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Laser Surface Micro-Texturing of Gray Cast Iron using Ultrafast Laser

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Abstract

Laser Surface micro-Texturing, a surface modification technique utilized for the fabrication of microfeatures, i.e., micro dimples, microgrooves, microprotrusions, micro crosshatches, etc. These micro features usually distributed in a specific pattern and covering only a fraction of the contacting material surfaces for modifying the surface tribological properties. These micro-textured surfaces offer several benefits for tribological applications such improved wear resistance, load capacity, lubrication lifetime and reduced friction coefficients. The surface micro-texturing of gray cast iron was performed using a Ultrafast laser. The effect of processing parameters such as laser pulse energy, pulse repetition rate, and processing speed, on the performance characteristics of the laser textured samples were investigated. The ultrafast laser irradiation creates micro-dimples with surface chemistry modification and formation of graphite film and opens up the graphite flakes on the surface. Tribological characterization of those textured specimens was performed by ball-on-disk tribometer. The friction coefficient for the untextured lubricated surface sample was ~ 0.077 and laser textured lubricated surface sample was ~ 0.041 at 70% texture area density.

Keywords: Laser surface micro-texturing, tribological applications, ultrafast laser, micro dimples.

1. INTRODUCTION

The demand for eco-friendly automobiles has headed an excessive amount of research curiosity in enhancing the automotive engines fuel efficiency. Since frictional losses consume a significant proportion of the energy in an automotive engine, the tribology of the mechanical parts is an essential factor in determining the engine efficiency. Automotive engine parts encounter more than one regime of lubrication during their operation. For instance, the lubrication regimes associated with a piston ring and cylinder liner, cam and follower, are a boundary, mixed and elastohydrodynamic [1].

In a diesel engine, up to 60% of these mechanical losses result from friction between cylinder walls and piston rings [2, 3]. As a result, it has been evaluated that diminishing this friction loss by even 10% can lead to a reduction in fuel utilization of up to 3%. Nowadays small incremental changes in engine efficiency, 3% is a considerable gain. In the long term, this friction additionally makes wear of cylinder liners and piston rings, decreasing engine efficiency, increasing fuel utilization and emissions.

Laser surface texturing was observed to extend the scope of the hydrodynamic lubrication regime regarding load and sliding speed furthermore to decrease the coefficient of friction considerably under comparative working conditions when evaluated with untextured surfaces [4, 5]. This low-friction technology has the potential for application in different engine parts, such as the interface between the face seal and cylinder liner/piston ring, connecting rod eyes/ pins, etc.

By optimizing the laser process parameters such as pulse energy, pulse duration, and no. of pulses, the collateral damage can be controlled. Recently, ultrafast laser with high pulse energy and repetition rates is readily available, and ultrafast processing is expected to minimize the melt ejection and heat-affected zone effects. Hence, it could be useful for application in surface texturing. We already investigated the effect of laser textured surface done by different laser sources on the tribological behavior of gray cast iron. we proved that laser surface texturing using femtosecond pulse duration resulted in significant improvement in tribological performance in comparison to the untextured as well as millisecond and nanosecond laser-textured surface under dry condition [6].

Here we report on laser surface micro-texturing of gray cast iron material by ultrafast laser with different texture area density and discuss its tribological behavior by measuring friction coefficient and wear rate by the ball-on-disk test.

2. EXPERIMENTAL DETAILS

2.1 Material and femtosecond laser surface micro-texturing

The Femtosecond laser surface micro-texturing were performed on the gray cast iron material coupons. Gray cast iron (ASTM A35) is commonly used material for manufacturing of the cylinder liners and piston rings in an automobile. It contains carbon as graphite flakes in its microstructure. The properties of gray cast iron are given in Table 1. The samples, 10mm x 10 mm x 4.5mm were manually polished to an average roughness of about 0.1 µm. Before laser surface texturing, these samples were cleaned with acetone. The laser utilized for laser surface texturing was a femtosecond pulsed Ti: Sapphire laser. The processing parameters for laser texturing are listed in Table 2. The surface morphology was imaged by Opto-Digital microscope (Olympus DSX510) and SEM (Hitachi S-3400). The texture density for uniformly distributed textures (see Fig. 1) is given as

$$\boldsymbol{\rho}_d = \frac{Area\ of\ texture}{Unit\ area} \times 100\% = \frac{\pi r^2}{a^2} \times 100\%$$

where ‘r’ is the radius of the dimple (d/2) and ‘a’ is the length of the unit cell.

