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The Effects of Dimple Distribution Angle on the Tribology Performance of a Laser Surface Textured Cylinder Piston Ring System

J. ZHAN* AND M-J. YANG

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

The effectiveness of the distribution angle of the dimples was researched by means of a wear test of cylinder liner/piston ring system. The wear of cylinder block was measured when the Nd:YAG laser-texturing dimples distribution angle was altered. According to comparing wear of the system the effect of dimples distribution angle to the wear of the system was discussed, and remaining depth to diameter ratio was 0.10 and area density was 20% unchanged essentially, the wear value of cylinder liner was lowest at the dimples distribution angle was 45°. It was found that the laser texturing could result in less wear rate compared to mechanical honing

Keywords: Nd:YAG laser, laser texturing, laser surface textured (LST), tribology, cylinder piston ring, dimples distribution angle, wear

1 INTRODUCTION

Cylinder liner and piston rings worked in high temperature, high-speed and high pressure conditions, which was prone to causing all kinds of wear. Since 1990 the researchers have began to study the effect of friction and wear behaviour after using laser micro-morphology, which could increase hydrodynamic lubrication oil load pressure and reduce friction coefficient of cylinder wall-piston ring. Laser texturing cylinder wall included two main morphologies: one was grooves mainly, which was beneficial to remove loose material particles, and the other was dimples mainly, for

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*Corresponding author: Tel: +86 (0)10 8254 4260; Fax: +86 (0)10 8254 4261;
E-mail: zhanjian@imech.ac.cn

increasing the oil reservoir and load pressure, and the collection ability of the wear particles.

Most of the total engine friction, about 50 to 60%, comes from the cylinder and piston ring system. The service life of the engine depends on this friction system to a large extend. The friction and wear characteristics of the cylinder/piston ring system have long been the focus of related research works.

Ronen *et al* [1] studied the piston ring-cylinder system with laser surface textured piston rings and found that a friction reduction of 30% or more was feasible with textured surfaces. Ryk *et al* [2] found good correlation in a subsequent experimental work, with two laser surface textured (LST) modes are available for reducing the friction loss. The first is the piston ring LST mode (concept proposed in Kligerman *et al* [3]) and the second is cylinder wall LST. Ryk *et al* [4] found that with LST barrel-shaped rings the reduction in friction was much less than that with flat specimen. Yu *et al* [5] found that the friction torque and friction coefficient of laser-textured mechanical seals with a porous face were much lower compared with conventional mechanical seals. Kovalchenko *et al* [6, 7] studied the impact of LST on lubricating-regime transitions and found that the beneficial effects of LST were more pronounced at higher speeds and loads and for oils with higher viscosity {6, 7].

Most of this research was focus on the dimples depth and area density, and there was no report about the research of the relationship between dimples distribution and the system friction wear. Since 2000 the Laser Texturing Centre in the Institute of Mechanics, Chinese Academy of Sciences, has put forward that the process of texturing dimples could achieve to fast speed and high efficiency, which had very important significance to internal combustion engine, based on laser texturing technology. This paper researched the effect of wear property with different laser texturing dimples distributions on the cylinder wall.

2 LUBRICATION THEORY FOR CYLINDER LINER/PISTON RING SYSTEM WITH LASER SURFACE TEXTURED DIMPLES

According to fluid lubrication theory the oil film pressure, P, of the system under full lubrication and high reciprocating velocity condition could be calculated by the Reynolds equation:

$$\frac{\partial}{\partial x}(h^3\frac{\partial P}{\partial x})+\frac{\partial}{\partial y}(h^3\frac{\partial P}{\partial y})=6\mu U\frac{\partial h}{\partial x}+12\mu\frac{\partial h}{\partial t} \tag{1}$$

with

$$h(t) = c(t) + h_p - h_p(x^2 + y^2) / r_p^2 \tag{2a}$$

in the dimples and

$$h(t) = c(t) \tag{2b}$$

in the other areas, with

$$m\frac{\partial^2 c(t)}{\partial t^2} = F_h - F_e \tag{3}$$

and

$$U = r_c \omega(\sin \alpha + \frac{r_c}{2l_c} \sin 2\alpha) \tag{4}$$

and

$$x = 0, P = 0; x = 4r_x, p = 0, \quad P(x,0) = P(x,6r_y); \frac{\partial P}{\partial x}(x,0) = \frac{\partial P}{\partial x}(x,6r_y) \tag{5}$$

