Tribological behavior of femtosecond laser textured surfaces of 20CrNiMo/beryllium bronze tribo-pairs

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Abstract

Purpose – This paper aims to carry out tribological experiments to explore the applications of femtosecond laser surface texturing technology on rock bit sliding bearing to enhance the lifetime and working performance of rock bit sliding bearing under high temperature and heavy load conditions.

Design/methodology/approach – Surface textures on beryllium bronze specimen were fabricated by femtosecond laser ablation (800 nm wavelength, 40 fs pulse duration, 1 kHz pulse repetition frequency), and then the tribological behaviors of pin-on-disc configuration of rock bit bearing were performed with 20CrNiMo/beryllium bronze tribo-pairs under non-Newtonian lubrication of rock bit grease.

Findings – The results showed that the surface texture on beryllium bronze specimens with specific geometrical features can be achieved by optimizing femtosecond laser processing via adjusting laser peak power and exposure time; more than 52 per cent of friction reduction was obtained from surface texture with a depth-to-diameter ratio of 0.165 and area ratio of 5 per cent at a shear rate of 1301 s^{-1} under the heavy load of 20 MPa and high temperature of 120°C, and the lubrication regime of rock bit bearing unit tribo-pairs was improved from boundary to mixed lubrication, which indicated that femtosecond laser ablation technique showed great potential in promoting service life and working performance of rock bit bearing.

Originality/value – Femtosecond laser-irradiated surface texture has the potential possibility for application in rock bit sliding bearing to improve the lubrication performance. Because proper micro dimples showed good lubrication and wear resistance performance for unit tribo-pairs of rock bit sliding bearing under high temperature, heavy load and non-Newtonian lubrication conditions, which is very important to improve the efficiency of breaking rock and accelerate the development of deep-water oil and gas resources.

Keywords Friction, Surface texture, 20CrNiMo/Beryllium bronze, Femtosecond laser, Rheological property

Paper type Research paper

1. Introduction

Tribological properties of rock bit sliding bearings have crucial influences on the service life of rock bit. Due to high temperature, heavy load and harsh lubrication conditions, the early stage damage of sliding bearing was accounted for 80 per cent of rock bit total failure (Wu and Ma, 1998). The failure form of tribo-pairs of rock bit sliding bearing, which were respectively made of 20CrNiMo and beryllium bronze, was mainly adhesive wear (Wang *et al.*, 2006). The tribological behavior of 20CrNiMo/beryllium bronze has become one significant guideline estimating the life of rock bit sliding bearing. Its performance directly influences drilling costs and efficiency (Wang and Liu, 2012). Reduction of friction is therefore considered to be a necessary requirement for

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improved the working performance of rock bit sliding bearing, which is desirable in deep-water drilling .

In recent years, surface texture has emerged as a viable option for improving friction properties and lubrication regime of mechanical components. Fundamental research work on surface texturing has been carried out via experiment and numerical simulations for tribological application; the results demonstrated that suitable surface texture had remarkable capacity of enhancing tribological performance (Etsion, 2005; Wakuda *et al.*, 2003; Segu *et al.*, 2013; Wu *et al.*, 2012), and the shapes, geometrical parameters and distribution of surface textures were the main factors which affect load-carrying capacity and lubricating property of tribo-pairs (Yu *et al.*, 2010; Ma *et al.*, 2013; Mo *et al.*, 2013; Wahl *et al.*, 2012). The friction properties of laser surface texture by a pin-on-disk tribometer under different regimes were investigated. The results obtained 75 per cent of friction reduction under testing conditions, which was because that textured surface inhibited the transition from hydrodynamic to mixed or boundary lubrication regime (Borghi *et al.*, 2008). Friction properties of surface texture under line contact conditions showed that dimple with diameter of 20 μm presented the effect of friction reduction and hydrodynamic pressure generation (Wang *et al.*, 2009). And honed cylinder liners with additional surface texturing, created by burnishing method, were characterized by oil film capacity higher by 50 per cent than plateau honed reference cylinder liner surfaces (Grabon *et al.*, 2013). The principle for improving lubricating properties includes three points: serving as micro-hydrodynamic bearings under hydrodynamic lubrication, acting as lubricant reservoirs under mixed lubrication as well as trapping wear debris under boundary condition (Wang *et al.*, 2010).