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2.2 Friction and wear test

The Friction and wear tests were performed with a commercial tribometer (Ducom TR-208-M2) using a ball-on-disk configuration. The ball used is Al_2O_3 ceramic ball with 8mm diameter. The properties of the Al_2O_3 ceramic ball is given in Table 1.

All the experiments were executed under starved lubricated contact conditions with sliding speed of 63.1mm/s and the normal force of 49.05 N. All these experimentations were performed at a relative humidity of 50 ± 5 % and the room temperature (27 ± 2^0C). Lubricant SAE 15W 40 used in all tests was designed for Diesel engines. The detailed experimental parameters used in this tribometer study are summarized in Table 3.

Before every tribometer test, only 3 drops (~0.07ml) of lubricant was dropped on the contact surface of the specimen, and unnecessary lubricant was expelled from the surface of the specimen during the experiment automatically due to centrifugal force. After the evacuation of lubricant, only a thin layer of lubricant appeared on the surface of the untextured specimen. For textured specimens, because of the presence of micro dimples, the major quantity of lubricant was stored in the dimples, and a minor amount stayed on the untextured areas.

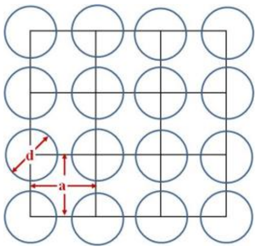

Fig. 1 Schematic diagram of Micro-dimple in dimple unit

Table 1
Properties of the ASTM A35 Gray cast iron and Al_2O_3 ceramic ball

Material	Gray cast iron	Al_2O_3
Density (g/cm^3)	7.2	3.92
Young's modulus (GPa)	119	340
Poisson's ratio	0.211	0.22
Compressive strength (MPa)	860	2200
Tensile strength (MPa)	270	-

Table 2
Parameters for laser surface texturing

Process parameters	Femtosecond laser (Ti:Sapphire, 800nm)
Pulse duration (fs)	100
Pulse energy (mJ)	0.5
Repetition rate (Hz)	1000
Processing speed (mm/sec)	20,30,35,60
Focus beam diameter at the sample surface (µm)	20
Number of pulses per dimple	1

Table 3 Parameters for Tribometer test

Parameters (units)	Parameter Value
Load (N)	49.05
Sliding Speed (m/s)	63.1
Sliding Distance (km)	0.227
Lubricant	SAE 15W 40
Duration (min)	60
Track Radius (mm)	6
Speed (rpm)	200
Temperature (^{0}C)	27 ± 2
Humidity (%)	50 ± 5

3. RESULTS AND DISCUSSION

3.1 Morphology of Femtosecond Laser surface textured samples

The SEM images of the femtosecond laser- textured surface of Gray Cast Iron are shown in Fig 2. The dimple diameter is 25 µm, and dimple to dimple pitch was 40 µm. The Laser texturing was made using a focused ultrafast Laser beam with a single pass, moving with a speed of 40 mm/s to produce a micro-dimple with an average depth of 1-1.2 µm and the surface texturing coverage area density of 30%. The micro-dimples show minor re-solidification and very less spatter around its outside edge.

