Wear 334-335 (2015) 1–12

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Oil film lifetime and wear particle analysis of laser-patterned stainless steel surfaces

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ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form
6 April 2015
Accepted 7 April 2015
Available online 15 April 2015

Keywords:
Laser surface texturing
Mixed lubrication
Oil film lifetime
Wear particle analysis

ABSTRACT

In this experimental study, periodic cross-like patterns with different structural wavelengths (6 and 9 μm) were fabricated by laser-interference patterning on stainless steel samples (AISI-304). Tribological tests with a ball-on-disc tribometer in rotational sliding mode were performed under mixed lubrication. Spin coating was used to produce homogeneously distributed oil films with a defined initial oil film thickness in order to ensure reproducible testing conditions for all tested samples. By means of an advanced electrical resistivity circuit, a sharp increase in the coefficient of friction was well correlated with a change in the lubrication regime from mixed to boundary lubrication. This event defines the oil film lifetime at the corresponding cycle count. An oil film lifetime of 1000 sliding cycles was determined for the polished reference samples which is independent of the initial oil film thickness. For the laser-patterned surfaces, the oil film lifetime increases with decreasing initial oil film thickness. Moreover, the cross-like pattern with a structural wavelength of 6 μm shows a significant improvement in the oil film lifetime by a factor of 130 compared to the unpatterned reference. A subsequent analysis of the wear particles was able to demonstrate that the wear particles being produced for the laser-patterned surfaces are typically smaller than half of the used structural wavelength. As a consequence, the produced wear particles can be effectively trapped in the topographic minima positions. Consequently, those particles do not remain in the contact area thus reducing the abrasive wear component and increasing the oil film lifetime.

1. Introduction

The friction force can be defined as the resistance of two contacting surfaces against relative motion with a certain sliding velocity [1]. Friction and related phenomena such as wear and lubrication play an important role in daily applications (for example ground transportation). Holmberg et al. recently published a study discussing the different contributions to energy losses in passenger cars [2]. A comparison of various fuel energy dissipation mechanisms demonstrated that a large amount of the energy is dissipated only to overcome frictional losses (around 33%) [2–4]. Frictional losses can be separated into two main categories: rolling friction with regard to the tyre–road contact and friction related to the engine system [2–4]. The piston assembly, bearings and valve train, all operating in different lubrication regimes, bear the highest frictional loading among passenger car parts [2–11].

To reduce friction and wear, several methods and techniques exist which can be applied to specifically loaded components. The use of coatings with low shear strength or a defined change of surface roughness by surface patterning can lead to significant improvements in the tribological behaviour [6,12,13]. However, the separation of the contacting surfaces by an oil film seems to be the easiest and most effective way to reduce friction and wear. The effectiveness is mainly determined by the ratio of the oil film thickness to the combined surface roughness which is given by the λ parameter. By means of this parameter and the well-known Stribeck curve, three different lubrication regimes can be identified [14]. A λ parameter larger than 3 typically defines the hydrodynamic lubrication regime. In this regime, the fluid film completely separates both contacting surfaces and no solid–solid contact occurs. In the mixed lubrication regime ($1 < \lambda < 3$), the load is partially supported by the fluid film and contacting asperities [15,16]. In boundary lubrication, where λ is typically smaller than 1, the load is completely carried by contacting asperities and a friction reduction compared to solid state friction is achieved by chemisorption and tribochemical reactions with the oil molecules [15–17].

In the last 20 years, numerous research works have been carried out in order to study the effect of laser-patterned surfaces under mixed and boundary lubrication. Suh et al. [18,19] investigated the effect of patterned Cu- and Ti-surfaces (pad width between 20 and 550 μm) on the frictional response. They were

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http://dx.doi.org/10.1016/j.wear.2015.04.006
0043-1648/

able to demonstrate that the coefficient of friction is significantly reduced due to surface patterning. This could be explained by the storage of the produced wear particles in the topographic valleys thus reducing abrasive wear and therefore lowering the coefficient of friction [18,19].

Kovalchenko et al. [20–22] studied the possibility of influencing the tribological behaviour in conformal contacts by fabricating a well-defined surface pattern. Experimental results of laser-patterned surfaces demonstrate, for the transition from mixed to hydrodynamic lubrication, a shift to higher loads and lower relative velocities [20–22]. Borghi et al. [23] also investigated the effect of patterned dimples 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 [23].

Hartl et al. investigated the film thickness build-up with both real roughness features and artificially produced micro-dents in non-conformal contacts under mixed lubricated conditions. Furthermore, they also studied the resulting rolling contact fatigue in order to correlate the oil film thickness with the fatigue properties. They were able to prove that lubricant emitted by the micro dents can lead to locally increased oil film thickness thus producing an additional lift-off and an enhanced tribological behaviour. Moreover, no negative and sometimes even a positive effect of the surface patterns on the contact fatigue due to the larger amount of oil in the contact zone was shown [24–28].