Recent studies in tribology aim at the development of micromachining techniques to improve the microscopic geometry of the functional surface because of their ability to optimize the frictional behavior. Micromachining methods of surface texture mainly include laser processing (Wahl *et al.*, 2012), rolling (Ike, 1996), precise diamond turning (Gao *et al.*, 2003), embossing technique (Pettersson and Jacobson, 2006), etching (Fornies *et al.*, 2005), vibrorolling (Bulatov *et al.*, 1997) and so on. Because of high efficiency and low cost, laser surface texturing has been widely used. However, there are still some issues involved in traditional laser processing, such as recasting of ablated material around the textured edge (Vilhena *et al.*, 2009; Amanov *et al.*, 2013; Bathe *et al.*, 2014), thermal diffusion and heat accumulation effects (Gualtieri *et al.*, 2009). Compared with the laser processing techniques that use longer-pulse or continuous-wave lasers, femtosecond (fs) laser micromachining offers several key advantages due to its unique characteristics of ultrashort pulse width and extremely high peak intensity. The advantages include reduction of heat-affected zone formation around the irradiated area, high spatial resolution beyond the diffraction limit and versatility in terms of the materials that can be processed (Chichkov *et al.*, 1996; Gattass and Mazur, 2008; Sugioka and Cheng, 2014). Therefore, fs laser has been extensively exploited to process micro/nano structure on metallic material (Yang *et al.*, 2013; Jung-Kyu *et al.*, 2012; Ahmmed *et al.*, 2014). Femtosecond laser surface processing became one of the best ways to create surface structures at nano- and micro-scales on metals due to its flexibility, simplicity and controllability in creating various types of nano/microstructures that are suitable for a wide range of applications (Anatoliy and Guo, 2013). Femtosecond laser-induced surface texture showed good lubricating property in sliding contact friction pairs and potential benefit for tribological applications (Bonse *et al.*, 2014; Ancona *et al.*, 2014). Therefore, efficient use of fs laser for 20CrNiMo/beryllium bronze material micro/nano structure processing is a prerequisite and the basis of optimizing tribological properties of rock bit bearing. Kango and Sharma (2010) investigated the combined influence of surface texture and non-Newtonian lubricants. It showed that shear thickening fluids and surface textures significantly affected the performance characteristics of bearings. Michael *et al.* developed a precision-aligned setup for a gap-controlled tribo-rheometry-based rotational rheometer, which allowed for the exploration of micro-texture and non-Newtonian fluid co-designs. The results indicated that micro-textured surfaces reduced friction under gap-controlled conditions (Johnston *et al.*, 2015). Satish *et al.* investigated the effects of spherical and conical micro-dimple geometries on the performance characteristics of textured hybrid thrust bearings operating with non-Newtonian lubricant using the modified Reynolds equation and finite element method, which indicated that the load-carrying capacity and lubrication properties of the textured hybrid thrust bearings were significantly affected by the behaviors of the non-Newtonian lubricant (Sharma and Yadav, 2014). However, it has found little study of fs laser surface texturing in friction reduction of rock bit sliding bearing under high temperature, heavy load and non-Newtonian lubrication conditions.

The purpose of this paper is to explore the application of fs laser surface texturing on mating components of rock bit sliding bearings, by focusing on the effects of fs laser power and pulse numbers on geometrical characteristics of the surface textures, and comparing the tribological behavior of textured surface and un-textured surfaces in high temperature, heavy load and non-Newtonian lubrication conditions. The results showed that fs laser micromachining provided potential possibilities for applications of surface texture in life improvement of rock bit bearing.

2. Experiment

2.1 Femtosecond surface texturing processing

In this experiment, the disc specimen, with a size of outside diameter of 54 mm, internal diameter of 38 mm and a thickness of 10 mm, was made of beryllium bronze. The surface, which was polished using 2.5-μm diamond suspensions, has a roughness of Ra 0.06 μm (YDYQ, Inc., JB-8C). The hardness of the disc sample, measured with a hardness meter (Shanghai Taiming Optical instrument co., Ltd, HXD-1000TM), was approximately HRC36 using a diamond indenter at 500 mN load. The specimen was cleaned in acetone for 10 minutes using an ultrasonic bath before and after fs-laser machining and stored in a desiccator to avoid chemical reactions with the ambient air atmosphere.

