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The effect of laser surface texturing on frictional performance of sliding pair

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Abstract
In this paper, a Nd:YAG laser was used to generate micropores on SiC surface and the structure and morphology features of surface micropores were observed. Tribological experiments were conducted with pin-on-disc tester under various loads and speeds. The article concentrates on identification of friction processes and also attempts to find a correlation between surface energy, friction force and topography of surface with geometrical texture.

Introduction

Energy losses resulting from friction between contact surfaces in an internal combustion engine have been studied intensively by a considerable number of tribologists. Progress in this field has brought numerous economically effective solutions, which enable mass production of motor vehicles. Still, the automotive industry needs further improvements to reduce friction-related energy losses in engines and drive systems. For instance, the losses of energy generated in a piston-ring-cylinder system account for 45% of all the losses of energy due to friction in the whole engine. Numerous reports suggest that the problem can be solved by applying porous surfaces generated, for example, by laser surface texturing.

The first publication on surface texturing appeared in Germany in 1995 [1]. It discussed the use of an excimer laser to texture elements of a magnetic memory disk drive with the aim of reducing friction at the start. Further experiments in this area involved texturing surfaces of punches applied to plastic forming. It was found that the process caused a 169% increase in the punch service life.

The current studies focus on the influence of texturing on the performance of various friction systems in internal combustion engines, e.g. precision bearing systems. Texturing is used to improve heat removal, vaporization, wettability, biological functions, absorptivity, etc.

Reference [2] compares results of tribological tests conducted by means of pin-on-disk devices, where the disk surfaces were polished, ground and textured (using three methods of texturing). The textured surface was covered with laser-generated pores, 4–6.5 μm in depth and 58–80 μm in diameter. Numerous tests show that texturing can be used to extend the ranges of load and sliding velocity within which hydrodynamic lubrication occurs. The hydrodynamic lubrication is observed when low- and high-viscosity lubricants are applied. Another finding is that the rough rims of cavities produced by laser beams need to be removed by lapping to ensure an optimal hydrodynamic effect. A comparative analysis was conducted to determine the friction coefficients for the polished, ground and textured surfaces. The effects of laser texturing were most visible when the values of sliding velocity were low, ranging between 0.075 and 0.3 m/s. Moreover, the high density of cavities was responsible for an increase in the friction coefficient. The results presented in the form of Stribeck curves illustrate that there was a significant reduction in friction for lubricated friction pairs operating in the boundary regime of friction.

The tests described in Ref. [3] aimed at determining the effect of laser texturing on the performance of a ring being in contact with a cylinder liner. Pores with diameters of 75–78 μm and depths of 7–9 μm covered the whole or parts of the ring surface. The pore area coverage ranged between 10 and 50%. The friction observed for textured surfaces was lower than that for non-textured ones. The greatest falls in friction were reported for a pore area coverage of 30%; they were 40–45% and 23–35% for a rotational speed of 500 rev/min and 1200 rev/min, respectively. It should be noted that the decrease in friction was greater for a partly textured ring. This reduction (12–29%) was observed in the whole range of loads and rotational speeds.

Reference [4] discusses results of in-service tests conducted for face seals with textured carbide rings used in the petrochemical industry. The results were positive, because there was a decrease in the process temperature and an increase in the ring service life. Reference [5] illustrates that laser surface texturing caused an improvement in fretting fatigue life of steel tool elements.

This analysis shows that the effects of laser texturing were measured at pre-determined parameters of performance of the sliding pair; the pore depth and diameter (or their ratio) and the pore area coverage were the most significant parameters of texturing. It was found that effective reduction in friction could be obtained also for partially porous surfaces. The problems to be solved in further research include determining precisely the relations between the texturing parameters, ring geometry, and the parameters of performance of the friction system for which the desired reduction in friction occurs. The current research focuses on establishing the effect of laser surface texturing on the mechanical properties of materials, particularly their fatigue strength.

Laser surface texturing

Laser surface texturing is one of the most common and promising methods of surface roughening. Categorized as a metal removal process, laser texturing is usually performed at a power density of 10^6–10^9 W/cm^2. At present, it accounts for about 2% of all laser-based material processing processes used in the world. In laser surface texturing, a pulsed laser beam is focused on a material to melt a hole. The hole depth is dependent mainly on the power density and the pulse duration. The drilling debris is removed from a hole being drilled using compressed air or another inert gas.

