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Surface Texturing for Low Friction Mechanical Components

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Abstract – Laser surface texturing (LST), a surface engineering modification, has been considered as one of the new processes used to improve tribological characteristics of materials by creating artificially patterned microstructure on the contact surface of mechanical components. In LST technology, the laser is optimized to obtain or manufacture the dimples with maximum precision. The micro-dimples reduce the coefficients of friction and also improve the wear resistance of materials. This study investigates the effect of dimple density is investigated. For this purpose, a ball-on-disc type tester is used with AISI 52100 bearing steel as the test material. Discs are textured with a 5% and 10% dimple density. Experimental work is performed with normal loads of 5 N, 10 N, and 15 N under a fixed speed of 150 rpm at room temperature. The effect of the textured surface is compared to that of the untextured one. Experimental results show that the textured surface yields lower friction coefficients compared to those of untextured surfaces. Specifically, the 10% dimple density textured surface shows better friction reduction behavior than the 5% dimple density textured sample, and has an 18% improvement in friction reduction compared with the untextured samples. Microscopic observation using a scanning electron microscope (SEM) shows that the major friction mechanisms of the AISI 52100 bearing steel are adhesion, plastic deformation, and ploughing.

Keywords – laser surface texturing, friction, dimple density, bearing steel, mechanical components

1. Introduction

Recently, energy saving and high performance of tribosystems have increasingly become global issues. Since 1966, tribology technology, defined as the science and technology of interacting surfaces in relative motion, is one of the solutions used to counter these global issues, especially in industrial sectors, where long service life and maintenance-free mechanical components are few examples of the aforementioned hot issuesFor these hot issues, surface texturing technology has been investigated for low friction and long service life [1]. Wakuda *et al.* [2] showed that a dimple size of 100 μm is recommended for ceramic and steel materials in lubricated sliding contact. Segu *et al.* [3] reported that the dimple shape plays an important role in the friction reduction, and that elliptical, circle, and half circle shapes have the largest friction reductions compared with other shapes. Li *et al.* [4] stated that texture density is also an important factor in the reduction of friction. Surfaces with a texture density of 13% had the lowest friction and best wear performance.

However, the potential use of laser surface texturing in the field of bearings has not been comprehensively studied. Moreover, the effects of such texture on load capacity are always issued in terms of its bearing life.

The main purpose of this study is to investigate the friction behavior and mechanism of action of textured

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and untextured surfaces of bearing steel in dry conditions at room temperature.

2. Experimental Procedure

2-1. Specimen and texturing procedure

AISI 52100 bearing steel was used as the mechanical component in this study. Note that this material is the most commonly used material in the engineering sectors, and commercially available. The specimen was prepared using a laser surface texturing (LST) method. LST is a process used to improve tribological characteristics of materials by creating patterned microstructures on the contact surface. LST technology uses a pulsated laser beam to create patterned microstructures or dimples on the surface through a material ablation process, which can improve anti-seizing ability by reserving lubricant, trapping wear debris to prevent further abrasive wear, decreasing the contact area to reduce adhesion, and generating hydrodynamic pressure to improve additional lift [3].

Since the contact of the ball on the disc was a non-conformal contact, the Hertzian contact modeling can be used in order to determine the desired dimple diameter, for which the calculated contact width should be greater than or equal to the dimple diameter. Hence, the contact width was determined based on the Hertzian Contact theory.

Fig. 1 shows that the contact area is equal to 2a under non-conformal contact. In this study, the design of the dimple diameter should not be greater than 2a (2a 2d). For the minimum load (5 N), a Hertzian contact width of 100 μm was chosen as the dimple diameter.

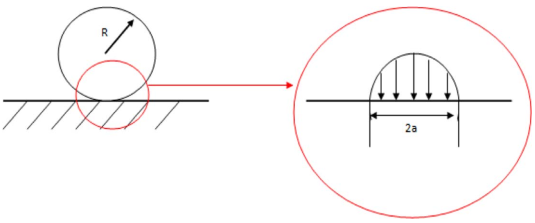


Fig. 1. Schematic drawing of Hertzian Contact.