The textured specimens prepared are shown in Figure 1(a), and Figure 1(b) is the partial enlarged view, in which L

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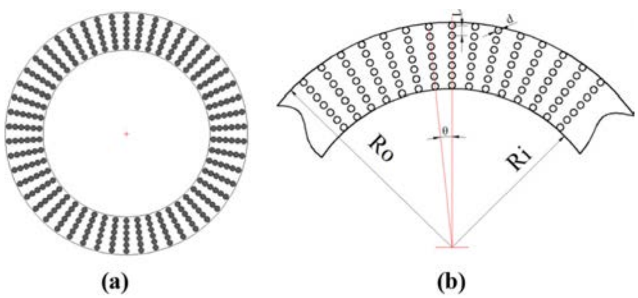
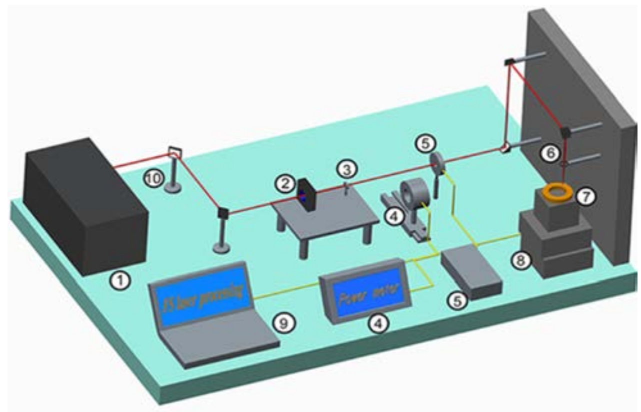
Figure 1 The shape and arrangement of femtosecond laser texture



Notes: (a) Whole distribution view; (b) partial enlarged view

Figure 2 Femtosecond laser processing schematic diagram



Notes: (1) Femtosecond laser; (2) neutral density filter; (3) aperture; (4) power meter; (5) shutter and controller; (6) focusing lens; (7) sample; (8) 3-D translation stage; (9) computer; (10) mirror

denotes the center distance of adjacent texture in radial direction and θ denotes the angle of line connecting between the adjacent texture center and the disc specimen center in the circumferential direction. Table I shows the geometrical parameters for conical texture. Note that the specimen C is a smooth plain which is made for comparison purpose. Texture arrangement in disc specimens is kept uniform in distribution, while the dimple diameters and the number of conical dimples are changed to obtain the desired texture density ratio, which is defined as:

$$R_p = \frac{S_P}{S} = \frac{Nr_P^2}{(r_o^2 - r_i^2)} \quad (1)$$

Where, S_P is the total dimple area, S is the total surface area, N is the total number of conical dimples, r_p denotes the texture radius and r_i and r_o are the disc's inner and outer radius, respectively.

Surface textures on beryllium bronze specimens were fabricated by using an fs laser micromachining system, which consists of an fs laser source (Coherent, Inc., center wavelength: 800 nm, pulse width: 40 fs, repetition rate: 1 kHz), a computer-controlled XYZ translation stage, beam control devices and optics delivery, as shown in Figure 2. The Gaussian laser beam with an initial 8.8 mm diameter was trimmed by a 6-mm-diameter circular aperture to produce a high-quality beam for fabrication. The laser pulse energy was adjusted by a set of neutral density filters. The laser pulse energies were measured with a power meter (Coherent, Lab Max) equipped with a thermopile sensor (Coherent, PM model). The exposure time was controlled by a laser shutter and controller (UNIBLITZ® LS6 series shutters). The laser beam travels along the red line and focuses on the sample surfaces using a lens with 80 mm focal length to give a spot diameter of about 0.4 μm at the focal plane. For minimizing the pulse duration of fs laser pulses at the target, dispersion pre-compensation was performed by adjusting the grating separation in the pulse compressor, and the pulse duration of the fs laser was then characterized by use of an interferometric autocorrelation. The optimized pulse duration is about 40 $\pm$ 5 fs. Disc specimens were mounted on an X-Y-Z translation stage (Olympus, with a resolution of 1 μm) and placed normal to the incident laser beam aimed to reduce the nonlinear effects induced by the fs-laser beam in air. A relative motion between the laser beam and the samples was achieved by a computer-controlled three-dimensional (3D) translation stage. So, the geometrical features of surface texture such as shape, orientation, array, size and depth can be controlled by changing the parameters of the laser and X-Y-Z stage translation. All the fs laser micromachining was done in air and at atmospheric pressure. Morphology of fs-laser-ablated surface regions was characterized by optical microscopy (OLYMPUS, DSX 500) equipped with a 3D imaging surface structure analyzer and scanning electron microscope (Zeiss Auriga 40).

