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From lab to application - Improved frictional performance of journal bearings induced by single- and multi-scale surface patterns

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ABSTRACT

The present study experimentally examines the effect of selected single-scale and multi-scale surface patterns fabricated by roller-coining and/or direct laser interference patterning on the frictional performance of journal bearings. For this purpose, surface patterns showing beneficial effects in preliminary laboratory tests were selected and fabricated onto the shaft of journal bearings made of stainless steel (AISI 304). The frictional performance of these patterns was evaluated on a special test rig by recording Stribeck-like curves. The results show greatly reduced coefficients of friction and a shift in the transition from mixed to hydrodynamic lubrication to smaller rotational speeds for all patterned samples compared to the reference sample. The observed friction reduction matches well with results observed in the previous laboratory tests.

1. Introduction

Tribology, involving friction, wear and lubrication, is an important aspect in our daily life since it can be directly connected with energy efficiency, maintenance intervals and costs of machine components but also with quality of life. The latter can be realized when thinking about tribological problems occurring in contact lenses or artificial joints both being addressed in bio-tribology [1–3]. Historically, tribology is associated with moving mechanical components under a certain normal load such as bearings, piston rings or cam followers. In this context, friction and wear greatly influence the efficiency and lifetime of these components. In passenger cars, roughly one third of the entire energy is needed to overcome frictional losses [4]. A similar picture can be found in mining industry, where roughly 38% of the energy is used to compensate friction and wear losses [5]. Holmberg et al. estimated that the friction and wear losses can be reduced by approximately 60% when using advanced next-generation technologies. Those technologies comprise new coatings, modern surface engineering, improved lubricants, new material systems as well as a better mechanical design [4,5]. It is straight forward to conclude that this would have a tremendous impact on aspects such as energy efficiency and reliability but also sustainability and CO_2-emissions [6].

During the last 20 years, surface engineering, in particular surface patterning, has emerged as an interesting approach to precisely tailor tribological properties. Starting with the pioneering work by Etsion et al. [7], numerous manuscripts have been published demonstrating the successful use of surface patterning to improve friction and wear under dry and lubricated conditions including boundary, mixed, elastohydrodynamic and hydrodynamic lubrication [8–10]. Depending on the experimental conditions and the underlying lubrication regime, different aspects contribute to the observed friction and wear reduction. In this context, the reduction of the real contact area [11], the trapping of wear particles [12–15], the reduction of stress raisers and edge effects [16], the storage of lubricant [12–14], the build-up of an additional hydrodynamic pressure [12,13,17] can be named as potential contributions. Over time, several techniques such as laser surface patterning, embossing/micro-coining, lithographic methods and many more, have been used to fabricate patterns on different scales [9,18]. Thereby, the selection of the appropriate technique depends on the respective frictional characteristics and contact conditions of the corresponding tribological system [9]. Taking the available techniques into consideration, it can be stated that laser surface patterning and embossing/micro-coining are fast, reliable and environmentally-friendly methods, which enable the fabrication of patterns with variable pattern geometries and feature sizes on different scales.

One of the components, which is responsible for frictional losses in

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Table 1
Surface roughness parameters measured prior to and after machining and burnishing using a tactile measuring device.

Process step	R_a/µm			R_q/µm			R_z/µm			R_{Sk}/µm		
Initial bar	0.88	±	0.18	1.14	±	0.24	6.04	±	1.17	−1.21	±	0.30
Machining	0.44	±	0.01	0.53	±	0.01	2.60	±	0.14	0.01	±	0.06
Burnishing	0.16	±	0.02	0.20	±	0.02	1.07	±	0.09	−0.67	±	0.20

mechanical systems, are bearings [19,20]. For instance, journal bearings are used in many applications such as combustion engines, turbomachinery, construction and oil-field equipment [20–22]. Those bearings especially suffer from high friction and wear if start-stop-cycles occur during operation [20]. Furthermore, bearings installed in heavy-duty machinery often work under mixed or even boundary lubrication and therefore show a tendency for increased friction and/or wear [22]. It could be shown that the surface roughness has a significant effect on the performance of journal bearings [23]. As a consequence, there have been increasing efforts to modify the surface roughness (i.e. by introducing surface patterns) to understand the influence of the roughness on the resulting performance, and to further reduce friction and wear in journal bearings. Lu and Khonsari fabricated dimples on the inner surface of the journal bearing's bushings by machining and chemical etching [24]. Their results showed that friction in a journal bearing can be reduced by an appropriate selection of the pattern geometry. Tala-Ighil and Fillon qualitatively verified the results of Lu and Khonsari by a numerical study [19]. Furthermore, they showed that an improved frictional performance is strongly linked with the operating conditions. Moreover, they proved that larger dimples (diameter = 4 mm) are more effective than smaller ones. Sinanoğlu et al. investigated the effect of shafts' surface patterns on the frictional performance in journal bearings [25]. They concluded that the load bearing capacity for shafts with a trapezoidal profile is better than for saw profiles. Additionally, greater profile heights have a positive effect on the load bearing capacity. Brizmer and Kligerman theoretically examined the use of micro-dimples manufactured by laser surface patterning to improve the performance of journal bearings [26]. Their main finding is that partial patterning can, in contrast to a patterning of the entire surface, improve the bearing's performance. Due to the substantial improvements in terms of the frictional and wear behavior due to surface patterning, it can be expected that especially the surface topography will be the focus of future design guidelines for those bearings [19,27].

