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Friction reduction under mixed and full film EHL induced by hot micro-coined surface patterns

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ABSTRACT

Hemispherical structures with different area densities and depths were fabricated by hot micro-coining on stainless steel samples. The tribological properties were studied using a ball-on-disc tribometer in rotational sliding mode with different sliding velocities in order to study the frictional behaviour under different lubricated conditions. For low sliding velocities (mixed EHL), all coined surfaces demonstrate a significant friction reduction, whereas only some of the structures lead to an improved frictional behaviour under full-film EHL (higher velocities). Furthermore, the influence of an additional pressure build-up and cavitation is discussed. The largest improvement (friction reduction by a factor of 3 for all velocities) is achieved using a pattern with a pocket depth of 25 μm and an area density of 5%.

1. Introduction

The lubrication conditions, the kinematics and the applied load are the most influencing factors with regard to the tribological performance and efficiency of machine components. A poor lubrication state can lead to an increased coefficient of friction (COF) or wear rate thus decreasing the lifetime and stability of these components [1]. By means of the well-known Stribeck-curve in combination with the λ parameter (film thickness divided by combined surface roughness), boundary, mixed and hydrodynamic lubrication can be distinguished [2,3]. In addition to these lubrication regimes, especially in non-conformal contacts under high load, μ-EHL and EHL have to be considered as well [4,5].

Under boundary lubrication, the tribological properties are mainly determined by the surface roughness and the surface chemistry of the contacting surfaces as well as the lubricant used. The latter typically contains a suitable additive thus generating a boundary film with low shear strength induced by chemical reactions [6–8]. Considering mixed lubrication, the load is partly carried by the contacting surface asperities as well as by the lubricant film. As a consequence, the frictional properties can be tailored by modifying the surface topography and thereby the contact area [9–11]. For rigid materials operating in lubricated non-conformal point- or line-contacts, EHL typically occurs [4]. Due to high contact pressures, the contacting surfaces elastically deform and the viscosity of the lubricant is significantly increased so that the film thickness may be large enough to completely separate the moving surfaces [4]. Under lower contact pressures, e.g., for rigid materials in conformal contacts, hydrodynamic lubrication may form a thick lubricant film that separates both surfaces completely from each other. Consequently, the tribological behaviour is mainly influenced by the properties of the lubricant, but also to a certain extent by the underlying surface topography. The choice of the correct surface topography can induce an additional hydrodynamic pressure thus increasing the load carrying capacity under hydrodynamic lubrication [12–14].

From the literature, it is well accepted that a deterministic surface topography can significantly improve the tribological properties in all the different lubrication regimes ranging from boundary to hydrodynamic lubrication [14–19]. In order to produce deterministic surface topographies, laser patterning/texturing [20–23], lithographic methods [16,24], embossing/coining [25,26], etc. can be used. The choice of the fabrication methods mainly depends on the production capacity and the desired structural parameters (e.g. structural depth and width).

The pioneering work of Etsion et al. proved the beneficial behaviour of laser-patterned machine components (piston rings, seals, thrust bearings) [27–30]. Both analytical simulations and subsequent experimental studies were able to show that the area density and the structural depth-to-diameter ratio are the most influencing factors with regard to the tribological behaviour under lubricated conditions. The right combination of said factors can lead to a significant reduction in friction [27–30].

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Kovalchenko et al. recorded Stribeck-curves for laser-patterned surfaces using line- and point-contacts. The authors were able to show that the transition from mixed to boundary and from hydrodynamic to mixed lubrication can be shifted to higher loads and smaller relative velocities by laser surface patterning [20–22]. Borghi et al. also investigated the effect of patterned surfaces on the Stribeck curve. A friction reduction of around 75% compared to the polished reference was determined and a shift in the transition from mixed to hydrodynamic lubrication to lower velocities was also verified [31].

Pawlus et al. investigated the effect of circular and elliptical dimples produced by micro-coining on the tribological behaviour under mixed lubrication. They showed that the coined surfaces can act as a secondary oil source and trap wear particles thus improving the run-in behaviour and finally reducing the COF. Summarising, they could demonstrate that the coined surfaces with small area densities extend the oil film lifetime by a factor of 5 [32–37].

A lot of research works deal with the efficiency of dimpled (hemispherical) surface structures varying the structural depth and width as well as the area density. It has been shown that small or intermediate area densities are beneficial to reduce the COF under lubricated conditions [38–44].

