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Wear debris and electrical resistance in textured Sn-coated Cu contacts subjected to fretting

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ABSTRACT

Fretting wear is the most common failure mechanism in electrical connectors for automotive applications. In this study, the fretting wear behavior of laser-textured tin-coated copper contacts has been investigated, focusing on the temporal evolution of wear debris formation and its relation to the electrical contact resistance. The dot-like pattern was produced on the samples by interfering laser beams with a period of 7.5 μm. A fretting apparatus was used for testing, applying two different normal loads (2.5 and 5.0 N). The fretting-induced chemical and topographical changes were studied by scanning electron microscopy, focused ion beam, Raman spectroscopy, and X-ray diffraction. This analysis revealed the formation of oxide particles (SnO and CuO) and of a closed intermetallic layer (Cu_6Sn_5). For CuO, the transition from loosely-packed wear particles to a dense layer is observed. During the entire experiment, the SnO particles remain as compact agglomerates without showing any layer formation. Based upon these observations, a model for the non-textured reference was developed, describing the processes taking place during fretting wear. Furthermore, it can be concluded that under the studied conditions the laser interference pattering reduces the coefficient of friction and the contact resistance by up to approx. 12% and 71%, respectively.

1. Introduction

Electrical connectors for automotive applications are used to power and network electric and electronic systems. In a modern car, up to 400 connector terminals with more than 3000 individual connections are used. This number is set to increase in the near future [1]. In light of miniaturization, not only the number of connectors is rising but also the demands on them. Connectors are exposed to strong vibrations, corrosive media and rising operation temperatures. Due to a more compact design of the engine compartment, automotive connectors created to work at 125 °C must now reliably perform at temperatures of 150 °C [2,3]. In addition, since, for the foreseeable future, they require manual installation and maintenance, their increasing numbers call for lower contact forces [4–7]. In conclusion, an electrical connector has to be highly wear resistant, while having a low and stable contact resistance under low contact forces.

The combination of increasing operation temperatures and decreasing contact loads leads to more pronounced wear phenomena for the widely used tin-coated copper connectors. The main wear mechanism acting on this type of connectors is so-called fretting wear. This kind of wear is the result of micro-vibrations, which lead to the development of electrically insulating oxide layers and thus to connector malfunction [8]. Fretting wear causes about 60% of all electrical failures in cars [3].

Laser surface texturing (LST) is a well-known tool to influence the frictional and wear behavior of contacting metal surfaces. The periodic features of a surface texture can act as micro-reservoirs for lubricants and as micro-hydrodynamic bearings [9–14]. The pioneering work of Etsion et al. showed the benefits of laser-textures in machine components (e.g. thrust bearing, seals and piston rings) [15–18]. Analytical simulations and experimental studies were able to demonstrate a friction reduction of up to 50% for seals and 40% for piston rings [16–18].

Another well-known advantage of surface textures is their effective micro-trapping of wear debris under lubricated and dry conditions [19–22]. This can lead to an improvement of the friction properties under fretting wear as shown by Varenberg et al. [22]. They explored the effect of LST on the fretting wear of steel–steel and steel–bronze pairings. Moreover, Varenberg et al. studied the effect of normal load on the electrical contact resistance (ECR) and showed that LST leads to a significant improvement of the

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electrical behavior under fretting conditions. A variation of the normal load from 5 to 25 N causes a drop in contact resistance of 3% on the reference samples and of 32% on the textured samples (steel–steel pairings). The mean ECR in the load range between 5 and 25 N drops about 69% on the steel–steel pairing and about 84% on the steel–bronze pairing due to LST. The authors attributed this to the trapping of wear debris in the dimples of the texture during the fretting experiment. This inhibits the formation of an electrically insulating surface layer. The authors also studied the evolution of the coefficient of friction (COF) in the same study. They showed that a thin layer of wear debris can act as a solid lubricant if adhesion is the dominant fretting wear mechanism, with a consequent increase in the COF due to LST. On the contrary, if abrasive mechanism is predominant, LST leads to a reduction of the COF and the fretting wear effects.

Volchok et al. studied the influence of LST on the fretting fatigue of steel samples under dry conditions [23]. They used two cylindrical contact pads, which were pressed against a beam specimen, with either the cylinders or the beam laser textured. In both cases, LST lead to a significant increase in fretting fatigue life compared to non-textured contacts (55% with the textured beam, 81% with the textured cylinders). They ascribed this effect to the aforementioned trapping of wear debris in the dimples introduced by LST.

Within LST, direct laser interference patterning (DLIP) can create periodic surface patterns in a single laser pulse, without the need for sequential structuring or sample repositioning. Feature sizes in the μm range can cover areas of several mm^2 to cm^2. Depending on the number of interfering sub-beams and the angle between them, line-, cross- and dot-like surface patterns can be fabricated [24,25].