The calculated formula of fs laser focal spot radius is as follows (Mannion *et al.*, 2004):

$$w_o = l * \frac{\lambda}{(pi * d)} \quad (2)$$

Where l is the focal length, w_o is focal spot radius, parameter λ is wavelength of the laser and d is the incident laser beam diameter onto the focusing lens.

The focal spot area, S, is expressed as follows:

$$S = pi * w_o^2 \quad (3)$$

Table I Parameters of microstructures by femtosecond laser micromachining

No.	Texture diameter (μm)	Texture depth (μm)	Depth-to-diameter ratio (χ)	Texture density (%)	Specimen OD (mm)	Specimen ID (mm)
A	169.266	28.007	0.165	5	54	38
B	70.398	33.983	0.483	5	54	38
C	0	0	0	0	54	38

The single pulse energy is calculated as:

$$E_p = \frac{P}{f} \tag{4}$$

Where P (W) is the average power of the laser beam measured by a power meter, and f (Hz) is the frequency (also called repetition rate) of the laser.

Laser fluence, F_l, is defined as:

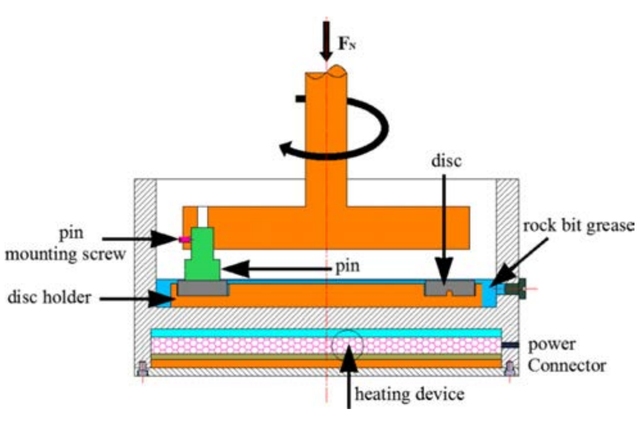
$$F_l = \frac{E_p}{w_P \times S} \tag{5}$$

Where w_p is pulse width.

2.2 Tribological testing

In the literature (Wang *et al.*, 2014), the pin-on-disc model was proposed to study the tribological behavior of sliding bearing. In this experiment, the tribological tests of rock bit bearing were performed in a tribometer (Jinan Chenda Inc., MDW-1) by sliding tribo-pairs with a pin-on-disc configuration under boundary lubrication (as shown in Figure 3). The tribological test of pin-on-disc configuration of rock bit bearing utilizes non-Newtonian lubricant of rock bit grease (RBG). Under the high temperature of 120°C, the dynamic viscosity varied with shear rate is shown in Table II. During the tribological test, the RBG was supplied in a lubricated cup through a pressure pump and kept liquid level over frictional interface 1 mm in the whole testing. The friction coefficient of sliding tribo-pairs with a pin-on-disc configuration against η U/W under the heavy load of 975 N is between 0.080 and 0.075, which reveals that the system is in the regime known as boundary lubrication (Hutchings, 1992). The pin specimens was made of 20CrNiMo, which had a diameter of 8 mm and height of 8 mm, with roughness of Ra 0.08 μm and surface hardness of 60 HRC. The disc specimen was fixed in the disc holder and the frictional radius (the distance from the center line of disc to the center line of pin) was set at 23 mm. All the tests were carried out under boundary lubricating regime with normal load of 975 N (equivalent to the pressure of 20MPa) and lubrication temperature of 120°C to mimic rock bit bearing realistic conditions. During the tribological tests, the sliding speed was decreased stepwise from the velocity of 1.657 to 0.09 m/s, holding each of the six steps for 300 s. The measurement was repeated three times with complete new pin and disc. So the friction coefficient at each sliding speed was the mean value of tests. The dynamic viscosity of RBG was measured by a HAAKE VT500 rotational rheometer from Thermo Scientific (Li *et al.*, 2006), which was varied from 0.378 Pa.s at shear ratio of 99.92 s^{-1} to 0.08166 Pa.s at shear ratio of 1,301 s^{-1}. Shear rheology schematic diagram of rock bit bearing grease is shown in Figure 4; the equation of shear rate $\dot{\gamma}$ was as follows:

Figure 3 Tribological tests of rock bearing unit tribo-pairs



$$\dot{\gamma} = \frac{dv}{dy} \tag{6}$$

Where, v is flow rate of lubrication medium, and y is clearance height.

