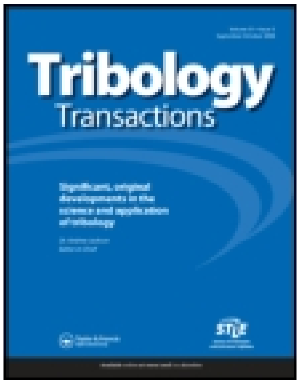

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Investigation on Dimples Distribution Angle in Laser Texturing of Cylinder–Piston Ring System

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The effectiveness of laser surface texturing in reducing wear rate was studied, with emphasis on dimple distribution angle. Experiments were performed by varying the texturing parameters *to derive variational rulesof the wear* scar depth *on laser-textured cylinder walls under starved lubrication conditions, and the optimum laser texturing dimple distribution angle was obtained. It was found that the laser texturing could result in less wear rate compared to mechanical honing.*

KEY WORDS

Wear; Starved Lubrication; Laser Texturing; Dimple Distribution Angle

INTRODUCTION

Most of the total engine friction, about 50–60%, comes from the cylinder and piston ring system (see Kligerman, et al. *(1)*). The service life of the engine depends to a large extent on this friction system. The friction and wear characteristics of the cylinder–piston ring system have long been the focus of research works in this field.

Ronen, et al. *(2)* studied the piston ring–cylinder system with laser surface–textured piston rings. It was found that a friction reduction of 30% or more was feasible with textured surfaces. Ryk, et al. *(3)* found a good correlation in a subsequent experimental work. Two laser surface texturing (LST) modes are available for reducing the friction loss. The first is piston ring LST mode (see Kligerman, et al. *(1)*), and the second is cylinder wall LST mode. Ryk, et al. *(4)* found that with LST barrel-shaped rings the reduction in friction was much less than that with flat specimens. Yu, et al. *(5)* found that the friction torque and friction coefficient of LST mechanical seals with a porous face were much lower compared to conventional mechanical seals. Kovalchenko, et al. *(6)*, *(7)* studied the impact of LST on lubrication regime transitions and found that the beneficial effects of LST were more pronounced at higher speeds and loads and for oils with higher viscosity. However, not much work has been focused on systematic investigations of the tribological aspects of laser-textured dimple parameters under starved lubrication conditions. Varenberg, et al. *(8)* found that the escape of oxide wear debrisinto the micropores resulted in an up to 84% reduction in the electrical contact resistance of the textured fretting surfaces. Volchok, et al. *(9)* studied the possibility of increasing the fretting fatigue life of a tribopair using LST technology and found that regular micropores created by laser texturing in the fretted zone on the cylinder almost doubled the fretting fatigue life compared to a common nontextured fretting zone.