where h is the lubrication oil film thickness r_p is the radius of the dimples, r_c is the crank shaft radius, l_c is the connecting rod length, $c(t)$ is the minimum oil film thickness, F_h is the carrying pressure of the lubrication oil, F_e is the operating normal load of the system, m is the viscosity of lubrication oil, a is the crank shaft angle, h_p is the maximum depth of the dimples, m is the quality of the piston ring in the test, w is the crank angular velocity and U is the system's reciprocating velocity. In this test F_e was 13.72 MPa, r_c was 40 mm, l_c was 175 mm and w was 100 rad/s and was the boundary condition used for calculation.

Figure 1 shows texturing dimples distribution schematic diagram on the cylinder wall, and θ was the distribution angle of the dimple along the piston ring movement direction. P was calculated by finite difference method, in which r_p=60 μm, and the results were shown in Figure 2, where S_p was dimples area density (the ratio of the dimples area to the total laser texturing area). "Average capacity" was the average pressure of lubrication oil *per* unit area, and "dimensionless average capacity" was the ratio of the average pressure to atmospheric pressure.

The results showed that when the value of θ was 30°, the average hydrodynamic lubrication oil load pressure of dimples was better compared with other cases. On the other hand, when OB>2r_p (for point O, B and A, refer to Figure 1), there were some wear particles not meeting any dimple along

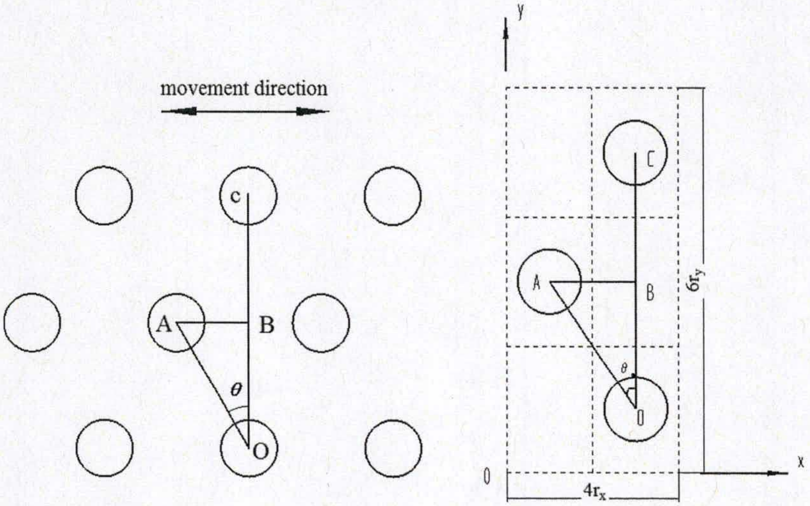

FIGURE 1
Schematic diagram of dimple distribution.