After the calculations for the dimple diameter were complete, the dimples were sketched using SolidWorks Simulation software. This was to ensure that every dimple was placed in the correct location before being machined. It was also done to save time and reduce costs. The centers of the specimens did not need any dimples since the test and wear track did not take place there. Only a portion of the samples were textured with dimples. After sketching was complete, the samples were sent for laser surface texturing with a Nd:YAG laser machine [1]. The commercially used Q switch Nd:YAG laser operating at a frequency of 7-10 kHz and having a pulse duration of 200 ns was used for the purpose of making the micro-dimples on the surface. The laser surface conditions of our study are shown in Table 2. All specimens were polished to have a smooth mirror-like surface to ensure that the surfaces had a similar average roughness of 1 μm before testing. After being polished, the specimens were cleansed by using acetone solution via ultrasonic cleaning method to remove any metal fragments or

Table 1. Chemical compositions and properties of the AISI 52100 bearing steel

Composition (%)	C1.05, Cr1.50, Fe96.8, Mn0.35, Si0.30
Hardness (Hv)	7.8 GPa
Poisson's ratio (v)	0.3
Young's modulus (GPa)	208
Roughness (μm)	1
Size (mm)	Ø 35 mm × 5 mm

Table 2. Laser surface texture conditions

Parameters	Conditions
Speed	2 mm/s
Power	18-20%
Frequency	7-10 kHz
Pulse duration	200 ns
Pulse energy	1 mJ
Pulse repetition rate	15 kHz
Depth of dimples, um	5.5

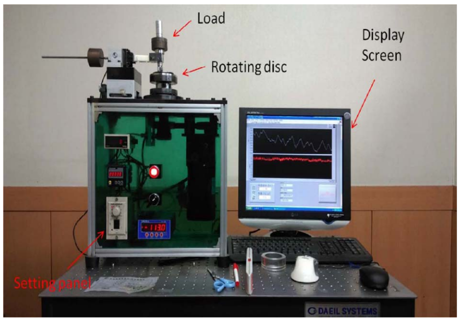


Fig. 2. Photograph of ball-on-disc type friction tester.

any other attachments trapped in the dimples or on the surface of the specimens. This was done to prevent the existence of any contaminants on the surface that could affect the outcome of the test. The cleaning was done twice for each specimen to ensure a better cleaning, both before and after a friction test on the ball-on-disc type test. The specimens were fully submersed in the acetone solution, and the cleaning duration was set to 5-10 minutes.

2-1-1. Friction test

Friction tests were done on the ball-on-disc type test model (Fig. 2). The material of ball was AISI 52100 and the size was 8 mm in diameter. The test piece was revolved about the center of the disc. Non-conformal contact and sliding effects between the test piece and the stationary pin occurred during the test. The sliding path was a circle on the disc surface. The stationary pin applied pressure at the required load and slid against the rotating disc. The coefficient of friction was continuously recorded by an X-Y recorder attached to the tester. The morphology of worn surfaces was observed and analyzed using a scanning electron microscope (SEM). All tests were performed in dry conditions at room temperature, to ensure that no lubricant from the atmosphere was applied between the contact surface of the disc and the ball. The rotational speed of the disc was maintained at 150 rpm (0.36 m/s) while the load was manipulated. The loads used were 5 N, 10 N, and 15 N. Dimple densities of the textured surfaces were 5% and 10%. Every test was performed for a duration of 3600 s and repeated 5 times for each condition.

3. Results and Discussion

3-1. Relationship between the friction coefficient and sliding time

Figs. 3-5 show the relationship between the friction coefficient and sliding time for each test condition. The friction coefficient was recorded by an X-Y recorder attached to the tester. In general, all the textured surfaces showed lower friction coefficients as compared with the untextured samples. All experiments showed similar trends, with the friction coefficient curves having two distinct stages, an initial sharply increasing segment followed by a steady segment. This trend was reported in other laser textured samples [3].