Raillard et al. studied dry sliding between an alumina ball and DLIP-textured copper [26]. Line and cross-like patterns reduced the COF 70% and 80%, respectively. Since very small loads were used (2 mN), no wear features were visible. The decrease in friction can hence be attributed to a reduction in the real contact area.

Studies by Gachot et al. and Rosenkranz et al. showed that DLIP of both contacting surfaces can also have beneficial effects on the friction behavior [27,28]. They textured a steel ball and a steel flat with linear textures and performed tribological experiments with the latter at 0° and 90° (normal load 1 mN). The textured surfaces (0° orientation) show a higher COF at the beginning of the experiment, compared to a polished reference sample. They explain this by interlocking of asperities. After the run-in, the highest asperities are worn off and become flattened. As a consequence, the COF decreases to a level below the reference state. This is explained by a change in surface chemistry as result of the laser irradiation as well as by a decrease in the real contact area.

To the best of our knowledge, no research has been published so far dealing with laser-textured tin coated copper contacts under fretting wear. Therefore, the goal of our study is to investigate the effect of a hexagonally-arranged dot-like surface pattern on the COF and the ECR under fretting.

2. Experimental setup

2.1. Sample preparation and surface texturing

Fretting experiments were conducted on copper rings (Fig. 1(a)). These rings were covered by a 633 ± 185 nm thick tin layer, produced by electroless plating. The surface roughness R_a of the tin layer after polishing was 6.7 ± 0.8 nm. The tribo-pairs used in the fretting experiments consisted of two ring specimens, one of them with three protruded legs 120° apart, created by milling (Fig. 1(b)). The total area of these legs was about 100 mm^2.

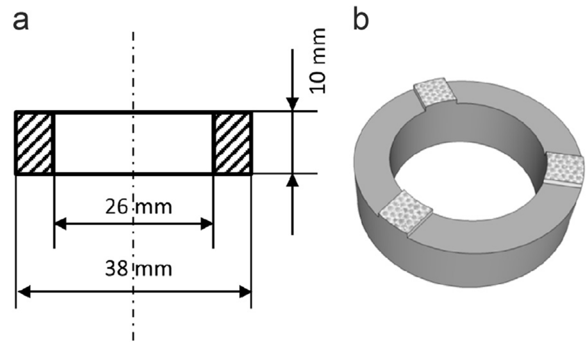

Fig. 1. (a) Schematic diagram of the upper ring; (b) Illustration of the lower ring. Used period: 7.5 μm.

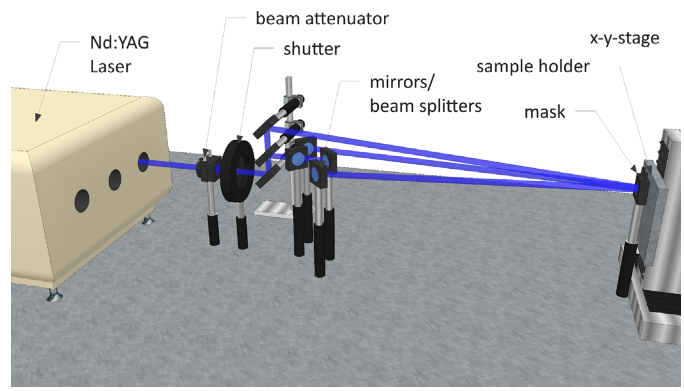

Fig. 2. Schematic illustration of the direct laser interference patterning setup (DLIP, three-beam interference).

Surface texturing was done by interfering laser beams, using a pulsed Nd:YAG laser (Spectra Physics, Quanta Ray PRO 290) with a pulse duration of 10 ns. The laser interference principle is shown in Fig. 2. The DLIP method is explained in detail elsewhere [24]. In principal, the interference causes a spatial intensity variation on the surface, thus leading to a periodic temperature gradient. The ensuing surface tension gradient thus results in the formation of a periodic surface topography. In this work, the primary beam is split into three sub-beams which interfere on the surface of the sample (Fig. 2). The resulting dot-like texture is arranged in a hexagonal lattice (period of 7.5 μm). The 355 nm wavelength produced a total energy density of the interfering beams of 515 mJ/cm^2 in one pulse. The hexagonal texture was chosen for the fretting experiments due to a reduced orientation dependency compared to linear textures.

2.2. Fretting test

All fretting tests were conducted with the test setup shown in Fig. 3. A detailed description of this apparatus is given in [22]. In this study, the displacement amplitude was 120 μm with a frequency of 16.7 Hz under normal loads of 2.5 and 5.0 N. Non-textured and textured samples were tested up to a maximum of 45,000 cycles. The electrical resistance was monitored during fretting tests, using four-wire sensing in order to eliminate the inherent resistance of the measuring leads.

2.3. Sample characterization

The surface roughness prior to and after texturing was measured by white light interferometry (WLI) (Zygo New View 7300)