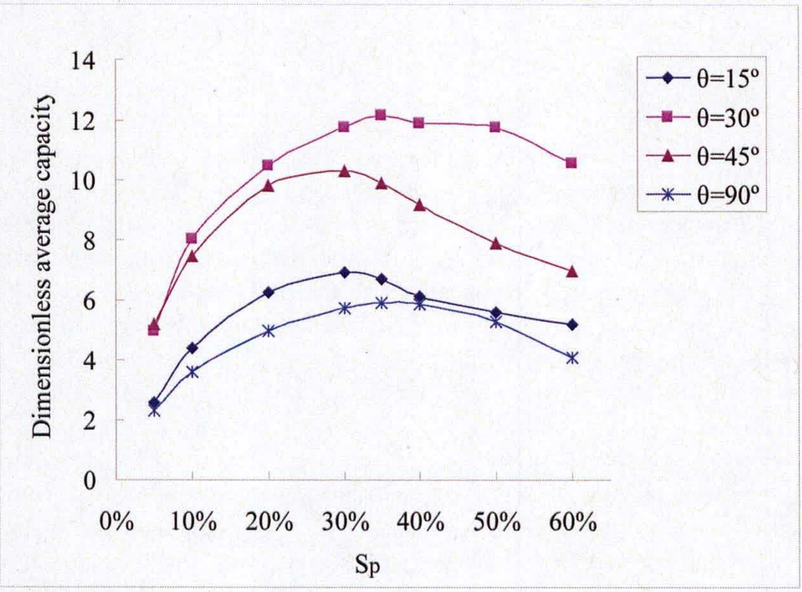

FIGURE 2
Graph showing the relationship between the average capacity and θ.

stripes with a width of OB-$2r_p$, and thus these wear particles would not be collected at all by any dimple. So it was found that the wear-particles-collecting ability was optimal when $OB \leq 2r_p$. If depth to diameter ratio ε and area density S_p were kept at constant values, when θ was increased, the length of

OB was reduced and the length of AB was increased. If AB continued to increase but OB≤$2r_p$ still held, the wear rate of the AB region was increased. So, there existed an optimum value of the dimples distribution angle to make sure OB=$2r_p$, at which the probability for the wear particles on the frictional surface to meet dimples along the sliding direction was the largest.

When the radius of the dimples was 50 μm, S_p=20% and θ=60°, it was calculated that OB=106 μm, which was approximately equal to the diameter of the dimples. So, when θ was altered from 0 to 90°, the best θ was 60° from this aspect of the wear particle collecting ability.

3 EXPERIMENTAL APPARATUS AND PROCEDURES

3.1 Laser texturing test equipment and analysis

The test equipment was all fabricated in-house. The cylinder was fixed on the four jaw chuck of the machine, and Nd:YAG laser (Powerlite DLS 9000; Continuum, Inc.) pulse passed through the optical guidance system to process its wall, as shown in Figure 3. As the coaxial encoder with 100,000 lines accuracy was installed on the machine, the dimples distribution angle were controlled by altering the machine parameters, such as dot pitch, screw pitch, and rotating speed. By laser texturing technology, the laser pulse power den-

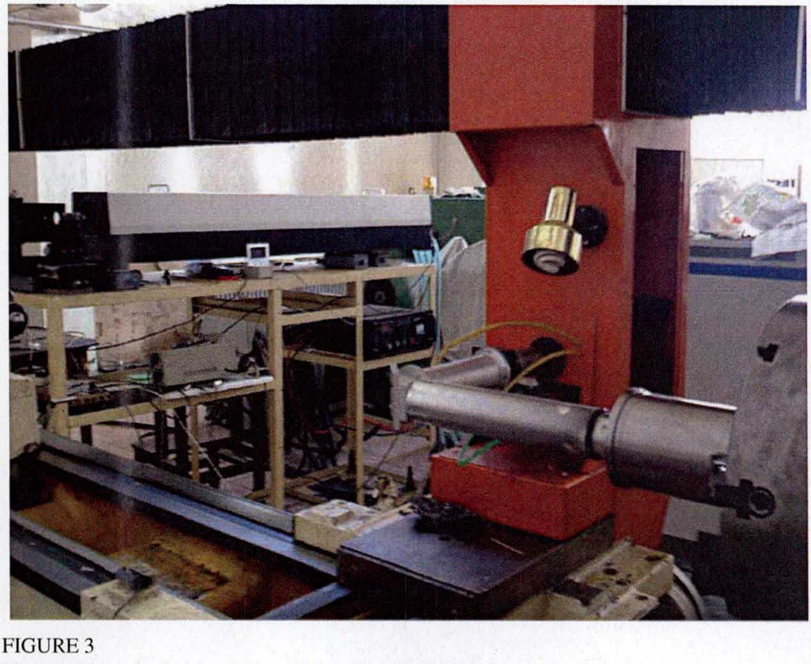

FIGURE 3
Photograph of the laser texturing device of cylinder liner.

sity was controlled in the range of 2.5×10^7 to 5×10^7 W/cm^2, with the pulse width of 5 μs. In this test the material of the cylinder liner was not changed and laser processing parameters were the same, so the dimples' diameter value of 100 μm was fixed.

