	0.1

Table 2
Young's modulus and Poisson's ratio of the used steel substrate and steel ball.

Part	Material	Young's modulus (GPa)	Poisson's ratio (dimensionless)
Substrate	AISI 304	200 [14]	0.24 [14]
Ball	AISI52100	208 [15]	0.30 [15]

2.3. Sputtering

A layer of Au80Pd20 with a thickness of roughly 10 nm was sputtered on both polished and laser-patterned samples by physical vapor deposition (PVD). Au80Pd20 was used as a target material for two reasons. First, its mechanical properties differ from the ones of the steel substrate (please refer to Table 2). In addition to that, by means of SEM, Au80Pd20 and steel can be easily distinguished by material contrast.

For the deposition of the layer, a glow-discharge sputter unit (*Emitech K950X* with *K350 attachment)* was used. This unit consists of a vacuum chamber filled with Argon as a processing gas, the Au80Pd20 target (cathode) and the sample as the substrate (anode). The electric current was kept constant between 20 and 25 mA and the process time was set to 5 min.

2.4. Ball-on-disk tribometer

The samples with the deposited Au80Pd20 layer are brought into contact with a steel ball of 6 mm diameter by means of a ball-on-disk tribometer (*CSM Instruments*). Two different normal loads, namely 1 and 5 N, applied by a dead weight were used. The contact was hold for 60 s and subsequently, the bodies were separated again by raising the ball. Prior to the experiments, both samples and ball were cleaned with cyclohexane, acetone and isopropanol in an ultrasonic bath to remove all non-polar and polar contaminations. Each experiment was then performed twice.

2.5. White light interferometry (WLI)

In order to analyze the contact area, a white light interferometer *(NewView 7300, Zygo)* with a nominal depth resolution of < 0.1 nm and a lateral resolution of 0.71 μm (magnification of 20x) was used. The underlying principle of WLI is based on a Michelson interferometer. The resulting signal is recorded by a CCD (charge-coupled device) sensor.