3. Result and discussion

3.1 Effect of fs laser on texture geometry parameter

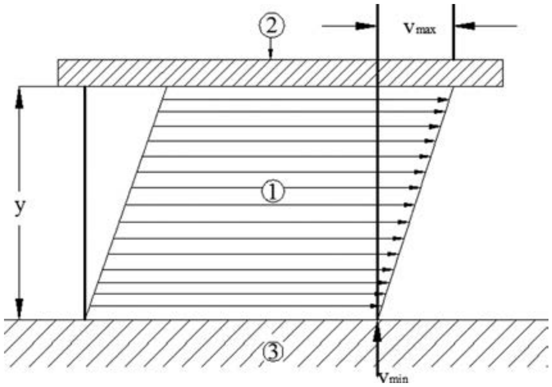
The fs laser-induced surface textures were observed using optical microscopy (OLYMPUS, DSX 500) and scanning electron microscopy (Zeiss Auriga 40). 3D morphology and sectional dimensions of a microstructure are shown in Figure 5. The surface of A# specimen was irradiated with laser fluence of 1.3 × 10^{18} W/cm^2 and exposure time of 220 ms (220 pulses). The shape, depth and diameter parameters were measured by OLYMPUS optical microscopy. The profile of ablated microstructure indicated that there were no bulges at the texture edge region [see Figure 5 (a and c)]. Similarly, the surface texture of B# specimen was obtained with laser fluence of 0.3 × 10^{18} W/cm^2 and exposure time of 200 ms (200 pulses) [as shown in Figure 5 (b and c)]. Compared with A# specimen, the geometric observation of fs laser-induced microstructures showed that parameters of fs laser fluence and exposure time had important influence on the depth and diameter parameters of microstructures. Measurements of fs laser texturing showed that the texture depth of A# specimen at a higher laser fluence is less than B# specimen at the lower laser fluence (as shown in Table I and Figure 5), it was because the fs laser fluence and processing were affected by transient defocusing of the fs-laser beam by Kerr-effect, which changed the spatial energy distribution of the fs-laser beam. So, the effect of the numbers of pulses on texture size, as well as the increasing laser fluence, should be investigated for disc specimens.

The effect of laser fluence and number of pulses on the evolution of diameter as well as depth was studied. Femtosecond laser fluence was fixed at 0.5 × 10^{18}, 1.5 × 10^{18} and 2.5 × 10^{18} W/cm^2, respectively. The number of pulses

