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Study on friction and wear reducing surface micro-structures for a positive displacement pump handling highly abrasive shale oil

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ABSTRACT

In the recent years the capability of laser manufactured micro-structures to reduce friction has been investigated. The aim of this paper is to investigate the potential of surface texturing through ultra-short-pulse laser ablation to improve the performance of special positive displacement pumps handling shale oil, which contains highly abrasive particles. In this work pin-on-disc tests were carried out on picosecond laser structured samples. The most suitable texturing parameters were experimentally found and the effect of each parameter on friction reduction was analyzed. Results revealed that friction and wear generated on the pumps may be considerably reduced and that the aspect ratio of the applied micro-dimples is in this case the most critical texturing parameter.

1. Introduction

Positive displacement rotary pumps are widely used in many industries such as in food processing, oil, chemical and petrochemical, shipbuilding, refineries, central heating systems, and paper and pulp production industries, among others. Their working principle consists in forcing a specific amount of lubricant from the inlet pressure section to the discharge side of the pump.

Low energy consumption and wear resistance are the undeniable main requirements not only of positive displacement pumps but of all the kind of pumps, in general. Pump design, operating conditions and fluid characteristics are some of the most important factors to take into account when selecting the most suitable pump for each application. Hence, tribological conditions of the sliding parts play an important role in the performance and efficiency of positive displacement pumps. In other words, the energy losses in pumps due to the friction originated between components and the induced wear should be reduced to the extent possible. Positive displacement rotary pumps are characterized by close fitting parts in order to avoid the fluid transfer from the high pressure part to the low pressure one [1]. Thus, due to these low design clearances between specific moving parts of the pumps, they are not always able to operate with fluids containing abrasives such as shale oils that may lead to a severe wear and a rapid degradation of the mating surfaces, and subsequently to a premature failure of the pumps. Hence, the main goal of this work is to investigate the potential of surface texturing in order to improve the tribological performance of positive displacements pumps operating under abrasive shale oil environments. In particular, the aim is the improvement of the tribological performance of a commercially available positive displacement pump, owned by SNC Promex AS (Estonia). To this end, particular areas of the pumps were structured by means of the implementation of an innovative ultra-short laser ablation surface structuring technique. The design concept of the considered pump is based on a rotary piston technology (Fig. 1) that offers major advantages over conventional pump designs, such as the possibility to operate with high viscosity oils and low leakages due to the small clearances between the rotary piston and the housing (< 0.02 mm) [2]. The application of texturing has the potential to reduce friction for tight tolerances, decrease vibrations and facilitate components downsizing.

In the past decades, many researchers invested much effort in studying the possibilities and applicable techniques to improve the tribological behavior in highly stressed lubricated contacts [3–15]. Recent methods that pursue this goal are mainly focused on manufacturing micro-textures with a certain pattern on the surface such as dimple shape structures [4–7,9,10,16]. Dimples are basically micro-cavities, which can be optimized for different applications. They can be manufactured in several shapes, sizes and patterns distributions, resulting in the possibility to tailor the tribological behavior of the

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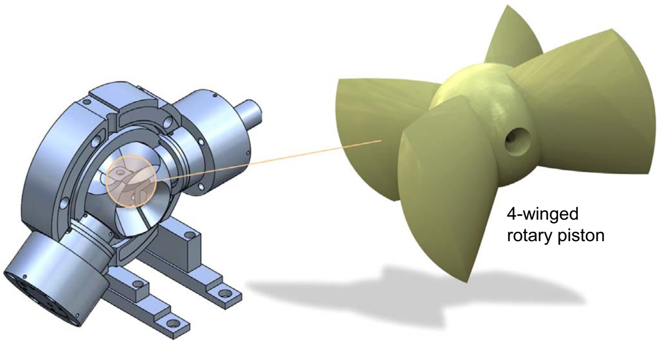

Fig. 1. Rotary piston displacement pump (SNC Promex AS, Estonia) [2].

surfaces in contact and operating under certain conditions. Regarding manufacturing techniques, several studies have already demonstrated that ultra-short-pulsed lasers are useful tools in order to manufacture surface micro-structures [11,12,17]. The main advantage of ultra-short-pulse laser ablation techniques is that they may be applied to almost all kind of materials, with high accuracy and avoiding finishing post processing steps. Contactless and forceless processing without tool wear and with high automation possibilities are the main common advantages of laser ablation techniques. In general, laser ablation may be conducted using either short-pulse or ultra-short-pulse lasers. The former emits pulses in nanosecond (1 ns=10^{-9} s) regime, and the latter emits pulses in pico- (1 ns=10^{-12} s) and femtosecond (1 ns=10^{-15} s) regime. In the case of short-pulse-laser ablation, the physical process of ablation follows the common physical sequence of heating, melting and vaporization on a quite small time scale of nanoseconds. In the ultra-short-pulse laser case, the material is superheated within a time scale shorter than the electron-lattice relaxation time, leading to an enhanced fraction of irradiated material being vaporized rather than melted [18]. Due to the reduction of the melting phase during the sublimation process to a nanometer thick layer, no further post processing is needed whereas short-pulse laser ablation usually involves material removal (in form of burr).