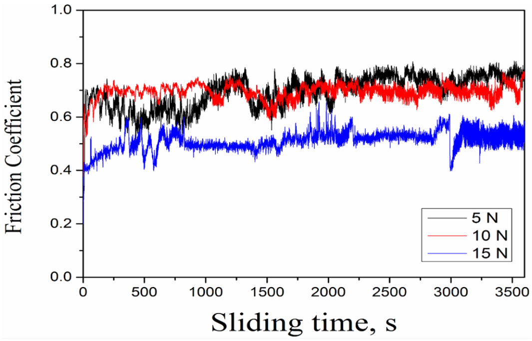


Fig. 3. Effect of load capacity on the friction coefficient of untextured samples.

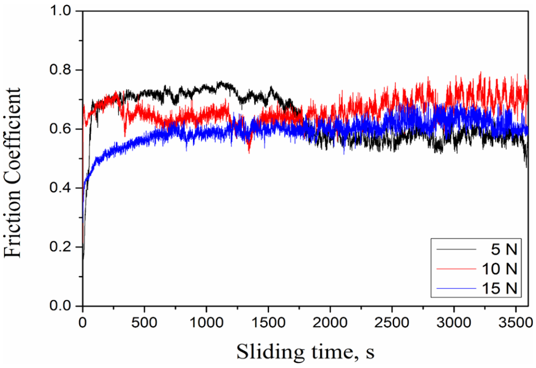


Fig. 4. Effect of load capacity on the friction coefficient of 5% textured samples.

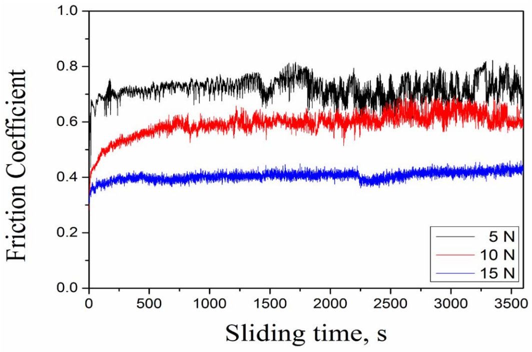


Fig. 5. Effect of load capacity on the friction coefficient of 10% textured samples.

The friction coefficients increased slightly from the initial value, and became steady after about 1000 s in the friction test. This phenomenon is known as running-in. Friction coefficients were relatively high during this particular period. During this period, the ball and disc were in contact for the first time, a time in which the ultimate load-carrying capacity was much less than after running for a long time. Thus, the friction was quite high.

However, as the experiment proceeded, the surfaces became smoother and more prominent asperities were lost or flattened, which indicated that the wear rate and frictions fell into a steady state. During this period, a number of mechanical wear process, especially those that depend on adhesion or abrasion, were likely to be operating simultaneously. This running-in or a sudden surge of the frictions would theoretically occur again, once the materials undergo a fatigue process, ultimately resulting in failure of the materials [5].

Based on the above findings, frictions did not increase with increased sliding times. It was found that two surfaces in contact with each other for the first time displayed a period during which the friction was high. The friction became stable after this initial period ended, also indicating that the system had entered steady state.

3-2. Relationship between the friction coefficient and normal load

Fig. 4 shows that the friction coefficient was low at the higher loads of 15 N. Previous research shows that this phenomenon happened due to several reasons.

The main cause was the formation of debris between the ball and the disc that were sliding together. The formation of wear debris on the wear track can affect the friction greatly. These particles have small sizes and many shapes. The wear debris can be "rolled over" into cylindrical, spherical and needle-like particles [6]. Particles could be detached from rubbing surfaces to form a more-or-less continuous interfacial layer. They are capable of transmitting forces, moments, and displacements (translational and rotational) at the contact interface. Freshly generated wear debris can escape to the interface where it is processed further, and crushed into finer particles or compacted into large debris. This would result in the change of the wear debris form into other shapes such as spheres and cylinders. Spherical and cylindrical wear particles roll over each other to produce low friction. It has also been reported that, as a result of the rolling effect, the coefficient of friction undergoes transition to lower values by a factor of three, and the wear decreases by several orders of magnitude. The coefficient of friction in the presence of rolls usually ranges from 0.1 to 0.4. It has been suggested that cylindrical debris can act as miniature roller bearings or "solid lubricants", so that sliding friction can be reduced [6].

