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Full Length Article

Investigations on femtosecond laser modified micro-textured surface with anti-friction property on bearing steel GCr15

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ABSTRACT

This work puts forward femtosecond laser modification of micro-textured surface on bearing steel GCr15 in order to reduce frictional wear and enhance load capacity during its application. Multi pulses femtosecond laser ablation experiments are established for the confirmation of laser spot radius as well as single pulse threshold fluence and pulse incubation coefficient of bulk material. Analytical models are set up in combination with hydrodynamics lubrication theory. Corresponding simulations are carried out on to explore influences of surface and cross sectional morphology of textures on hydrodynamics lubrication effect based on Navier-Stokes (N-S) equation. Technological experiments focus on the impacts of femtosecond laser machining variables, like scanning times, scanning velocity, pulse frequency and scanning gap on morphology of grooves as well as realization of optimized textures proposed by simulations, mechanisms of which are analyzed from multiple perspectives. Results of unidirectional rotating friction tests suggest that spherical texture with depth-to-width ratio of 0.2 can significantly improve tribological properties at low loading and velocity condition comparing with un-textured and other textured surfaces, which also verifies the accuracy of simulations and feasibility of femtosecond laser in modification of micro-textured surface.

1. Introduction

The desire for reducing frictional wear on bearing involved in sliding contact is ever existing. The reliability and durability of bearings depend on the friction condition that occurs at the sliding surface. Moreover, the increase of load capacity and higher severity of surface interaction for bearing are in urgent need.The introduction of specific textures on the sliding surface, involving flat and smooth lands interrupted by local depressions in different shapes, is an approach to improve tribological properties of bearing [1]. One of the functions of these structures is to store abrasive dusts. The elimination of abrasive dusts from the friction pair can get rid of the ploughing wear effect and deformation of critical components [2]. Another important function is to act as reservoirs of lubricants, which is capable of feeding the lubricants directly and maintaining lubricating film during tribological contacts [3,4]. These functions contributes to the prolongation of lubricants endurance and lifetime of bearing.

Whilst there are many surface modification techniques available, such as reactive ion etching [5], surface shot peening [6], pulsed air arc treatment (PAAT) [7] and laser surface texturing (LST) [8]. Among these techniques, LST has several characteristics, these include, but are not limited to, well processing flexibility, high machining repeatability and accuracy, lack of tool wear. Kovalchenko et al. firstly reported on the transition from the boundary to the hydrodynamic regime in the case of a texture constituted by a lattice of circular holes on H-13 steel and the beneficial effects of LST are more pronounced at higher speeds and loads and with higher viscosity oil [9]. Galda et al. discussed the effect of hole shape and laser machining parameters on the Stribeck curve of 42CrMo4. It was found out that shape and distribution of oil pockets are the main factors affecting the lubrication kinds [10]. Vilhena et al. studied the relationship between the laser processing parameters and qualitative as well as quantitative profile of the micro-pores on 100Cr6. And in the case of flat contact, where several micro-pores are present in the contact, LST was found to result in friction reduction sliding speed is relatively low [11].

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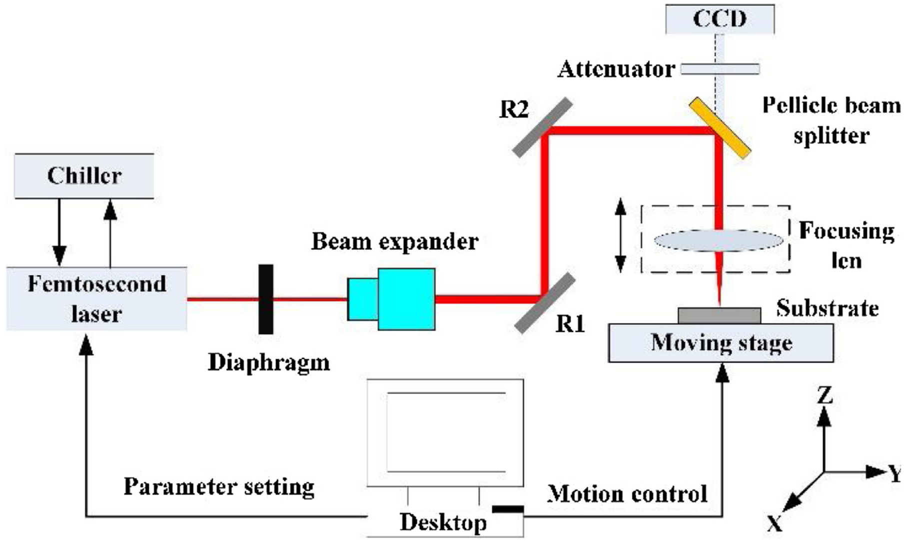

Fig. 1. Schematic diagram of experimental light path.