Table II Dynamic viscosity value of RBG under 120°C

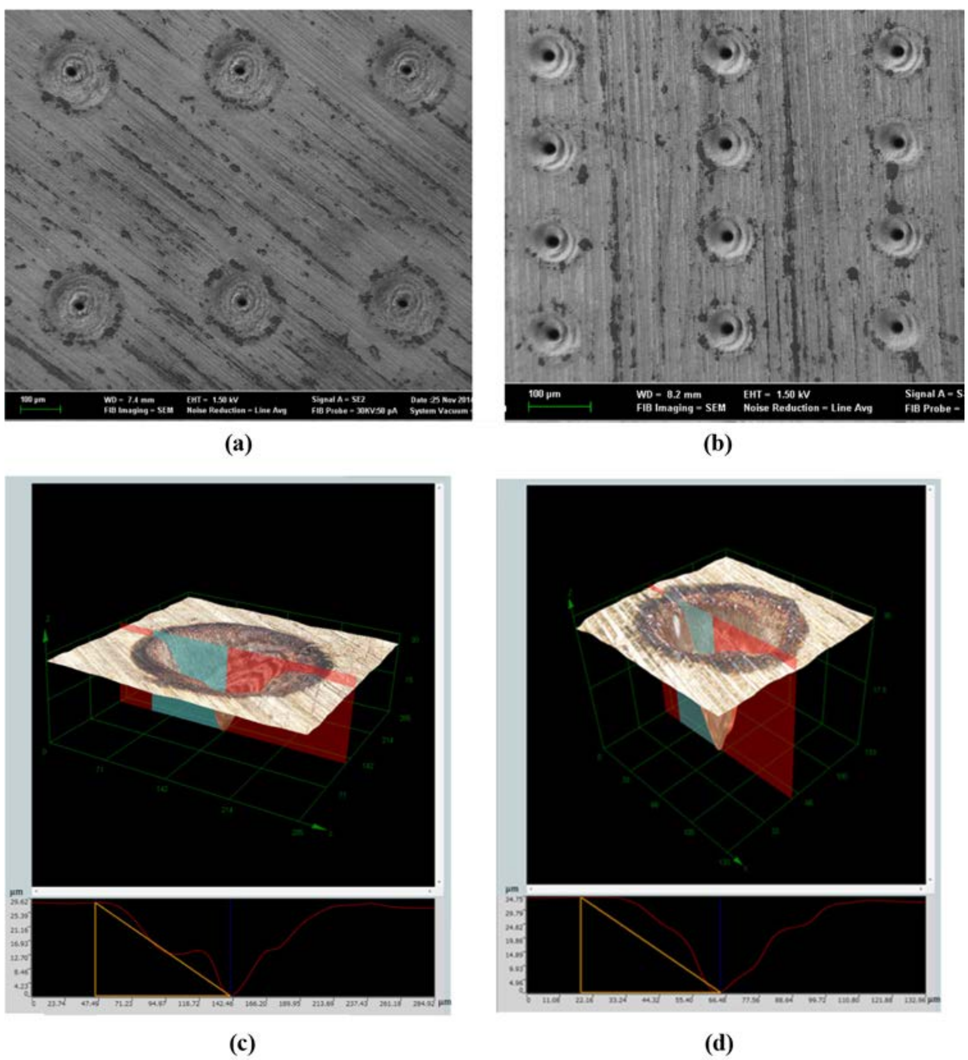
Shear rate (S^{-1})	99.92	500.1	699.7	898.6	1,102	1,301
Linear velocity (m/s)	0.089	0.446	0.624	0.802	0.982	1.651
Dynamic viscosity (Pa.s)	0.3478	0.1269	0.1064	0.09447	0.08765	0.08166

Figure 4 Shear rheology schematic diagram of rock bit bearing grease



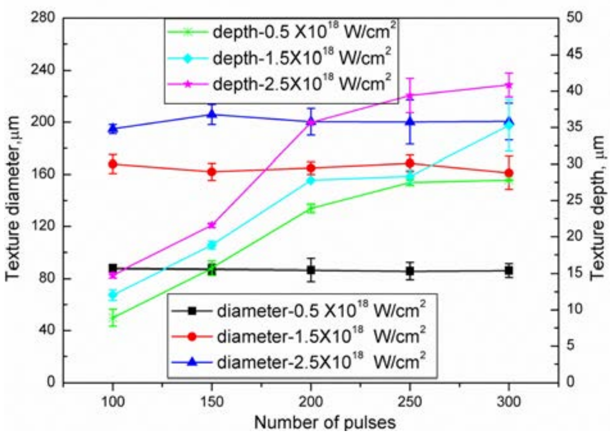
was varied from 100 to 300 with 50 intervals during six points of irradiation; also, the micromachining was repeated three times with the same laser parameters in three different regions of disc specimen surface. The effect of laser parameters on micromachining texture was evaluated with the average value. The curves of texture diameter and depth were plotted against laser pulses in Figure 6. The experimental results indicated that the depth of surface textures increased with the number of pulses at the fixed laser fluence of 0.5×10^{18}, 1.5×10^{18} and 2.5×10^{18} W/cm^2. However, the number of laser pulses had less influence on the texture diameter. Under the same number of pulses, texture depth increased with laser fluence for measured laser fluence, and the larger laser fluence produced greater diameter of surface texture between 0.5×10^{18} and 2.5×10^{18} W/cm^2 (Figure 6). According to the literature (Mannion *et al.*, 2004), the diameter of laser-ablated dimples varied with the number of laser shots for metal materials, which obey the change mechanism of equation (8).

Figure 5 3D morphology and SEM of femtosecond laser-induced surface texture



Notes: (a) SEM of A# specimen local region; (b) SEM of B# specimen local region; (c) 3D morphology of A# single dimple; (d) 3D morphology of B# single dimple

Figure 6 Curves of the diameter and depth of laser-induced microstructure plotted as a function of increasing pulses number



Compared with the influencing factors of incubation coefficients and single-shot ablation thresholds of irradiated metal material for fixed laser fluence, it can be seen that laser pulses do not influence the diameter of the irradiated dimples for the testing laser fluence when the number of laser pulses is more than 100. The experiments of surface texture by fs laser micromachining indicated that geometrical parameters of laser-induced microstructures can be precisely controlled and optimized by adjusting the laser parameter, and Kerr-effect should be considered in fs laser ablation.