Other research shows that wear compactness also influences the friction coefficients. As the load increases, the frictional heat becomes sufficient to aid in better compaction and larger coverage of the transfer layer, despite the production of more debris, resulting in lower friction. These compact layers containing solid lubricants can effectively decrease the direct metal to metal contact [7].

The effect of dimple density plays an important role on the friction coefficient. It was found that the friction coefficient, failure time, load carrying capacity, and wear resistance do not vary monotonically with texture density. There might be an optimal texture density at which the textured surface exhibits the best tribological performance. Similar results can be seen from previous research. Kangmei *et al*. concluded that

Table 3. Average Friction Coefficient results at each condition

Normal load	Untextured	5% dimple density textured	10% dimple density textured
5 N	0.77	0.59	0.66
10 N	0.77	0.69	0.58
15 N	0.51	0.58	0.42

texture density has a strong effect on the friction and wear behavior. Segu concluded that dimple density can be changed, in order to obtain the smallest friction coefficient, provided that the dimple diameter is fixed.

3-3. Relationship between friction coefficient and dimple density

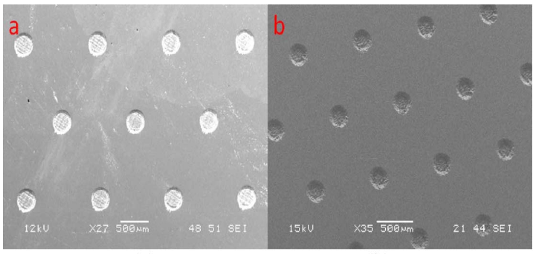
Table 3 shows the average result of the friction coefficient against normal load. The differences in both the textured and untextured surfaces are very obvious. Untextured surfaces show higher friction at values of 0.51-0.77 in this study. There was a friction reduction shown by the textured surfaces. However, not all of the textured surfaces demonstrated a reduction of friction behavior. At 15 N, the 5% textured surfaces showed a higher friction value of 0.58, as compared with the 0.51 friction value of the untextured one. The 10% textured surface showed a promising result since its friction coefficient was lower than that of the 5% textured sample. The lowest friction value of the untextured sample was 0.51, while the lowest for the 10% was 0.42.

Evidently, a lower friction coefficient was obtained using textured samples as compared with those of untextured samples. However, the friction coefficients of the textured samples were not the same. There was a difference between both the textured samples. The 10% textured sample showed a better friction reduction compared to the 5% textured one. The density of the dimple plays an important role in the resulting friction coefficient.

Similar results can be seen from previous research. Kangmei *et al.* [4] concluded that texture density has strong effect on the friction and wear behavior. It was found that the friction coefficient, failure time, load carrying capacity, and wear resistance do not vary monotonically with the texture density. There might exist an optimal texture density, at which the textured surface exhibits its best tribological performance. Segu [1] concluded that dimple density can be changed in order to get the smallest friction coefficient, provided that the dimple diameter is fixed.

3-3. Microscopic evaluation of the worn surface

Textured surfaces produced by the Nd:YAG laser were examined by SEM prior to tribological test. Fig. 6 shows the representative morphology of the 5% and 10% textured densities. It also shows that there was a clear difference between the morphologies of the textured surfaces and those of the untextured ones. The textured surfaces had small holes called dimples



(a) (b)

Fig. 6. SEM images of (a) 5% textured, (b) 10% textured surface.

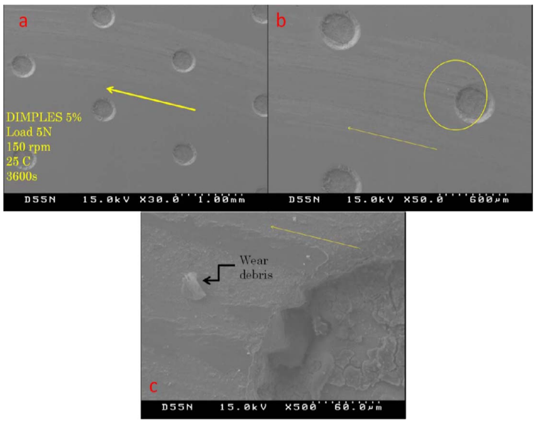


Fig. 7. SEM images of the 5% dimples density under 5 N of load and 150 rpm of speed after one hour test.