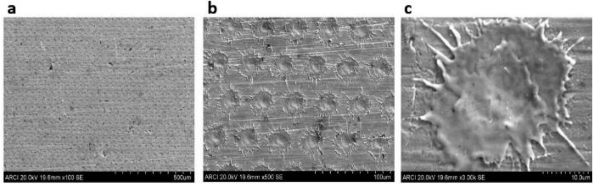

Fig. 2 Femtosecond Laser surface textured sample a) At 100x b) At 500x c) At 3000x

3.2 Friction behavior of Femtosecond Laser surface textured samples

The friction and wear analysis was carried out comparing the performance of textured and untextured surfaces under similar tribological conditions at different texture densities. Fig.3(a) illustrates the difference in the friction coefficient with sliding time for the untextured and different area density Laser textured sample investigations under starved lubrication conditions. In starved lubrication condition, the lubricant film layer is very thin to separate the two solid surfaces completely, so some opposing asperities touch each other. The friction coefficient now depends on both the solid-liquid friction and the solid-solid friction [7].

Here the coefficient of friction curves of the femtosecond Laser surface textured samples was smoother & stable under starved lubrication condition. Despite the friction-reduction mechanism under starved lubrication condition, the competition was viewed between fluid/wear debris reservoirs function and the actual contact pressure during starved lubrication sliding condition [8]. FSLST treatment effectively reduced the friction at 70% textured area density in starved lubrication condition.

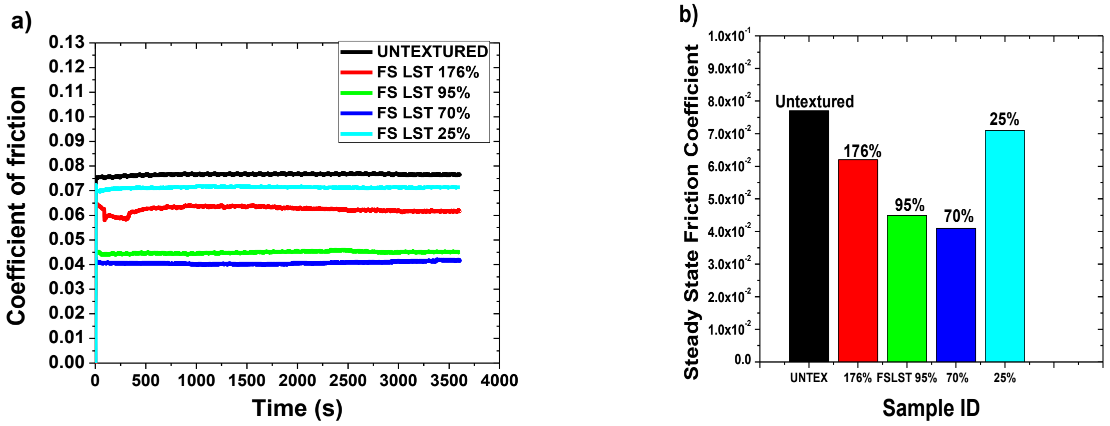

Fig.3 Ball-on-disk test: a) coefficient of friction vs. time and b) steady-state friction coefficient for untextured and textured samples

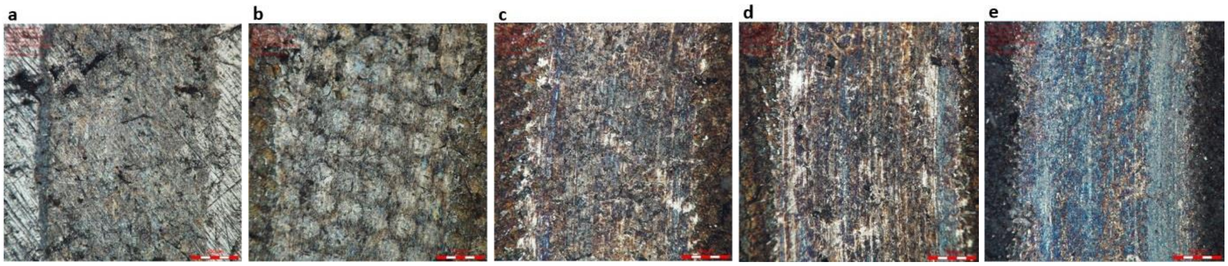

Fig.4 Opto-Digital microscope images of wear track of a) untextured b) FSLST 25%, c) FSLST 70%, d) FSLST 95%, e) FSLST 176%

Thus, FSLST treatment can enhance starved lubrication as texture density reaches an appropriate value. Suppose the texture density was excessively low, the dimples, as micro-reservoirs for liquid lubricants, can't be proficiently supplied to the contact surface while friction to form a liquid film with adequate thickness. In case if the texture density increased ahead of an appropriate value, an adverse effect on the tribological characteristics was observed as the actual contact surface decreases the average contact pressure increases on the sliding surface and therefore considerably reduce lubricant film thickness [9].