The surface topography parameters of the cylinder wall after mechanical honing (plateau honing) were as follows: Ra was equal to 0.529 μm and the maximum honing depth, *Rz*, was 7.599 μm, which corresponds to a specific type of cylinder liner's diesel engine called XiChai6110. All of the dimples described in Figure 5 were textured after mechanical honing and then polished to remove the molten rim around the dimple.

3.2 Experimental arrangement

Through the experiment of cylinder liner-piston ring block reciprocating friction and wear, the friction and wear characteristics of the friction system after laser texturing the cylinder wall were researched. Figure 4 shows the experiment schematic diagram. The piston back pressure was loaded directly by the loading device, and the piston rings were reciprocating sliding on the cylinder block by motor crank movement. The lubrication oil of the system was in flooded, which was provided by guiding oil hole with a certain speed from oil cup.

The ultimate load was 13.72 MPa, the maximum speed was 960 rpm, the effective sliding distance was 160 mm *per* revolution, and the adding oil

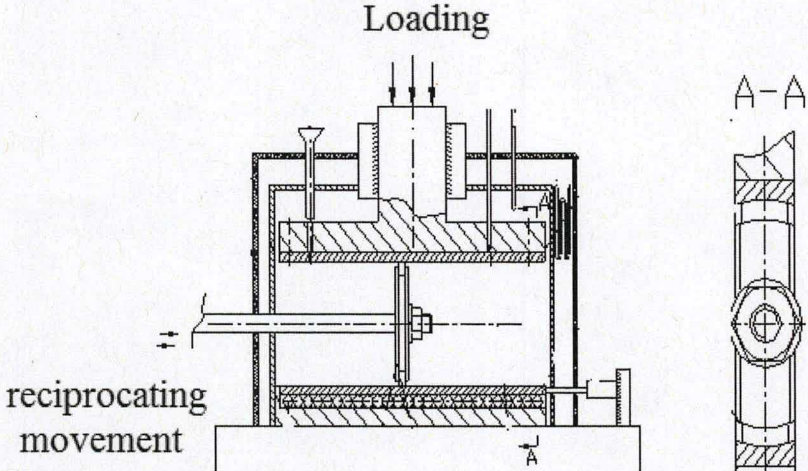

FIGURE 4
Technical drawing of the cylinder-piston ring reciprocating test.

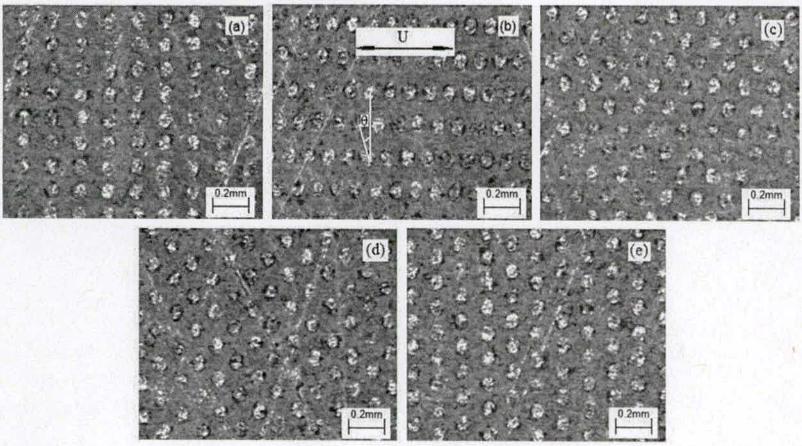

FIGURE 5
Optical micrographs of the topography of the laser textured surface for different values of θ: (a) θ = 0°, (b) θ =15°, (c) θ = 30°, (d) θ = 45°, (e) θ = 60°.

speed was 1 drop/s. The total test time was 8 hours, and the test temperature of cylinder wall was about 140°C. The test friction was collected by a pressure sensor, according to an oscilloscope with a receiver. Wear was measured by the weighing method. Before and after test of each block was weighed, and take the difference value as the wear value. And the wear test was repeated six times to get the results.