It has already been proven that those kind of micro-cavities are able to reduce friction in certain tribological environments due to specific phenomena occurring at the surface [3,5,6,13,14,19–22]. In particular, it was found that micro-cavities may act as “hydrodynamic micro-bearings” and as “debris-trapping-cavities” under specific operating and surface conditions [5,6,8–10,12,14]. Each of those effects is dominant under specific conditions. In lubricated systems, with rather high relative velocity between contacting surfaces, the effect of micro-cavities acting as single or collective hydrodynamic micro-bearings that increase the load-carrying capacity is usually dominant. In fact, in this case, a fluid film that separates the adjacent surfaces during motion, avoiding solid body contact and mixed lubrication, is formed. In other cases, however, the so called “debris trap” phenomenon may be considered to be the dominant factor. The micro-structures may trap the particles temporally or permanently preventing them from causing severe wear on the contacting surfaces. Etsion et al. and Zhou et al. demonstrated the potential of laser techniques to improve the tribological performance of many mechanical devices such as piston ring/cylinder contact in combustion engines [5,22], mechanical seals [6] as well as thrust and journal bearings [23,24].

In this work, the potential effect of micro-dimples textured by ultra-short ablation techniques to reduce the friction of a positive displacement pump lubricated with highly abrasive shale oil has been investigated. To this aim, friction tests on laser structured surfaces were carried out at laboratory scale using pin-on-disc configuration. The surfaces of the discs were structured using ultra-short-pulse laser ablation techniques installed in a prototype 5-axes precision milling machine tool with a picosecond laser source and a 4-axes optical beam guiding scanning system [12]. Furthermore, the effects of different texturing parameters such as dimple size, coverage and aspect ratio (depth to diameter) on the friction and wear generated between surfaces have been also studied in this work.

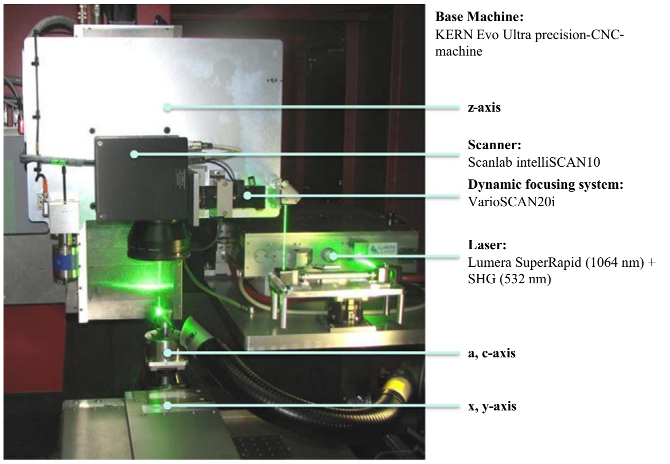

Fig. 2. 3D Laser structuring machine at Fraunhofer IPT.

2. Materials and methods

2.1. Laser texturing system

The laser texturing was conducted on a tailored laser processing machine based on a modified commercial 5-axes-milling machine Kern EVO (Fig. 2). A picosecond laser (wavelength: λ=532 nm) was installed into the machine together with an entire beam guiding system, including beam shaping lenses, mirrors and a high speed galvanometer scanner (IntelliScan10, Scanlab, Germany). The base machine offered 5 axes (X, Y, Z, B and C) for work piece positioning. Additionally, the laser scanner presented 2 high speed galvanometer axes (X, Y) and one opto-mechanical (Z) axis. An additional virtual C’-axis has been implemented enabling the relative alignment of programmed patterns. Embedded into a Computer-Aided (CAx) software framework enabling automated tool path generation for all mechanical and optical axes, the system offers 5+4-axes for real 3D-laser structuring. While the machine and scanner tolerances are in the order of sub-single micron for each axis, the total accuracy of the multi-axes manufacturing system is approximately 6 µm when all 9 axes are involved. In the present work, the dimples have been manufactured using a two-dimensional beam movement, so that the total lateral accuracy was about 1 µm. The accuracy of dimple depth manufacturing is dependent only on the ablation depth per processing layer, which is of the order of ten nanometers.

Although the laser machine is able to operate at two different wavelengths (see Table 1), only radiation of 532 nm wavelength was used in this work for a better absorption on the steel material. In

Table 1
Main specifications of the ultra-short pulse laser source (SuperRapid, Coherent, Germany).

	532 nm	1064 nm
Pulse duration	< 10 ps	< 10 ps
Pulse repetition rate	80..1000 kHz	80..1000 kHz
Pulse energy	110 µJ @ 80 kHz 4 µJ @ 100 kHz	165 µJ @ 80 kHz 19 µJ @ 100 kHz
Pulse peak power	> 13 MW @ 80 kHz > 0,5 MW @ 100 kHz	> 20 MW @ 80 kHz > 2 MW @ 100 kHz
Max average power	9 W	20 W
M^2	< 1,1	< 1,2