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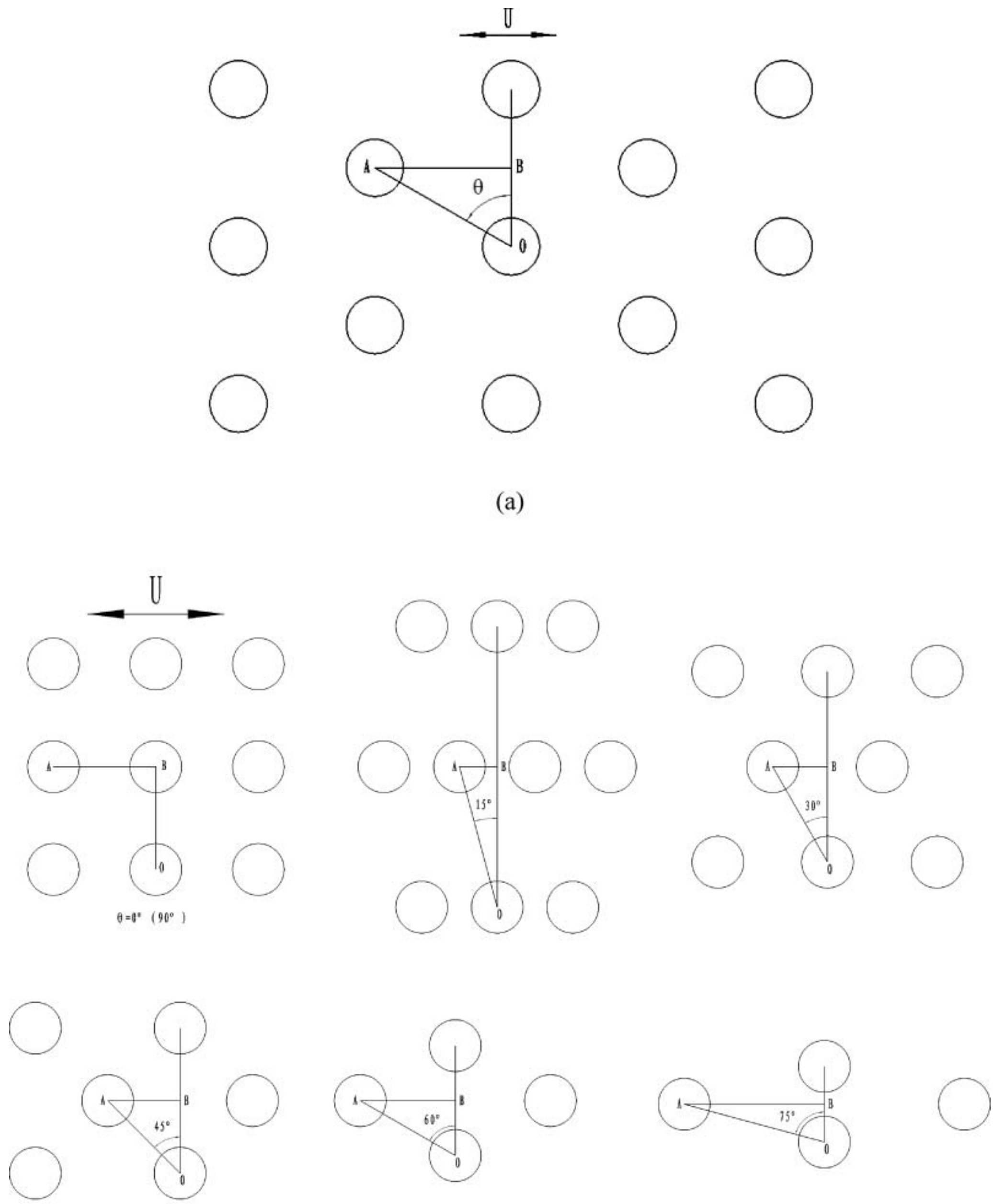
After the dimples were textured on the cylinder liner wall by laser beams, the variable parameters were dimple diameter $2r_p$, dimple depth h_p, area density S_p (the ratio of the dimple area to the total laser texturing area), and distribution angle θ (the angle between the dimples; see in Fig. 1a), which can describe the morphology of a single dimple and the distribution of multiple dimples. In this work, the effect of the controllable parameter θ, the laser-textured dimple angle, on the wear characteristics was studied under the conditions of starved lubrication and low reciprocation velocity.

EXPERIMENTAL PRINCIPLE

Three-body particle wear is generally the major wear mechanism for cylinder liner–piston ring systems adopted in internal combustion engines (Changlin and Ruhong *(10)*). The dimples can store lubrication oil and collect wear particles, which reduces the total wear of the system, and the wear particle collection capacity depends on the dimple distribution angle. Figure 1a shows a schematic diagram of the dimple distribution angle θ, and Fig. 1b shows the specific arrangements of θ that were tested in this study. The values of AB and OB (seen in Fig. 1b) are provided in Table 1 where the radius of the dimples was 50 μm and the condition $S_p = 20\%$ is satisfied.

When OB > $2r_p$ (for points O, B, and A; here r_p was the radius of a dimple), some wear particles did not meet any dimple along the stripes with width of OB-$2r_p$ (the gap between the dimples), and thus these wear particles were not collected. Therefore, it was found that the wear particle collection capacity was optimal when OB $\leq 2r_p$. If the depth-to-diameter ratio ε and area density S_p were kept at constant values, as θ was increased, the length of OB was reduced and the length of AB was increased. If AB continued to increase but OB $\leq 2r_p$ still held, the wear rate of region AB was increased. Therefore, there existed an optimum value of the dimple distribution angle to realize OB $= 2r_p$ at which the



(a)

(b)

Fig. 1—Schematic diagram of (a) dimple distribution angle θ and (b) different θ angles.

TABLE 1—VALUES OF AB AND OB

θ (°)	AB (μm)	OB (μm)
0 (90°)	198	198
15	73	271
30	106	184
45	140	140
60	184	106
75	271	73

probability for the wear particles on the frictional surface to meet dimples along the sliding direction was the highest.