4 RESULTS AND DISCUSSION

The value of θ was selected as 0, 15, 30, 45 and 60° successively (seen in Figure 5), with ε=0.10 (the depth of dimples is 10 μm, and the diameter of dimples is 100 μm) and S_p=20% remained unchanged.

Figure 6 shows the average and standard deviation values of wear for different θ. When θ value was 0, 15, 30, 45 and 60°, the wear value was 19.0, 15.7, 11.3, 5.5 and 15.6 mg, respectively. It was found that the θ value corresponding to the best wear characteristic was 45°. This is explained by θ affecting the system's wear by two ways: one was the minimum film clearance altered by film load pressure and the other was the collection ability of loose material particles. When θ was altered from 30 to 60°, on the one hand, the film load pressure was reduced, then the system minimum film clearance was decreased correspondingly, which increased the system wear; on the other hand, the ability of the dimples collecting the loose material particles was increased, which decreased the system wear. In a word, the system wear was minimum when σ was 45° in the test.

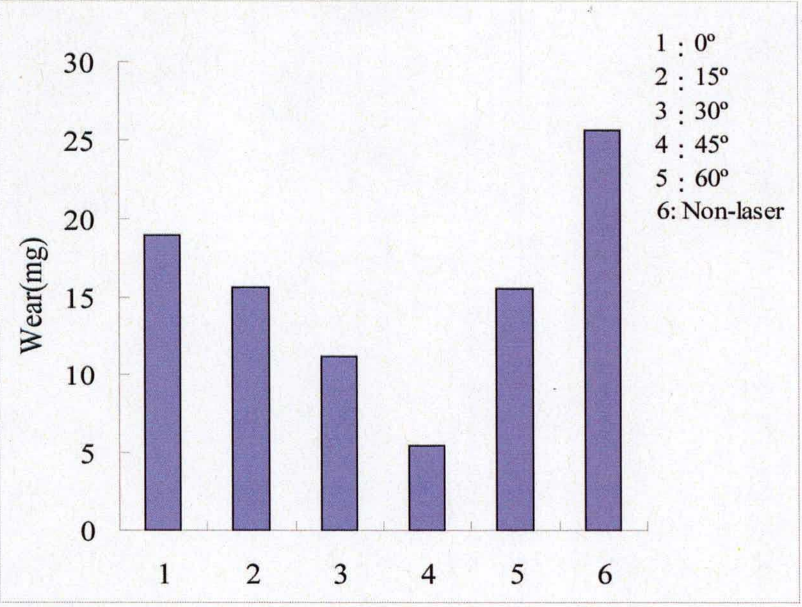

FIGURE 6
Chart showing wear value for different θ.

Figure 6 shows the wear values for two different processing methods. For non-laser and laser texturing, the wear values were 25.7 and 5.5 mg, respectively. Compared with non-laser processing, the laser texturing reduced the wear scar depth by 78.6%. It was thus concluded that laser texturing could more effectively reduce the friction system's wear rate under flooded lubrication conditions.

It should be noted here that the present test was limited to a single diameter of dimples being 100 μm. Hence, the present conclusion may be valid for this configuration only. Different texturing aspect ratios (depth over diameter ratio of the dimples), and other different experimental conditions (for example, oil viscosities) could lead to different results. These different results could present even smaller wear rates, compared to the results reported in this study.

5 CONCLUSIONS

For a barrel-shaped piston ring and cylinder honing roughness profile with Ra of 0.529 μm and maximum depth, *Rz*, of 7.599 μm, an experimental study was performed to evaluate the effect of laser-textured dimple distribution angle under flooded lubrication oil condition in reciprocating automotive components when the dimple diameter, depth, and area density were kept unchanged and equal to 100 μm, 10 μm, and 20%, respectively. The following conclusions summarize the results of the present study:

1. The wear characteristics of the textured cylinder liner–piston ring system are strongly related to the laser-textured dimple distribution angle;
2. The wear characteristics were best when the laser-textured dimple distribution angle was 45°; and
3. Laser texturing can reduce the cylinder liner wear by 78.6% compared to non-laser processing.

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