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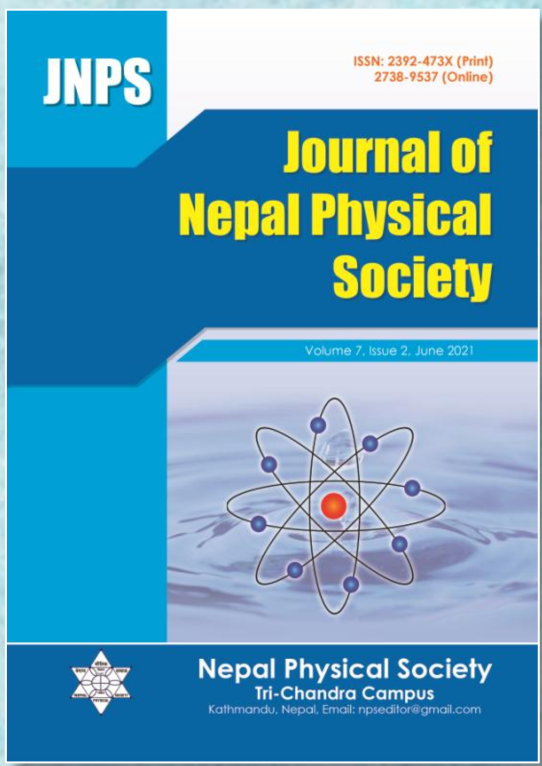

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Improving Tribological Behavior of ICE's Cylinder Surface by Laser Surface Texturing (LST)

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ABSTRACT

This study investigates the effect of laser surface texturing (LST) on the friction and wear behavior of grey cast iron (GCI) of internal combustion engine (ICE) cylinder in lubricated conditions. The dimples having diameter of about (58-60) μm and depth of about 10 μm were created on the surface with various dimple densities ranging from 5 to 50%. A ball-on-disc friction tests were performed for all the specimens under 5W30 and 15W50 oils with different viscosities. The tests were carried out at a load of 5N and speed of 5cm/s. The coefficient of friction of the dimpled specimen was reduced significantly by approximately 32% as compared to the polished speciemen. Specimen with 15% dimples exhibits the lowest coefficient of friction of all the dimpled specimens in both low and high viscous oils. The high viscous oil found to be more efficient regarding coefficeint of friction compared to the low viscous oil. The degree of wear of the specimens was analyzed on the basis of wear scar developed on the counter surface as it supplements the wear during the friction tests. The resistance to wear of the sliding specimens was found to be increased in high viscous oil compared to that in low viscous oil.

Keywords: Grey cast iron, Internal combustion engine, Friction, Wear, Laser surface texturing

1. INTRODUCTION

Surface topography has a significant influence on the friction, wear, and lubrication of materials, plays a vital role in improving the tribological properties of internal combustion engine [1-3]. Performance of a tribological system can be improved by creating some geometrical designs or geometrical structures instead of a perfectly smooth surface. Among various ways of enhancing tribological properties of mechanical components like grey cast iron of internal combustion engine, surface texturing is well known for many years [4]. There are mainly three processes [5] of surface topography optimization or texturing of the surfaces: a) mechanical, b) lithographical and c) energy beam processes [6]. Among all, laser surface texturing (LST) has become an most applied method [7], owing to its advantages such as it is extremely fast, clean to the environment, and also provides an excellent control over the shape and size of micro-structures over other surface texturing techniques[8-11]. LST has created huge influence in texturing, because it can be used on variety of materials such as metals, ceramics and glass, to produce different topographical features.

Friction and wear can be minimized by the introduction of selective micro-structures on the sliding surfaces using LST [12-21]. Most studies showed that these microstructures can serve either as micro-traps for wear debris in both dry and lubricating contacts, or micro-reservoirs for lubricant in the cases of starved lubrication conditions, or micro-hydrodynamic bearing in the cases of full or mixed lubrication [22-25]. Thus, textured surface helps to maintain the oil film thickness between the mated surface such that the transition of lubrication regime from the boundary lubrication regime on to mixed lubrication regime and then into hydrodynamic regime may take place [26, 27]. Hence it reduces the frictional force developed during the relative motion of the surfaces. In addition, closed micro cavities, like small circular pits, can perform the function of a hydrostatic micro-bearing [5]. Actually, when two mated surfaces come close to each other during sliding; the fluid in the cavities gets compressed and produces a bearing pressure. The kind of structures, the geometry and the density of the cavities on the flat surface play an important role on the tribological properties. In most cases, an optimized structure can only be achieved if it is adapted to the tribological system.