While the untextured sample exhibited 0.077 steady-state friction coefficient and FSLST 70 % density ~ 0.041 (47 % reduction) were observed under normal force of 49.05N and slid speed of 63.1mm/s. So, therefore, it is confirmed that texture area density of 70% (FSLST 70%) is the optimum area density.

Fig.3(b) illustrates the steady state coefficient plot for the untextured and different density femtosecond Laser textured surfaces. The minimum friction situation is a competition between the FSLST 25%, FSLST 95% and FSLST 176% densities with FSLST 70% density shows lesser friction coefficient. For FSLST 70 % density sample, the effect of surface roughness is suppressed by the effective debris trapping capability of high-density textures and these micro-dimples acts as micro-lubricant reservoirs for liquid lubricants, it can be resourcefully supplied to surface contact during friction to form a liquid film with adequate thickness thereby showing lower friction coefficient.

The friction coefficient of the Femtosecond Laser textures samples decreased reasonably quickly compared to untextured sample. The lubricant film layer on Laser textured samples also remained comparatively clean, because these micro-dimples are capable of keeping hold of not only liquid lubricant but also the wear debris that was formed throughout the tribometer tests.

3.3 Wear track analysis of worn surfaces

The Opto-digital microscope images of the wear track of FSLST and untextured samples are shown in Fig. 4. The untextured sample surface shows a stretch of wear particle debris that covers the entire wear track region (Fig.4(a)). The wear debris particles which are produced by friction can affect untextured sample surface in the form of micro-plowing which may lead to three-body abrasive wear. Here adhesive wear is also there because lubrication failure took place with the absence of micro-dimples which will act as micro-lubricant reservoirs. A significant increase in the contact area of two mating surfaces leads to increase in frictional heat.

In Fig.4(b), both the adhesive wear and abrasive wear is detected from the topography of the worn wear track surface of FSLST 25%. Here micro-dimples are still present on the wear track region and these influenced on the wear resistance, but this effect was insignificant because of an inadequate number of dimples. For FSLST 70%, the increase in the texture area density enhanced the capability to reserve the lubricant and wear debris. Because of this capability, here only fewer scratches were detected on the worn wear track surface of FSLST 70%, and still some original surface topography with micro-dimples can be observed in Fig.4(c).

When the texture area density increases to 95%, more micro-dimples are there to store the lubricant which helps to cool the frictional surface and help to reduce the friction heat generation, this is the main cause for reduction of adhesive wear in FSLST 95% when compared with FSLST 25% as shown in Fig.4(d).

By increasing the texture area density to 176%, i.e., the full overlap of micro-dimples reduces the contact area simultaneously between the mating surfaces and increase in contact pressure which causes severe adhesive and abrasive wear as shown in Fig.4(e).

4. Conclusions

Surface micro-Texturing with different texture densities has been carried on polished gray cast iron employing femtosecond pulse width Ti: Sapphire Laser. Tribological effects of the different texture area density were investigated by measuring the friction coefficient using ball-on-disk test. Femtosecond laser surface texturing improves tribological behavior: showed that lower friction coefficient of ~ 0.041. The reduction of the friction coefficient by a factor of up to ~ 47 % at 70% area density after femtosecond laser processing when compared to the untextured lubricated sample. Thus, Femtosecond Laser Surface micro-Texturing of functional surfaces is an opportunity to improve tribological performance; to achieve low friction resistance so increases the automotive engine components lifetime and reduces lubricant quantities.

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