EXPERIMENTAL DETAILS

Figure 2a shows a magnified image of a certain laser texturing region on the cylinder wall, where U is the reciprocating sliding movement velocity and θ is the dimple distribution angle. Figures 2b and 2c show the 3D topography of a dimple that is 100 μm in diameter and 9.85 μm in height. The degree of wear was evaluated in terms of the wear scar depths measured by a 3D profiler at seven points selected in the circumferential direction within the wear region.

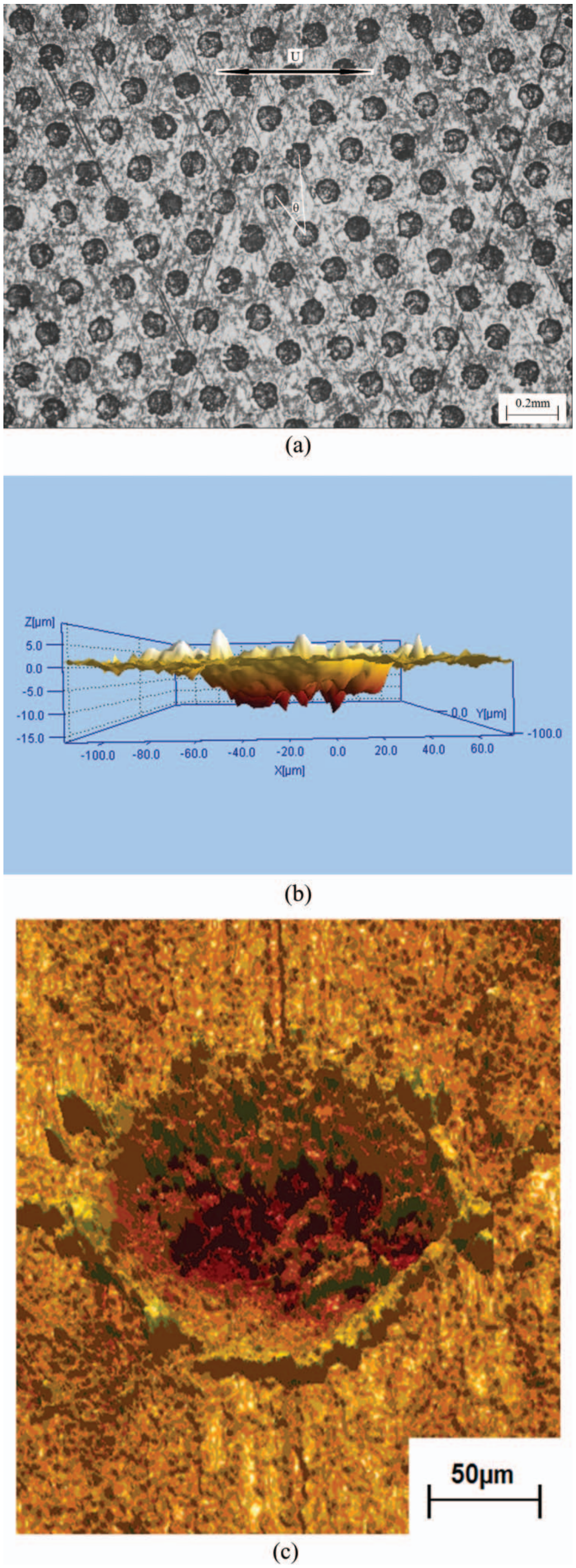


Fig. 2—Magnified image of the wear region and 3D topography of a dimple: (a) laser texturing region, (b) a single dimple (depth), and (c) a single dimple (diameter). (color figure available online.)

TABLE 2—LASER-TEXTURED DIMPLE PARAMETERS

Number	Dimple Depth (μm)	Dimple Distribution Angle ($^\circ$)
1	24.12	0
2	25.09	15
3	25.19	30
4	24.48	45
5	25.05	60
6	25.12	75

In this test, the dimples were produced by a 5-kHz pulsating Nd:YAG laser with a power of 200 W and 10-mJ pulses of 5-μs duration. As the number of laser pulses for etching one dimple increased, the depth of the dimples increased. The essential dimple parameters relevant to the test are presented in Table 2; all dimples were etched with two laser pulses for one dimple. The diameter of the dimples was kept at 100 μm or so, and the dimple area density in this test was 20%. The range of the dimple depth was 24.12–25.19 μm when the dimple distribution angle was changed from 0 to 75°, so the dimple depth was seen as a constant and the unique variable parameter was the dimple distribution angle.