The application of surface patterning in non-conformal contacts under mixed lubrication, EHL or mixed EHL can lead to a significant reduction in the resulting lubricant thickness and collapse of the lubricant film. In addition to that, patterned areas can increase subsurface stresses and reduce the contact fatigue life due to high contact pressure acting in these lubrication regimes [45]. Mourier et al. were able to demonstrate that deep micro-dimples produced by ultra-short pulse laser processing lead to detrimental effects because the lubricant film collapsed. In contrast to that, shallow dimples locally increased the oil film thickness [18,46]. Similar experimental findings related to the structural depth were found by Krupka et al. [45,47,48]. However, as pointed out by Wos et al. very recently, the effect of surface patterning under non-conformal contact conditions is still an open question and controversially discussed [49].

In this work, the frictional properties of hot micro-coined hemispherical surface structures under different lubricated conditions were studied by recording Stribeck-curves. The fabrication of the surface structures is done with a particularly designed hot micro-coining setup which enables also the processing of high strength steels by heating the material and thus reducing the flow stress. Hemispherical structures with different area densities (ranging from 5% to 28%) and structural depths (ranging from 24 to 96 μm) were fabricated. The tribological properties of all samples were studied using a ball-on-disc setup in rotational sliding mode with a normal load of 5 N and different sliding velocities (ranging from 0.001 to 0.5 m/s) in order to adjust different lubrication regimes.

2. Experimental procedure

2.1. Samples

Stainless steel blanks (AISI 304) with a thickness of 1 mm were used in these experiments. The chemical composition of the steel used is summarised in Table 1. The initial blank was cold rolled, heat treated, etched and skin pass rolled by the producer in the final production steps. In order to achieve a lower surface roughness, the samples (coined and non-coined) were polished. The roughness of the initial steel blank as well as of the coined and polished sample can be found in Table 2.

Table 1
Chemical composition of the steel used in wt.- % as specified by the supplier.

Used steel samples	Fe	Cr	Ni	Mn	Si	C	Mo
Stainless steel (AISI 304)	68.9	18	10	2	1	0.1	/

Table 2
Summary of the measured surface roughness after each processing step.

Process step	R_q/μm	R_z/μm	R_k/μm
Initial blank	0.20 ± 0.01	1.06 ± 0.12	0.30 ± 0.03
Hot coined	0.26 ± 0.04	1.71 ± 0.31	0.52 ± 0.05
Polished	0.026 ± 0.003	0.023 ± 0.004	0.28 ± 0.03

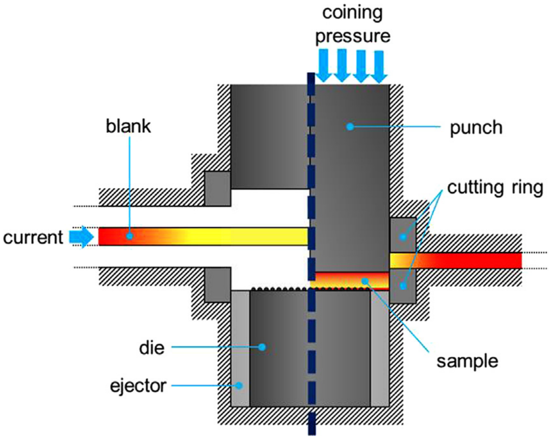

Fig. 1. Visualisation of the hot micro-coining process (left: heating process, right: coining process).

2.2. Micro coining

A closed die hot micro-coining setup as described in [25,26,50] was used to produce micro lubrication pockets on stainless steel substrates. The closed die setup prevents material flow out of the forming area and improves the form filling (ratio of coined pocket depth to the pattern height of the tool) homogeneity of the coined samples [51]. The coining of high strength materials, like stainless steel, requires a preheating of the samples to reduce the flow stress and thus the load on the die. Different studies with various tool materials, e.g. silicon, sapphire and hardened tool steel, etc., have been conducted to coin stainless steel [50,52,53]. However, in each study the tool was damaged, since the load on the die surpassed the yield stress of the tool material. Szurdak et al. successfully coined stainless steel blanks without die damage or measurable die wear [25,26]. The same heating and coining parameters as described in [25] were used in this work.

The heating of the blank was performed using a conductive heating system which allows for a specific temperature in a short time. The current density and the heating time were set to 35 $\mathrm{A/mm^2}$ and 5 s for all experiments thus leading to a temperature peak of 1200 °C [25]. In order to achieve a closed forming area, the blank was cut and coined in one tool movement. The tool velocity for the cutting and coining process was kept constant at 5 mm/s. The coining pressure was varied in order to determine the required pressure to obtain a specific form filling or pocket depth, respectively. Fig. 1 shows schematically the closed die hot micro-coining process. The coined samples were polished in order to remove the oxide layer and to improve the roughness of the produced surface (please refer to Table 2). Afterwards, the polished samples were cleaned in an ultrasonic bath with ethanol.