Table 1
Mass fraction of elements in GCr15 ω%.

Elements	Fe	C	Mn	Si	Cr	Mo	Ni	Cu
Mass fraction	base	0.95–1.05	0.2–0.4	0.15–0.35	1.30–1.65	≤0.10	≤0.30	≤0.25

Comparing with conventional long pulse laser, femtosecond laser has ultrashort pulse duration and ultrahigh peak power density, which is beneficial for restraining thermal diffusion effectively. Effect of thermal-induced defects like recast layer, heated affected zone and spatter on bulk material properties can be significantly restricted, which are particularly advantageous for micro-nano machining [12]. Bathe et al. investigated the influence of laser-textured surface produced by different laser sources on the tribological behavior of gray cast iron [13]. They proved that surface texturing using femtosecond laser resulted in significant improvement in tribological performance comparing with millisecond and nanosecond laser-textured surface under dry condition. Scaraggi et al. experimentally investigated frictional behavior of femtosecond laser induced textures on 100Cr6 spherical cap under lubricated conditions [14] .They found that the texture consists of a square lattice of micro holes can strongly reduce friction value over the entire range of lubrication regimes comparing with the texture consists of microgrooves. Wang et al. employed Ti-Sapphire femtosecond laser to produce textured surfaces with different micro groove spacing and inclination angles on surface of AISI304L steel [15]. Experimental results verified that femtosecond laser surface texturing has marked potential to reduce friction coefficient and wear rate comparing with un-textured surface. Meanwhile, the micro groove inclination angles have influence on the friction behavior of textured surface to a certain extent.

In view of the results of literature review, there is a scarcity of detailed investigations on ablation characteristic and manufacturing craft of specific micro textures on bearing steel by femtosecond laser. Moreover, researches on tribological properties of micro-textured surface are limited in one or two specific textures. In current work, bearing steel GCr15 is employed as substrate material, the threshold fluence and pulse incubation coefficient of which as well as the laser spot radius are derived from multi pulse femtosecond laser ablation experiments. Based on the analytical models for single texture, corresponding simulations are carried out on to analyze variations of tribological properties of textures with different surface and cross sectional morphology. Technological experiments are established to explore optimized parameter group for modifying micro-textured surface proposed by simulations, in which influence rules of multiple femtosecond laser machining variables on morphology of micro grooves are detailed analyzed. Follow-up unidirectional rotating friction contact tests are conducted to compare tribological properties of different micro-textured surfaces under different working conditions and discover the most ideal texture theoretically and experimentally.

2. Experimental setup

The micro-textured surface are modified using a femtosecond diode-pumped mode-locked pulsed solid state Yb: KGW laser (Pharos, Light Conversion), which emits a wavelength of 1030 nm with maximum average power of 15W and pulse duration of 255 fs. Repetition frequency is continuous adjustable from 1 Hz to 1.1 MHz. The laser beam is focused onto the substrate using a 50 mm focusing lens. Assisted compressed air with pressure of 7 bar is utilized in the experiments. Laser energy is measured before the focusing lens using an Ophir Nova II laser power/energy meter with a pyroelectric head (PE-10v2). Laser beam quality is observed by Ophir-spiricon (SP620). A full description of experimental light path is shown in Fig. 1.

The substrate used in this work is GCr15 bearing steel, which is widely applied in the manufacturing of bearing ball and bearing retainer. Main elementary composition is tested by X ray fluorescence spectrometer (AXIOS-PW4400), as shown in Table 1.

Before femtosecond laser processing, the substrate is cut into $\Phi 30 \times 8$ mm by wire-electrode cutting (DK7720) and then grounded into Ra 0.02 by precision grinding machine (FS420 LC). After femtosecond laser processing, the substrate is ultrasonic cleaned in ethanol for 5 min. The surface morphology and internal structure of substrate is characterized by digital microscope with a large depth-of-field (VHX5000) as well as scanning electron microscope (FEI Sirion).