Pawlus et al. [29–34] studied the influence of circular and elliptical dimples produced by micro-coining on the tribological behaviour under mixed lubrication. They proved that the coined surfaces can act as a secondary oil source and trap produced wear particles thus improving the run-in behaviour of the surfaces and finally reducing the coefficient of friction in the steady state regime. Summarising, they could demonstrate that the coined surfaces with small area densities extend the oil film lifetime by a factor of 5 before catastrophic wear is initiated [29–34].

In addition to that, Blatter et al. [35] studied the oil film lifetime of laser-patterned surfaces. They were able to prove that the oil film lifetime can be prolonged by a factor of 10 due to laser patterning. This was traced back to a higher load carrying capacity and reduced wear rate for smaller structural widths [35]. Moreover, Dumitru et al. [36] and Andersson et al. [37] investigated the oil film lifetime of dimpled patterns under mixed lubrication. A variation of the area density and structural depth in comparison to a polished reference showed that an increase in the oil film lifetime by a factor of 8 can be achieved [36,37]. Similar conclusions have been published by Hu et al. [38] demonstrating a 9-fold extension of the oil film lifetime. Finally, Duarte et al. [39] studied the tribological properties of line-like, dot-like and cross-like surfaces fabricated by laser interference metallurgy under mixed lubrication. They were able to verify that the cross-like pattern irradiated by the highest fluence, resulting in the largest structural depth (around 1 μm), shows the best tribological behaviour leading to an improvement of the oil film lifetime by a factor of about 16 [39].

In this work, we study the friction and wear behaviour of laser-patterned stainless steel surfaces under mixed lubrication using a ball-on-disc tribometer in rotational sliding mode. The laser patterning results from interfering beams from a solid-state Nd:YAG laser, producing homogeneous surface patterns with cross-like geometries and structural wavelengths of 6 and 9 μm as well as a structural depth of around 1 μm. Spin coating is used to record calibration curves for a defined oil film thickness depending on the oil volume and the spin coating velocity, ensuring reproducible testing conditions. Due to the fact that electrical resistivity measurements are well established in the tribological community [40–45], an electrical resistivity circuit was used to define the oil film lifetime of the polished and laser-patterned surfaces for different initial oil film thicknesses. It should be mentioned that the cycle number after which the coefficient of friction suddenly starts to increase is defined as the oil film lifetime. Finally, the resulting wear behaviour is characterised by means of a particle characterisation system (calibrated light microscope) evaluating the size distribution of the produced wear particles. The induced topographic changes are analysed by optical microscopy and white light interferometry (WLI).

2. Experimental procedure

Commercially available austenitic stainless steel samples (AISI 304) were used for the laser patterning and as reference material for the subsequent tribological characterisation under mixed lubrication. The flat 20 mmx20 mmx1 mm specimens had a mirror-like surface finish which results in a root mean square roughness (R_q) of about 30 nm. The hardness of the steel used (AISI 304) was around 2.3 GPa. The chemical composition of this steel is given in Table 1 as specified by the supplier. For the study of the oil film lifetime, an alumina (Al_2O_3) ball (Ø 6 mm) was selected as tribological counterbody due to its high hardness (around 1800 HV1 or 17.65 GPa) in order to avoid wear and plastic deformation of the ball.

The lubricant used in this study was a synthetic Poly-alpha-olefin (PAO) without additives. Additive effects can thus be excluded during the tribological experiments and the results correlated only with the surface topography. The tribological tests were performed with PAO 40 which has a kinematic viscosity of 40 cSt at 100 °C (387 cSt at 40 °C). This viscosity was selected due to the good ability to build up a certain pressure and therefore to allow for the generation of a specific oil film thickness. The properties of the oil used are summarised in Table 2 as specified by the supplier.

A high-power pulsed solid-state Nd:YAG laser (*Newport Spectra Physics, Quanta Ray PRO 290*) with a fundamental wavelength of 1064 nm, pulse duration of 10 ns and frequency of 10 Hz was used for the surface patterning. The wavelength of the laser was set at 355 nm. Furthermore, the patterning process was carried out under normal atmospheric conditions. The primary beam is split into two beams by means of a beam-splitter. The sub-beams interfere on the surface of the sample producing a line-like interference pattern with feature sizes in the micrometre range. After the first patterning step, the sample is rotated at 90° and a second pattern is superimposed resulting in a cross-like surface pattern. The structural wavelengths were set to 6 and 9 μm whereas the structural depth was kept constant around 1 μm. The laser fluence was set to 14 mJ/m^2 for all specimens in order to generate homogeneous surface patterns. Further details concerning the patterning technique have already been published elsewhere [46]. Prior to and after the laser patterning, the

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
Properties of the PAO oil used as specified by the supplier (Castrol).

Property	PAO 40
Kinematic viscosity at 100 °C/cSt	39.6
Viscosity index	147
Specific gravity	0.85