The surfaces of the rings were textured using a diode-pumped Nd:YAG laser, designed for the production of printed circuit boards. The laser emits ultraviolet light, and the wavelengths are specially selected to assure the most effective machining of copper. The maximum power of the laser beam is 2 W. The laser can be applied to drill microholes in laminates, for instance, copper-clad laminates, which are used for printed circuit boards. The device can be employed also to cut or drill holes in other materials; the maximum beam power, however, limits its application. It is suitable for cutting metal foils: steel and nickel up to 100 μm in thickness, and copper up to 200 μm in thickness. The maximum hit rate for this type of laser is more than 20,000 holes per hour. The focal spot size is 25 μm.

The application of a laser beam causes laser ablation of the material. The photon energy is converted on the material surface into electron, thermal and mechanical energies. In consequence, the material in contact with the laser beam is vapourized and removed from the solid surface in the form of neutral atoms and molecules, and positive and negative ions.

The tests were conducted for SiC rings (certificate of material excellence) with the following dimensions: an outer diameter d_o of 35.3 mm, an inner diameter d_i of 25.1 mm, and a height h of 7 mm. The texturing was performed using an ESI 5200 Nd:YAG laser (pulse mode). The wavelength $\lambda = 355$ nm (the laser uses radiation at the third harmonic frequency).

Device performance characteristic ESI laser:

Producer:	Electro Scientific Industries
Type of device:	Model 5200
Type of laser:	diode-pumped Nd:YAG laser, UV [355 nm]
Peak power:	>15 kW for 3 kHz
Pulse width:	30 ns for 3 kHz
Frequency:	100 Hz ÷ 20 kHz
Field size:	533 mm × 635 mm

The parameters of the laser surface texturing process were determined basing on the experimental results: the laser spot diameter $d = 0.78 \div 150$ μm; the laser power $P = 0.37 \div 0.4$ W; the laser beam velocity $V = 15.7 \div 23.56$ mm/s; the distance from the focus $\Delta f = 0$ mm; and the repetition frequency $f = 6400$ Hz.

The process of texturing was performed in two stages (two steps). In the fist step, holes with a predetermined diameter were drilled along a spiral path. In the second step, the drilling debris was removed from each pore, with the number and frequency of pulses being strictly defined The results of the laser surface texturing process are shown in tables 1 and figures 1 and 2.

Table 1. Parameter characterizing the geometrical surface texture on the face surface of a ring with d_o = 35.3 mm and d_i = 25.1 mm

Sample No.	Pore diameter $2R$ [μm]	Distance between pores S_m [μm]	Pore area [mm^2]	Pore area coverage [%]	Number of pores k [pcs]	Pore depth [μm]	Pore volume [mm^3]
1	78	162	88.106	18.208	18440	13	0.693
2	134	279	87.024	17.985	6216	13	0.668
3	78	106	205.740	42.520	43060	13	1.619
4	134	183	202.300	41.808	14450	13	1.553
5	150	256	132.894	27.464	7383	13	0.992
6	70	119	131.486	27.173	34170	13	1.047
7	102	128	241.698	49.951	29530	13	1.865
8	102	233	72.828	15.051	8913	13	0.562
9	102	174	130.572	26.985	15980	13	1.008
10	102	174	130.572	26.985	15980	13	1.008

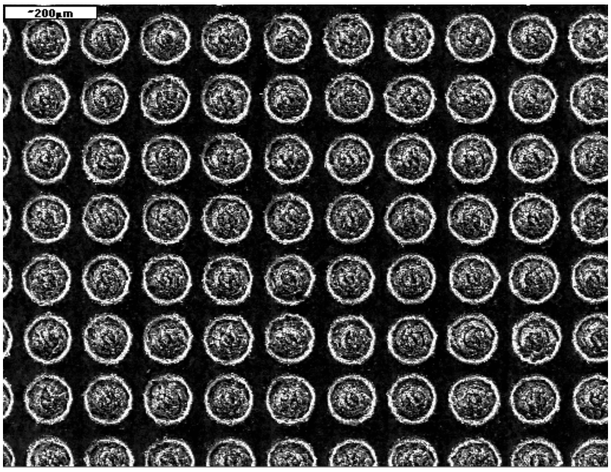

Fig. 1. A view of a system of pores on a SiC ring; pore area coverage – 42% (magnification ×100)