The peak fluence, Φ_0, is directly related by:

$$\Phi_0 = \frac{2E_p}{\pi w_0^2} \tag{7}$$

Where w_0 is the radius of focal spot.

The diameter, D, of ablated dimples is defined as follows:

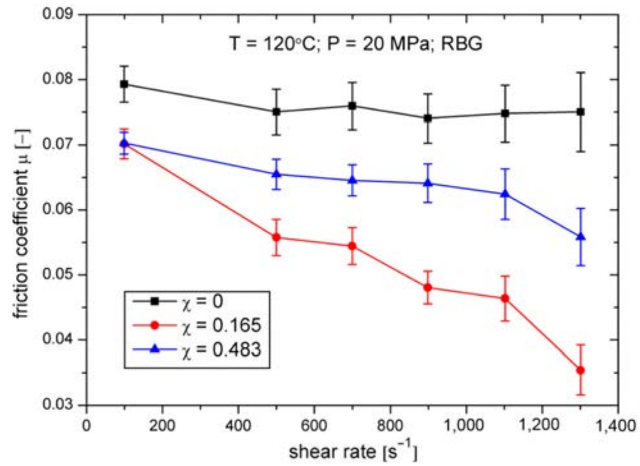
$$D = w_0\sqrt{2\ln\left(\frac{\Phi_0}{\Phi_{th}(1)N^{S-1}}\right)} \tag{8}$$

Where $\Phi_{th}(1)$ is the single-shot ablation threshold value, S denotes the incubation coefficients of ablated metal material and N is the number of laser pulses.

3.2 Effect of shear rate on friction of rock bit bearing tribo-pairs

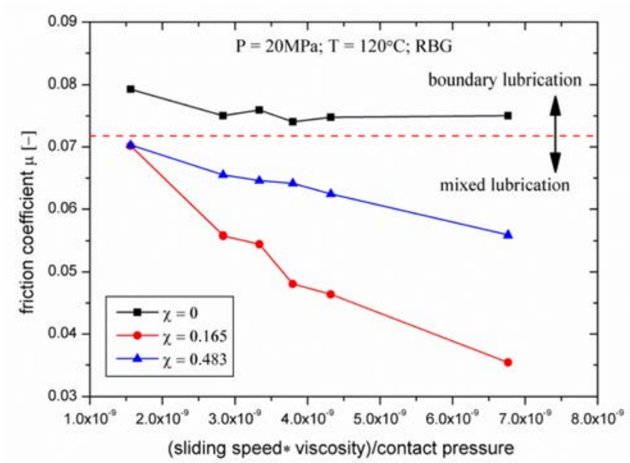
The friction coefficient, depending on shear rate, was tested by using a pin-on-disc configuration, comparing un-textured specimen with different depth-to-diameter ratio textured specimens, respectively. The parameters of surface texture are presented in Table I. During the tribological tests, texture density ratio was kept at constant of 5 per cent. The variations of friction coefficient with shear rate are shown in Figure 7. Clearly, textured surfaces with depth-to-diameter ratio of 0.165 and 0.483 showed lower friction. For un-textured specimens, the friction coefficient decreased with the increase in shear rate and tended toward stability when the shear rate was more than 500 s^{-1}. It was because that the rheological properties of RBG appeared typical BinHam fluid and shear thinning effect, suitable for high temperature (> 100°C) and