In this study, an Yb laser radiation (wavelength (λ) = 1064 nm) is used for creating structures on the GCI surface. The polished specimens are modified into dimpled specimens by adding the hemispherical depressions known as dimples. The dimples are created on the surface with dimple densities ranging from 5% to 50%. Since the size, shape and distribution of dimples produce preliminary effect on both friction [25] and on Stribeck curve in lubricating sliding [28], the dimple density could be obatined and varied as

$$Dimple\ density = \frac{Area\ of\ dimples\ on\ the\ dimpled\ surface}{Total\ area\ of\ the\ dimpled\ surface} \times 100\%$$

This study explores surface modification of ICE's cylinder surface by LST process and gives details about friction and wear properties of the GCI specimen before and after LST. Furthermore, it shows the influence of dimple density on friction and wear behavior of dimpled specimens. The tribological performance of different specimens is determined by using a tribological test facility at lubricated sliding environment.

2. EXPERIMENTAL

Materials Preparation

Specimens were prepared from commercial automotive ICE cylinder. First the cylinder surface is cut into parts and changed into specimens of dimension of 15 ×15 × 5 mm^3. The chemical composition of the GCI specimen from ICE is shown in Table 1, which was measured by using Energy-dispersive X-ray spectroscopy (EDS). Then, the plates were ground to flatness and further polished using alumina suspension down to particle size of ~1μm. The average roughness (R_a) and the hardness of the specimen were about 0.0115 μm and 220 HV, respectively. The specimens so prepared were then subjected to LST process.

Table 1 : Chemical composition on the surface of GCI specimen analysed by Energy Dispersive X-ray Spectroscopy (EDS).

Elements	C	Si	P	S	Cr	Mn	Ni	Cu
wt%	1.47±0.16	0.43±0.05	≤0.06	≤0.05	0.45±0.08	1.03±0.11	≤0.06	≤0.1

Laser Surface Texturing (LST)

INYA pulsed laser (INYA-20 watts, Germany; pulse width = 200 ns; frequency (f) = 20 KHz, wavelength (λ) = 1,064 nm) was used to create dimples on the GCI specimens [29]. The dimple parameters used in this study is presented in Table 2. During the process, an air pressure was used to remove the sediments. However, gentle re-polishing was done to remove the debris or bulges created around the dimples owing to the heat influence of the laser source in the process. It can be clearly seen the effect of re-polishing on the dimpled surface as shown in Fig. 1, which was observed through a Scanning electron microscope (SEM; Nanoeye, SNE-3000M, South Korea). All the specimens were ultrasonically cleaned for 5 min by ethanol post surface polishing.

Table 2 : Dimple parameters of specimens.

Dimple Parameters	Specimens			
	S1	**S2**	**S3**	**S4**
Average Diameter (μm)	60	60	60	60
Dimple pitch (μm)	80	100	150	200
Dimple density (%)	50	30	15	5

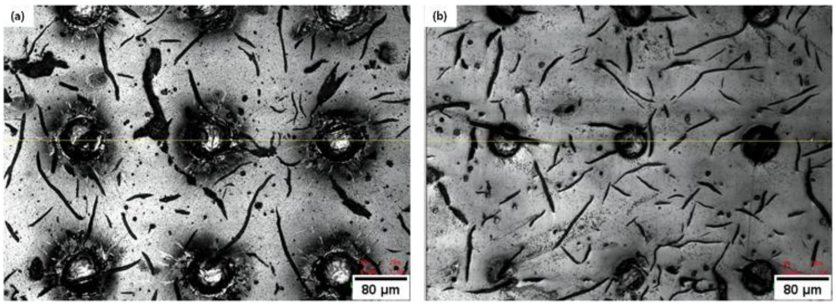

Fig.1: SEM images of a dimpled surface (a) before and (b) after the removal of debris owing to gentle polishing post LST process.

Friction and wear tests

A ball-on-disk tribometer (CSM Instruments, Switzerland) was used to assess the friction and wear behavior at room temperature and relative humidity of ~ (30-35)%. A load of 5N (Hertzian contact pressure = 0.63 GPa) and a speed of 5 cm/s for 1 h are applied during friction tests in lubricated condition. A wear track with a radius of 3 mm was used in rotating friction tests. A bearing steel (SAE52100 grade) ball with a diameter of 12.7 mm was used as a countersurface. Commercial engine oils 5W30 and 15W50 were used as lubricants with physics properties listed in Table 3.

Table 3 : The Physical properties of commercial lubricants used in the experiment.

Oil	SAE Grade	Density (g/ml)	Pour Point (℃)	Flash Point (℃)	Viscosity (cSt) at	
					40℃	100℃
Low viscous oil	5W30	0.855	-42	230	61.7	11
High viscous oil	15W50	0.87	-39	232	125	18

Surface Characterization

The surface hardness of the specimens was measured using a microhardness (Vickers) tester (Mitutoyo, Japan) at a load of 0.5 kgf for a dwell time of 15 s. The average surface roughness was measured using a 2D surface profilometer (Mitutoyo SJ-210, Japan). The chemical composition of the specimens was detected by energy-dispersive X-ray spectroscopy (EDS). The chemical composition of the cast iron specimen after polishing is listed in Table 1. The microstructure of the virgin and dimpled specimens was observed by a large-scaled measuring optical microscope (Model-STM6-LM-F31-2, Japan). The degee of wear of specimens was analyzed on the basis of wear scar developed on its counter surfaces (steel balls) thorugh the optical microzcopy (OM).