Fig. 8. Wear debris on the dimples after friction test.

on their surfaces.

Fig. 7 shows the SEM photo of the 5% dimple density under a 5 N load and 150 rpm speed, after one hour of testing. Adhesive and abrasive wear tracks were found on the worn surfaces. Not only that, plastic deformation was also observed on the surface during sliding friction. It can be clearly seen that there were minimal scratches and grooves on the surfaces of the samples. There was no severe wear observed in any of the textured specimens. Slide marks and scratches formed by the contact were also observed. The wear debris generated acted as an abrasive material between the two contacting surfaces. This effect led to scratch generation on the rubbing surfaces. Additionally, Fig. 7c shows wear debris on a sample, which proves that the three-body abrasion wear mechanism occurred on the surfaces.

In this case, however, the amount of abrasion was minimized by the dimples of the specimen. The presence of dimples acted like holes that trapped the debris to reduce the friction coefficient and the ploughing effect, which also reduced the wear of the specimens. There was debris observed within the dimples. Figure 8 shows the trapped debris inside the holes of the dimples that resulted in minimized wear and scratching on the rubbing surface. This was also reported by Segu *et al.* in his research [1]. He additionally found that the textured surfaces did not show any presence of debris on the worn track, but rather the wear debris was relocated from the contact region to inside the dimples. Some of the dimples were completely filled with debris. This shows that the dimples have a tendency to trap wear debris. The examination of the worn surface revealed that the dimples may act as reservoirs for debris and leave a debris-free interface between the ball and disc, thus reducing wear [3]. In particular, abrasive wear was reduced in this experiment. In order to get the optimum texturing conditions, research of design technology to manufacturing technology is required [9].

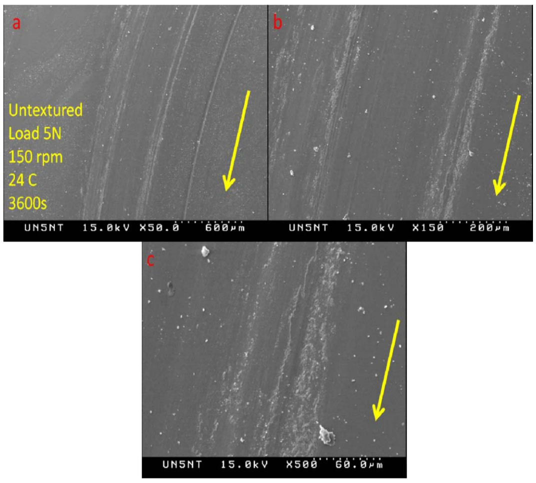


Fig. 9. SEM images of the untextured surfaces under 5 N of load and 150 rpm of speed after one hour test.

Fig. 9 shows an SEM photo of untextured worn surfaces under a 15 N load and 150 rpm speed, after one hour of testing. It can be clearly seen that there are deep scratches and grooves on the surface of the samples. There was severe wear observed on all the untextured specimens. The rubbing contact of the ball and the disc generated the presence of wear debris.

4. Conclusions

The results of this study show promise towards improvements in surface texturing methods to reduce friction. In this study, the 10% dimple density sample showed better friction reduction than that of the untextured and 5% textured samples. The average friction coefficient of the 10% dimple density samples, textured by LST, showed about an 18% greater reduction than the 5% dimple density and untextured samples. Furthermore, dimples also acted as reservoirs to trap wear debris generated in sliding friction. The microscopic evaluation using a scanning electron microscopic (SEM) showed that main friction mechanisms are abrasion, adhesion, and plastic deformation. Further research is required to obtain the optimum dimple density for the best friction reduction.

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