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How to guide lubricants – Tailored laser surface patterns on stainless steel

Philipp G. Grützmacher*, Andreas Rosenkranz, Carsten Gachot

Department of Functional Materials, Saarland University, 66123 Saarbruecken, Germany

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ABSTRACT

In this experimental study, periodic line-like structures with different periodicities (5, 10, 19, and 300 μm) and structural depths (approximately 1 and 4 μm) were fabricated on stainless steel samples (AISI-304) by short-pulse laser interference and ultrashort-pulse laser patterning. A detailed characterization of the resulting surface topography was performed by white light interferometry and scanning electron microscopy. The spreading dynamics of additive-free synthetic polyalphaolefine oil on a polished reference sample are compared to laser patterned surfaces. These studies are conducted using a newly developed test rig, which allowed for controlled temperature gradients and a precise recording of the spreading dynamics of lubricants on sample surfaces. It could be demonstrated that the spreading velocity parallel to the surface pattern is higher for all samples which can be explained by increased capillary forces and liquid pinning induced by the surface patterning. Furthermore, a decline of the spreading velocity over time for all samples and orientations is clearly visible which can be traced back to a viscosity increase induced by the temperature gradient and a reduced droplet volume. For parallel orientation, the experimental findings are in good agreement with the Lucas–Washburn equation and established models.

1. Introduction

Insufficient lubrication in loaded tribological contacts such as bearings and gears is a generalized problem that causes severe damage [1]. Due to frictional heating within the contact zone, a temperature gradient develops between the loaded contact (higher temperature) and the unloaded regions (lower temperature). This typically leads to a surface tension gradient within the lubricant and consequently migration from hotter to cooler regions by Marangoni-forces, finally yielding in a lack of lubricant in the zones where it is most urgently needed [2]. In contrast to that, there are stabilizing factors, such as capillary forces and the viscosity of the lubricant, which hold the liquid in the zone of higher temperature. All these factors are highly depending on temperature.

The possibly resulting inadequate lubrication conditions may produce changes in the lubrication regime leading to increased contact between the sliding surfaces, increased wear and component failure.

To counter this, identifying and controlling the governing forces involved in promoting or impeding lubricant migration becomes decisive. Temperature gradients, surface chemistry and topography effects play an important role in this context [3–5]. One approach could be to overcome the acting Marangoni forces by removing heat from the contact zone and thus compensating the temperature gradient. Another solution, used in precision mechanics for the lifetime lubrication of watches, may be the use of very thin fluororganic epilame films as antispread barriers [6]. Furthermore, Morita et al. reported about chemical patterns consisting of alternating hydrophobic and hydrophilic stripes which can be tailored to influence the lubrication migration [7]. However, a problem often encountered with thin organic layers, or chemical surface treatments in general, is the use of environmentally hazardous chemicals and their reduced resistance against abrasion [6].

Apart from chemical treatments, there are numerous techniques to create well-defined topographies and thereby manipulate wetting and lubricant spreading [3,8,9]. Introducing channel-like structures in material surfaces have the benefit of using capillary forces by guiding the lubricant to the tribologically stressed areas. Lithography-based methods such as UV, electron beam or interference lithography are quite common in this context [8]. Some mechanical approaches like micro-coining or roller burnishing are also used to create different pattern geometries on metal surfaces [10].

* Corresponding author.
E-mail address: philipp.gruetzmacher@uni-saarland.de (P.G. Grützmacher).

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Major drawbacks of most of the abovementioned methods include their multiple processing steps and their limitations in geometry and feature sizes. In this context, laser-patterning techniques are very efficient because they allow for fast and precise surface treatment of various materials [11]. In particular, ultrashort-pulsed lasers which are scanned over the substrate surface have some benefits in creating well-defined surface topographies due to their minimized heat input [12]. Another promising approach is the use of interfering laser beams and the resulting intensity distribution. This technique makes it possible to fabricate well defined, periodic surface patterns on metals with a great variability in lateral feature sizes in one single laser shot [13]. However, it should be mentioned that the maximum achievable structural depths using laser interference patterning are roughly between 1.5 and 2.5 μm [13]. In order to investigate larger structural depths, femtosecond laser processing was used in this study as well. The work by Rosenkranz et al. already clearly revealed the impact of laser-induced surface patterns by direct laser interference patterning (DLIP) on the spreading behavior of an additive-free polyalphaolefin (PAO) oil, yet without taking into account temperature gradients [14].