3. RESULTS AND DISCUSSION

Surface Topography

Fig. 2 shows OM images of polished, ground and dimpled specimens. It can be seen that the graphite flakes were uniformly distributed over the surface.

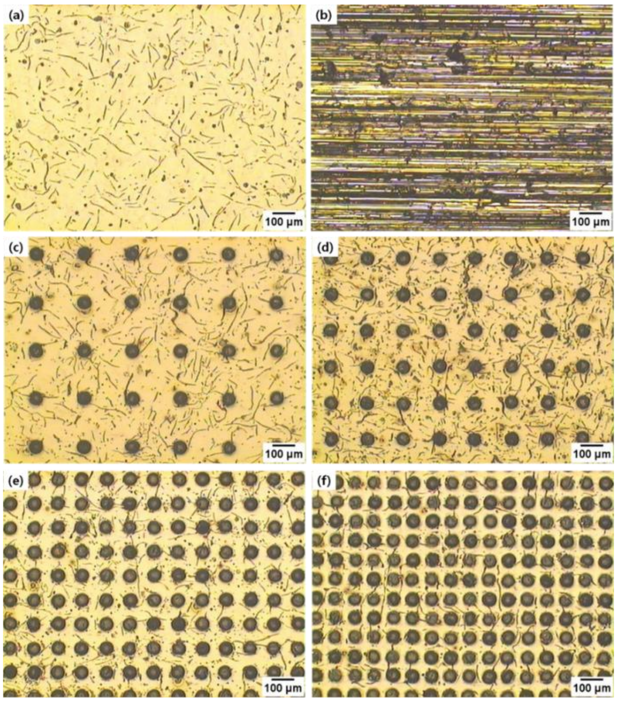

Fig. 2: Optical micrographs of (a) Polished, (b) Ground, and dimpled specimens with dimple densities of (c) 5%, (d) 15%, (e) 30%, and (f) 50%, respectively.

It has been reported earlier that the graphite flakes are responsible for the reduction in the coefficient of friction for the polished specimen, since graphite acts as a lubricious material at room temperature [30]. It shows that circular dimples are distributed uniformly over the surface with a square pattern with various dimple pitches/ densities. The surface characteristics of the dimples created on different specimens are listed in Table 2.

Friction Analysis

The variation of coefficient of friction as a function of sliding time for virgin and dimpled specimens are obtained as shown in Fig. 3. The evolution of the coefficient of friction during the test for each surface is same: the incipient value of the friction coefficient is much lower, then increases significantly and then decreases slightly and finally stabilizes.

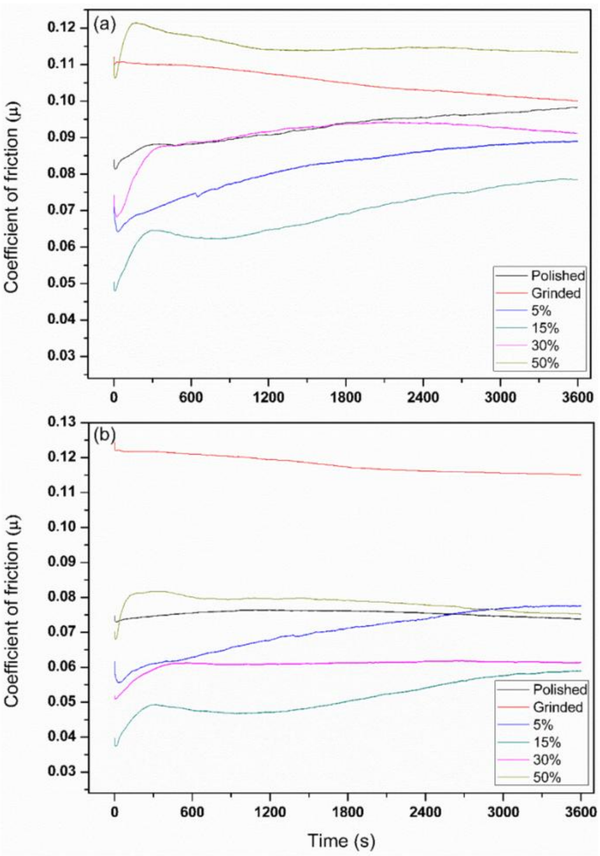

Fig. 3: Variation of coefficient of friction of specimens before and after laser surface texturing at lubricated condition using engine oils (a) 5W30, and (b) 15W50, respectively.