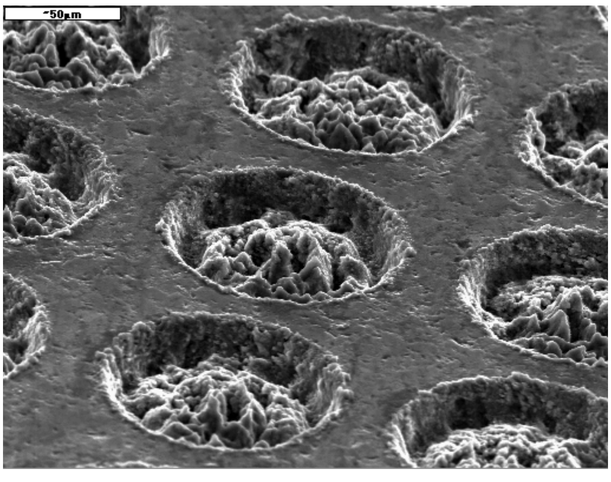

Fig. 2. A view of pores on the SiC ring

The main stage of the process was drilling a pore with a predetermined shape, diameter, and depth. The material processed was particularly susceptible to the action of the laser beam. Ablation occurred at low beam energy.

A Joel JSM-5400 scanning electron microscope was used to study the effects of laser surface texturing. Selected SEM images are presented in figures 1, 2. As can be seen, the surface structure after laser surface texturing is regular. The surface is covered by bumps and dimples resulting from phase and structural modifications and the accompanying specific volume changes in the laser affected zones.

Lapping and superfinish are used to obtain hard flat areas transferring normal loads and areas of pores where the hydrodynamic forces are generated during fluid lubrication. Surfaces with such a texture can be applied, for instance, to sliding friction systems.

The microscopic analysis showed that the removal of the drilling debris was not complete when the laser beam was focused locally. This was probably due to insufficient power density. The action of the thermocapillary forces and the convective motion resulted in the formation of rims, whose structure consisted of molten and then crystallized SiC. The images in figures 1 and 2 show textured surfaces of the ring before and after ultrasonic cleaning.

Pores generated with the aim of improving the tribological properties of the material were arranged regularly. In this analysis, we deal with a two-directional symmetry. It can be assumed that surface modelling involves producing blind holes in the shape of a cylinder or, more frequently, a truncated cone.

- The process of laser surface texturing performed by means of an ESI 5200 Nd:YAG laser μvia drill can be applied to produce predetermined pore patterns on sliding surfaces. Pores on metallic materials are reproducible in shape and depth; for SiC, reproducibility may reach a value of the order of several dozen μm.
- The software of the ESI 5200 Nd:YAG laser μvia drill can be used for texturing flat surfaces. Special-purpose equipment and software need to

be applied to texture cylindrical and other curvilinear surfaces.
- The pore shape is limited by the software used. Standard procedures allow drilling circular holes. Specially developed programs are necessary to drill holes other than circular.

Adhesion properties of the textured surface

Wetting and surface energy have been studied by researchers from different fields, including physics, chemistry, materials engineering and biotechnology. In some industrial processes such as gluing, sealing, painting, printing and depositing various protective coatings, knowledge of the wetting behaviour of a material is crucial. Wetting can be assessed using different measuring liquids. One of the most common methods for determining the contact angle for engineering materials is based on the drop geometry. The tests were conducted on SiC samples, whose basic geometric parameters are presented in table 2.

Table 2. Texture parameters of the ring-shaped samples

Sample No.	Pore diameter d [µm]	Interpore distance L [µm]	Pore area coverage [%]	Contact angle		Total surface energy [mJ/m]
				For water	For DIM	
1	78	162	18.2	56.03	38.11	60.6
2	134	279	17.9	54.12	32.47	63.4
3	78	106	42.5	67.49	34.44	56.2
4	134	183	41.8	69.94	32.15	55.9
5	150	256	27.4	66.72	34.16	56.7
6	70	119	27.1	70.16	31.66	55.9
7	102	128	49.9	67.69	26.06	58.8
8	102	233	15.1	59.52	32.01	60.9
9	102	174	26.9	67.89	32.95	56.5
10	102	174	26.9	66.7	34.02	56.8

A droplet placed on a surface has the shape of a spherical cap, thus the contact angle is calculated by measuring the height of the cap h and the radius of the drop base r. The height of the cap is defined by the formula $h = R(1 - \cos\Theta)$, whereas the radius of the droplet base is given by $r = R\sin\Theta$. From these relations we obtain:

$$\Theta = \frac{2h}{r} \tag{1}$$

Interfacial energy of engineering materials is determined in an indirect way by measuring the contact angles by means of suitable measuring liquids. The liquids used in this analysis were distilled water and diiodomethane (DIM). The drop geometry and the contact angle were analyzed using a stereoscopic microscope with a camera and MicroScan v. 1.3 software.