A cylinder liner–piston ring friction and wear tester was used in the current study, as shown schematically in Fig. 3a. A cylinder liner (1) was fixed on the fixture, which supplied the up-and-down reciprocating movement by a hydraulic equipment (6). The piston ring (2) was connected to two symmetrical

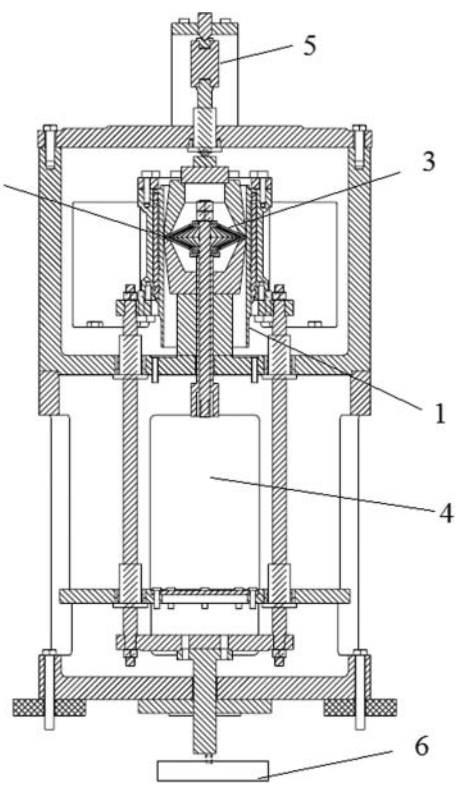


Fig. 3—Schematic diagram of the friction test rig.

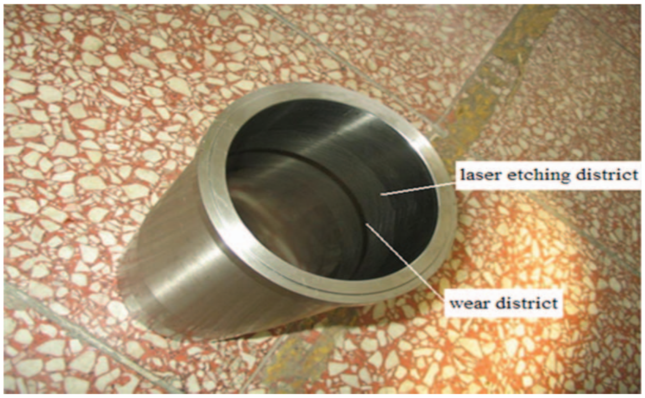


Fig. 4—Image of the laser texturing region and the tested wear region on a cylinder. (color figure available online.)

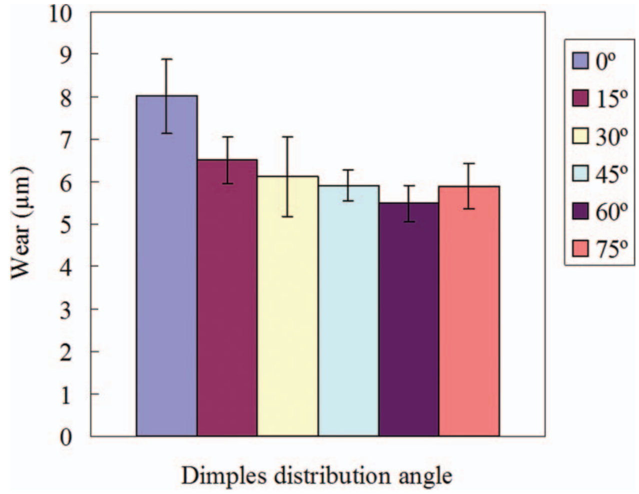


Fig. 5—Wear scar depth for different θ angles with laser texturing. (color figure available online.)

disc springs (3) by a hydraulic equipment (4), which included a pressure sensor. The hydraulic equipment supplied load on the surfaces of the frictional pair. The friction of the cylinder liner–piston ring system was recorded by a friction sensor (5). The surface topography parameters of the cylinder wall after mechanical honing (plateau honing) were as follows: R_a was equal to 0.393 μm and the maximum honing depth (R_z) was 4.599 μm, which corresponds to a specific type of cylinder liner's diesel engine called XiChai6107. All of the dimples described in Table 2 were textured after mechanical honing and then polished to remove the molten rim around the dimple.