In the work presented here, the spreading dynamics of additive-free, synthetic PAO 4 oil on polished stainless steel samples is compared to that of laser-patterned steel surfaces, studied by a newly developed test rig, which allows for controlled temperature gradients and a precise recording of the spreading dynamics of lubricants on sample surfaces. Four different line-like patterns were produced: periodicities of 5, 10 and 19 μm with a structural depth of approximately 1 μm were fabricated by DLIP; finally, sharper and deeper patterns with a line-spacing of 300 μm and depth of 4 μm were created by scanned, ultrashort femtosecond pulses. Apart from larger structural depths for the femtosecond laser processing, also the shape of the topography profiles differs from the ones produced by nanosecond interference patterning. Therefore, both techniques were applied in this study in order to reveal the effects of said differences on the lubricant spreading behavior.

2. Materials and methods

2.1. Materials

Commercially available austenitic stainless steel samples (AISI 304: 20 mm × 20 mm × 0.75 mm) with a mirror-like surface finish (root mean square roughness (R_q) of 30 nm) were used for the spreading experiments. The chemical composition of the used steel is given in Table 1 as specified by the supplier and confirmed by energy-dispersive X-ray spectroscopy (EDS). Prior to the spreading experiments, the samples were cleaned with a multi-step cleaning procedure in an ultrasonic bath employing cyclohexane, acetone and isopropanol 10 min each in the given order to remove polar and non-polar contamination.

2.2. Laser interference patterning

A well-defined, line-like surface topography with a periodicity of 5, 10 and 19 μm, which is defined by the laser wavelength λ and the angle between two interfering beams, was created by DLIP on the stainless steel substrates [13,15,16]. For this purpose, a high-power pulsed solid-state Nd:YAG laser (*Quanta Ray Pro 290, Newport Spectra Physics*) with a pulse duration of 10 ns, a wavelength of 355 nm and a repetition rate of 10 Hz was used. In order to obtain interference, the primary beam travels through an optical set-up which is described in a previous publication by Rosenkranz et al. [14]. Finally, the line-like pattern with the characteristic periodicity is produced on the substrate surface. The laser fluence was kept constant at 29 J/cm^2 for all sample types in order to produce a well-defined and homogeneous surface pattern. The DLIP was done under ambient conditions using a single laser pulse. Further details about the DLIP have been already published elsewhere [13,15,16].

Table 1
Chemical composition of the used steel samples in wt.% as specified by the supplier and confirmed by EDS.

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

2.3. Laser patterning using a femtosecond laser

One sample was patterned using ultrashort-pulse laser patterning (UPLP). To this end, a passively mode-locked ultrashort-pulsed Ti: Sapphire laser (*Spitfire, Newport Spectra Physics*) was used with a repetition rate of 1 kHz and a wavelength of 800 nm. The underlying physical principle of this laser system is chirped pulse amplification which allows for the production of ultrashort laser pulses (tuneable pulse duration ranging from ≈100 fs up to approximately 4 ps). The pulse duration (full width at half maximum) used in this study was 130 fs and was measured by autocorrelation. The primary laser beam was focused on top of the steel sample with a lens (focal length: 200 mm), which resulted in a beam diameter of 70 μm. The laser spot was scanned across the sample with a synchronized, automatic (sample) translation table, placing each pulse 35 μm apart within each line in order to produce a homogeneous line-like pattern. The lines were given a separation (periodicity) of 300 μm. To achieve a higher structural depth and sufficient homogeneity, each pattern line was scanned four times. The UPLP was performed under ambient conditions.

2.4. Topographical analysis

The topography of the samples was characterized by white light interferometry (WLI: *New View 7300, Zygo*) prior to and after the laser patterning (DLIP and UPLP) in order to study the surface roughness and the quality of the patterns. Typical roughness parameters such as the root-mean-square roughness R_q as well as structure-dependent parameters such as periodicity and structural depth were chosen to describe the surface topography of the laser-patterned surfaces. In addition to that, the resulting topography was imaged by scanning electron microscopy (SEM: *Helios 600, FEI*) in secondary electron contrast after patterning.

2.5. Surface temperature analysis

The linearity of the temperature gradient on the sample and the comparability of the temperature between sample table and specimen was determined by a thermal imaging camera (*FLIR i7*). The sample table was painted black in order to minimize the reflection of the copper sample table.

2.6. Spreading velocity measurements

For the spreading experiments, a new experimental setup with a copper table was designed which is illustrated in Fig. 1a. The sample table is heated on one side by a heating cartridge (*RS Components*) and cooled on the other side by water cooling in order to achieve a temperature gradient of approximately 2 °C/mm. In order to adjust the temperature gradient, the heating cartridge is controlled by a voltage regulator. The temperature gradient at the surface of the sample table is measured with NiCr-Ni thermocouples. In order to affirm a negligible temperature difference between the table surface and sample, thermal image measurements and a