Tribological analysis

The tribological analysis was conducted using a pin-on-disc tribometer. A ring-shaped SiC sample with a laser-textured face was applied as the disc. The sample parameters are presented in table 1. The pin was a truncated ball (Φ6.3) made of bearing steel fitted in an articulated fixture. The diameter of the flat surface obtained by ball truncation was 4.5 mm. The tests were conducted on ring-shaped samples single-lubricated with paraffin oil at variable revolutions ranging from 100 to 700 rev/min and variable loads ranging from 4.9 to 39.2 N.
Using the results of previous investigations [2] and various publications on the subject, e.g. Ref. [1, 6], we can assume that, in the case of a friction pair with a textured surface, the lubrication effectiveness should be considered separately in two different areas, i.e. fluid friction and mixed friction, according to the operating parameters (sliding rate, load, lubricant viscosity). Low sliding rates do not contribute to the occurrence of hydrodynamic effects on single texture elements. In such areas, it is the pore effect that ensures good lubrication in time proportional to the micropore volume. The surface texture is fully utilized for such matching of the parameters $p{\cdot}v$ when hydrodynamic (full film) lubrication occurs, which ensures high load-bearing capacity of the friction pair. In Reference [2], friction maps were plotted for each sample of the analyzed friction pair; they defined the set of parameters $p{\cdot}v$ for which there was an increase in the hydrodynamic load-bearing capacity (Fig. 3).

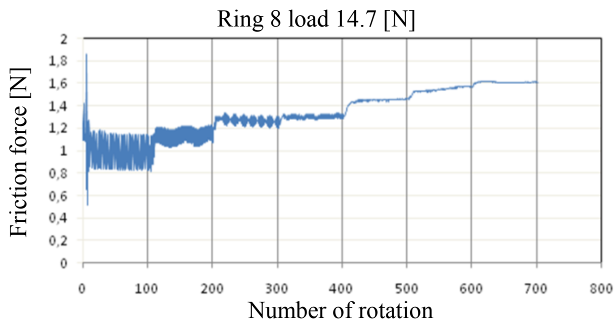

Fig. 3. An overview of the test cycle

The tests also aimed at assessing the relation between the texture parameters and the frictional resistance of areas where hydrodynamic effects were observed. The quantities analyzed included: pore diameter (d), pore area coverage (S_p), edge-to-edge distance (L–d) and interfacial energy (γ). The Statistica program was used to perform a multiple regression analysis in order to determine which of the characteristics considered had the greatest influence on the changes in the friction coefficient.

Conclusions

1. Changes in the texture parameters resulted in changes in the values of the contact angle and surface energy.
2. The analysis of the correlations between the texture parameters and the adhesion parameters showed that the interfacial energy was most affected by the edge-to-edge distance *L–d*.
3. When *L–d* was less than 80 µm, there were slight changes in the surface energy. On the other hand, an increase in *L–d* above that value, led to a rapid increase in the surface energy.
4. The texture parameter that had the largest influence on the friction coefficient in areas where hydrodynamic phenomena took place was surface energy. The next of importance were the pore area coverage (S_p) and the edge-to-edge distance (*L–d*).

References

1. ETSION I.: State of the Art in Laser Surface Texturing. Transaction of the ASME, January 2005, vol. 127.
2. ANTOSZEWSKI B.: A non-conventional metod for the improvement of the functional properties of sliding pairs. Eksploatacja i Niezawodność (Maintenance and Reliability), Nr 3(35), 2007, 57–62.
3. KOVALCHENKO A., AJAYI A., ERDEMIR A., FENSKE G., ETISON I.: The effect of laser surface texturing on transitions in lubrication regimes during unidirectional sliding contact. Tribology International, 38(2005), 219–225.
4. ERDEMIR A.: Review of engineered tribological interfaces for improved boundary lubrication. Tribology International, 38(2005), 249–256.
5. MCGEOUGH J.A., RASMUSSEN H.: A theoretical model of electrodischarge texturing. Journal of Materials Processing Technology, 68(1997), 172–178.
6. YU X.Q., HE S., CAI R.L.: Frictional characteristics of mechanical seals with a laser textured seal face. Journal of Materials Processing Technology, 129(2002), 463–466.

Others

7. ETSION I.: A laser surface textured hydrostatic mechanical seal. Sealing Technology, March 2003.
8. VOLCHOK A., HALPERIN G., ETSION I.: The effect of surface regular microtopography on fretting fatigue life. Wear 235(2002), 509–515.
9. WAKUDA MANABU, YAMAUCHI YUKIHIKO, KANAZAKI SHUZO, YASUDA YOSHIRTERU: Effect of surface texturing on friction reduction between ceramic and steel materials under lubricated sliding contact. Wear, 254(2003), 356–363.