The displacement and temperature of the test cylinder liner were controlled by a computer. The amount of lubrication oil was limited. The test conditions were set as follows: the frequency of the system was 4 Hz, the stroke was 6 mm, and the maximum contact pressure was 85 MPa, which was the piston ring contact pressure (the first ring, the geometry was barrel-shaped in this test). The total time for the experiment was 10 h: the test ran for 4 h with an oil feed rate of 1 drop/10 s and then for and 6 h with a zero feed rate; the temperature of the cylinder wall was kept at 100°C throughout the test. For each specimen listed in Table 2, the wear test was repeated six times. Figure 4 shows the laser texturing region and the tested wear region.

RESULTS AND DISCUSSION

Figure 5 shows the average values and standard deviations for the wear scar depth for different θ. When the θ values were 0, 15, 30, 45, 60, and 75°, the average wear scar depths were 8.01, 6.52, 6.12, 5.91, 5.48, and 5.89 μm, respectively. It was found that the θ value corresponding to the best wear characteristic was 60°.

When θ was 60°, the wear characteristics of the test system were best under starved lubrication conditions. According to the experimental principle in Fig. 1, when the radius of the dimples was 50 μm, with $S_p = 20\%$ and $\theta = 60°$, OB = 106 μm, which was approximately equal to the diameter of the dimples, consistent with the above analysis. When θ was 60°, the wear particle collection capacity was best, which led to the best friction and wear characteristics. When $\theta = 75°$, OB = 73 μm and AB = 271 μm; then OB < $2r_p$, but the overall wear rate was increased, because the wear rate in region AB was increased. Therefore, the optimum dimple distribution angle was 60°.

In the above test, the best results were obtained for No. 5 (see Table 2). Its wear characteristics were compared with those without laser texturing.

Figure 6 shows the average values and standard deviations for the wear scar depth for two different processing methods. For non-laser and laser texturing, the average wear scar depths were 7 and 5.48 μm, respectively. Compared with non-laser processing, the laser texturing reduced the wear scar depth by 21.7%. It was thus concluded that laser texturing could more effectively reduce the friction system's wear rate under starved lubrication conditions.

It should be noted that the present test was limited to a barrel-shaped piston ring, a single dimple diameter (100 μm), and just one honing roughness profile, with $R_a = 0.393$ μm and maximum depth $R_z = 4.599$ μm. Hence, the present conclusion, based on the comparison shown in Fig. 6, may be valid for this

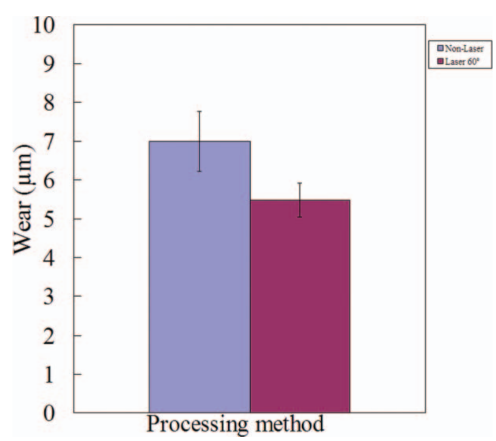


Fig. 6—Wear scar depth. (color figure available online.)

configuration only. Other configurations consisting, for example, of a cylindrical-shaped piston ring (see, e.g., Etsion and Sher *(11)*), different texturing aspect ratios (depth-to-diameter ratio of the dimples), and various honing roughness profiles could lead to different results, which could present even lower wear rates, either with non-laser or with laser texturing, than the results reported in this study.

CONCLUSIONS

For a barrel-shaped piston ring and cylinder honing roughness profile with $R_a = 0.393\ \mu$m and maximum depth $R_z = 4.599\ \mu$m, an experimental study was performed to evaluate the effect of laser-textured dimple distribution angle under starved lubrication conditions in reciprocating automotive components when the dimple diameter, depth, and area density were kept unchanged and equal to 100 μm, 25 μm, and 20%, respectively. The following conclusions summarize the results of the present study:

- The wear characteristics of the textured cylinder liner–piston ring system are strongly related to the laser-textured dimple distribution angle.
- The wear characteristics were best when the laser-textured dimple distribution angle, θ, was 60°.
- Laser texturing can reduce the cylinder liner wear scar depth by 21.7% compared to non-laser processing.

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