The goal of this study is to experimentally investigate the effect of selected single-scale and multi-scale surface patterns on the frictional performance of journal bearings. For this purpose, surface patterns showing beneficial effects in preliminary lab-experiments were selected. Those patterns were fabricated onto the shaft of a journal bearing and the tribological performance was tested on a special test rig by recording Stribeck-likes curves. Thereby, the rotational velocity was changed to adjust mixed and hydrodynamic lubrication as well as to record the transition between those regimes.

The results of preliminary tests in which micro-coined, laser-patterned and multi-scale (combining micro-coining and DLIP) samples have been tested using a ball-on-disc tribometer have been published in Refs. [14,16,28]. For the reader's convenience, a short summary of these results shall be given here. It could be demonstrated that the patterned samples usually led to a friction and wear reduction compared to a polished reference irrespective of the patterning method used. Nevertheless, the effectiveness of the patterns strongly depended on the used fabrication technique and geometry of the respective samples. Thereby, micro-coined samples with the lowest area densities (10%) and structural depths (25 µm) showed the best frictional behavior with a maximum friction reduction by a factor of 4 compared to the polished reference [16]. Regarding the laser-patterned samples, it was verified that cross-like patterns with smaller periodicities are more beneficial [14]. Finally, multi-scale patterns consisting of deeper micro-coined dimples (depth of 50 µm) superimposed by a cross-like surface pattern showed an improved frictional behavior compared to the purely micro-coined samples. In contrast, the coefficient of friction (COF) was increased for multi-scale patterns if micro-coined samples having lower depths (25 µm) were superimposed with an additional laser pattern [28].

2. Experimental procedure

2.1. Material and preprocessing

The shafts were fabricated by machining and burnishing of cold drawn bars made of stainless steel (AISI 304). The burnishing tool EG5T (Ecoroll, Germany) was used to improve the surface roughness after machining. In order to achieve a low surface roughness of the shaft, the roughness before burnishing and the axial displacement of the tool had to be low. Additionally, a high number of overpasses was required. With regard to the burnishing force, a low force is not sufficient to smoothen the surface whereas a high force can possibly increase the roughness again. Consequently, the burnishing force was varied between 1.1 and 2.3 kN taking the material's hardness of 386 ± 16 HV3 into account. This hardness is typical for a work hardened material. The axial movement of the burnishing tool was set to 0.1 mm/turn and the circumferential speed was 90 $\min^{-1}$. Prior to burnishing, the samples were thoroughly cleaned with ethanol. In total, three passes with a constant burnishing force were done whereby PAO40 oil was used as a lubricant. The lowest surface roughness was achieved for a burnishing force of 1.5 kN after three overpasses (see Table 1).

2.2. Analysis of the surface topography

To control the burnishing process and the roller-coining, the surface topography was measured using a digital light microscope (*Keyence VHX-1000*). Additionally, the surface roughness was determined with a tactile measuring device (*Mahr MarSurfPS1*). The measurements of the surface roughness were performed according to DIN EN ISO 4288. The wear marks as well as the geometry of the produced patterns were imaged by laser scanning microscopy LSM (*LEXT OLS 4100*, *Olympus*) and white light interferometry WLI (*New View 7300, Zygo*). Ten measurements at randomly selected positions of the sample were conducted to calculate mean values and standard deviations.

2.3. Direct laser interference patterning (DLIP)

To fabricate laser patterns with features sizes in the lower micron range, a pulsed solid-state Nd:YAG laser (*Quanta Ray PRO 290, Newport Spectra Physics*) with a fundamental wavelength of 1064 nm, an average power of 20 W, a pulse duration of 10 ns and a frequency of 10 Hz was used. By harmonic generation, a wavelength of 532 nm can be produced. This wavelength was used to fabricate surface patterns under normal atmospheric conditions. For this purpose, the primary laser beam was split up into two sub-beams and then these sub-beams were overlapped again with each other on the sample's surface thus inducing interference. Thereby, the primary beam passed through an attenuator, a shutter system and a lens (focal length 2000 mm) to adjust the respective laser power precisely, to select individual laser pulses and to