Figure 7 Curves of friction coefficient versus shear rate, for textured and un-textured discs with area density of 5 per cent, $p = 20$ MPa and T = 120°C



high shear rate (> 500 s^{-1}). Dynamic viscosity changed fast under low shear rate; meanwhile, the variation of RBG viscosity tended to be gentle when the shear rate was higher than 500 s^{-1}. However, the friction coefficient of textured specimens decreased monotonically with the increase in shear rate under the heavy load of 975 N and high temperature of 120°C. Moreover, the lubricating property of the textured specimen with $\chi = 0.165$ was optimal, which was consistent with research results that for a specified dimple area density, the performance of the dimpled specimen is related to dimple depth-to-diameter ratio, and an optimum χ exists if the dimple density remains fixed (Qiu and Khonsari, 2009). This was mainly because that fs laser-induced surface texture with appropriate parameters was not only beneficial to reduce the shear stress of RBG but also favorable to improve the boundary lubrication state under high temperature and heavy load conditions. The research of surface texture on tribological behavior under boundary lubrication showed that micro dimples revealed obvious friction reduction effect under low speed and heavy load (Yu *et al.*, 2013). The curve of friction coefficient varied with the Stribeck parameter is shown in Figure 8. Wen *et al.* put forward an evaluation method of lubrication state by comparing Stribeck curve with typical value of friction coefficient (Wen and Huang, 2008). According to the position of friction coefficient in typical value intervals, un-textured pin-on-disc configuration ($\chi = 0$) was evaluated in boundary lubrication state. However, there was a significant transition from boundary to mixed lubrication for the optimal textured specimens ($\chi = 0.165$ and $\chi = 0.483$ at the texture density of 5 per cent). It also hinted that the parameter of depth-to-diameter ratio, for RBG at 120°C, can be optimized to build up the load capacity of 20CrNiMo/beryllium bronze friction under the contact pressure of 20 MPa. Moreover, it was proved that fs laser-induced surface texture was an effective means to improve the lubrication and wear resistance of unit tribo-pairs of rock bit sliding bearing under high temperature and heavy load conditions. Bonse *et al.* reported that fs laser surface structuring had potential benefit for tribological applications (Bonse *et al.*, 2014). Due

Figure 8 Friction coefficient plotted against the Stribeck parameter [(sliding speed × viscosity)/contact pressure] for a selection of results (χ = 0, χ = 0.165 and χ = 0.483) under the conditions (p = 20 MPa; T = 120°C; RBG)



to the ablation microstructure on unit disc specimen surfaces of rock bit bearing acting as reservoirs of RBG and capturing some wear debris, it improves lubricating properties of tribo-pairs of rock bit sliding bearing under harsh conditions, especially reducing shear stress of lubricating film between sliding surface under high temperature and heavy load conditions.

4. Conclusion

An effective laser texturing processing on beryllium bronze disc specimens of rock bit bearing was achieved by using a fs laser. The diameter and depth parameters of micromachining periodic conical dimples were efficiently controlled by adjusting fs laser parameters. Tribological tests under boundary lubrication were performed with pin-on-disc configuration with RBG lubrication at the heavy load of 975 N and high temperature of 120°C. The texture density was kept at constant of 5 per cent, and depth-to-diameter ratio was 0.165 and 0.483. The results showed that rheological property of RBG and depth-to-diameter ratio parameters had a significant impact on the lubrication performance of tribo-pairs of rock bit bearing, which were made of 20 CrNiMo and beryllium bronze, respectively:

- Femtosecond laser micromachining is an effective way to optimize the geometrical features of conical micro dimples on beryllium bronze disc specimens through adjusting laser fluence and the number of pulses. Under the testing parameters, the depth of micro dimples increases with laser fluence and the number of pulses and the diameter of micro dimples mainly are affected by laser fluence.
- Under high temperature of 120°C, heavy load of 975 N and non-Newtonian lubrication of RBG conditions, dimple depth-to-diameter ratio has an obvious effect on friction reduction, and there exists an optimized depth-to-diameter ratio of 0.165 for a fixed area density of 5 per cent. Compared to un-textured specimens, the optimal depth-to-diameter ratio obtains friction reduction of 52.8 per cent at shear rate of $1301 s^{-1}$.
- The shear rate of RBG has an important influence on the tribological behavior of pin-on-disc mating pairs of rock bit bearing, and the friction coefficient of textured tribo-pairs with depth-to-diameter ratio of 0.165 and 0.483 decreases with the increase in shear rate for RBG. Compared to un-textured specimens, the lubrication regime of textured mating pairs of rock bit bearing has been improved from boundary to mixed lubrication.

To sum up, through experimental study of fs laser processing and tribological testing of rock bit bearing unit tribo-pairs, it can be concluded that fs laser-irradiated surface texture has the potential possibility for application in rock bit sliding bearing to improve the lubrication performance. However, the effect of textured geometric features and arrangement on the tribological behaviors needs to be further investigated under high temperature, heavy load and non-Newtonian lubrication conditions.

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