Fig. 3(a) shows the coefficient of friction of the specimens as a function of time in low viscous oil (5W30). The coefficient of friction of the ground specimen was approximately 0.11, whereas the polished specimen showed the value of about 0.095. The decrease in the coefficient of friction for the polished specimen is attributed to lesser surface roughness as compared to the ground speciemen. It also provides the utmost necessity of smooth surface with less average surface roughness for efficient tribological applications. With the dimpled specimens, the coefficient of friction further reduced to approxiamtely 0.065 as compared to the polished specimen. The dimpled surfaces having 5%, 15%, 30% and 50% dense dimples exhibited coefficient of friction of approximately 0.075, 0.065, 0.088 and 0.118, respectively. All the dimpled specimens showed significant reduction in friction as compared to polished and ground specimens except for the specimens with 50% dimples, that was found to approximately 0.118. The reduction in the coefficient of friction of the dimpled specimens can be attributed to the decrease in the contact area, increase in the surface roughness of the specimens post creating dimples and thus resulting smaller adhesive friction force for low loads [31]. The coefficient of friction for the specimen having 30% dimples was a bit lesser (<0.088) than that of the polished specimen. The specimens with 5% and 15% dimples showed a further decrease in the coefficient of friction as compared with the polished specimen. The coefficeint of friction of dimpled specimen with 15% and 5% dimples were approximately 0.065 and 0.075, respectively. The specimen with 15% dimples exhibited the least coefficient of friciton among all the dimpled specimens. The specimen with 50% dimples, however, exhibited the coefficient of friction approximately 0.118, which was the highest among all the specimens under study. The increase/decrease in the coefficient of frition of the dimpled specimens can be explained on the basis of difference in the roughness parameres such as skewness and kurtosis associated with the variation in dimple density. Our previous work explained about maximum negative skewness, and higher positive kurtosis for 10-20% dimples, exhibits the least coefficeint of friction among all the dimpled specimens [32]. The negative result was obtained for the specimens with 50% dimples, that can also be attributed to the unfavaorable roughness parameter for the highly densed dimpled surfaces as mentioned previously in some literature [33]. One of our previous studies also clarified the effect of roughness parameters in reducing the friction and wear of the dimpled specimens of grey cast iron at comparatively high-load conditions [29].

Fig. 3(b) shows the coefficient of friction of the specimens as a function of time in high viscous oil (15W50). The transition of coefficient of friction of the specimens using high viscous oil 15W50 is found to be similar with that obtained using 5W30 oil (low viscous lubricant). However, the coefficient of friction for polished and dimpled specimens in high viscous oil are found to be lower as compared to it was obtained in low viscous oil. The coefficient of friction of the ground specimen was approximately 0.125, whereas the polished specimen showed the value of about 0.075. The decrease in the friction for the polished surface as compared to the ground surface can be attributed to the removal of uneven features from the ground surface post polishing process. Similar to the results under low viscous oil, the friction of the dimpled specimens reduced significantly as compared to the polished specimen under high vioscous oil. The specimens having 5%, 15%, 30%, and 50% dimples are found to be approximately 0.07, 0.05, 0.06, and 0.08, repespectively. The friction for the dimpled specimen using high viscous oil is found to decreased in greater extent as compared to the case in the low viscous oil. The speciemen with 15% dimples exhibited lowest coefficient of friction under high viscous oil as in the case of low viscous oil. Similarly, the specimens with 50% dimples is found to have highest coefficient of friction of about ~0.08. The incerase/decrease in the coefficient of friction of the dimpled specimens under high viscous oil can be attributed to the difference in the roughness parameters such as skewness and kurtosis assocoated with the change in dimple density of the specimens. The maximum negative skewness and higher positive kurtosis for less densed dimpled specimens turned the surface with lower friction as already analysed in our previous publication [32]. The negative result i.e., higher coefficient of friction for the specimen with 50% dimples (even higher than the polished specimen) is attributed to the unfavorable parameters evolved on the contact surface due to closely packed dimples [29]. One of our previous study also explores about the correlation between the roughness parameters and friction behavior [32]. It also verifies the truthness on our results. The study thus gives more emphasis in the requireness of the optimization of dimple parameters for low friction.

Wear Analysis

Due to presence of wear on the specimens under study showed negligible wear on the surfaces due to the presence of lubricants at the sliding contacts. It was difficult to quantify the wear of specimens exactly. It is also due to the presence of closely spaced dimples on the specimens. Therefore, it is thought to analyze the wear based on the wear scar developed on the couter surface i.e. steel ball that slid against the polished and dimpled specimens. Fig. 4 shows the wear scar width on the balls slid against all the specimens in both low and high viscous oils.

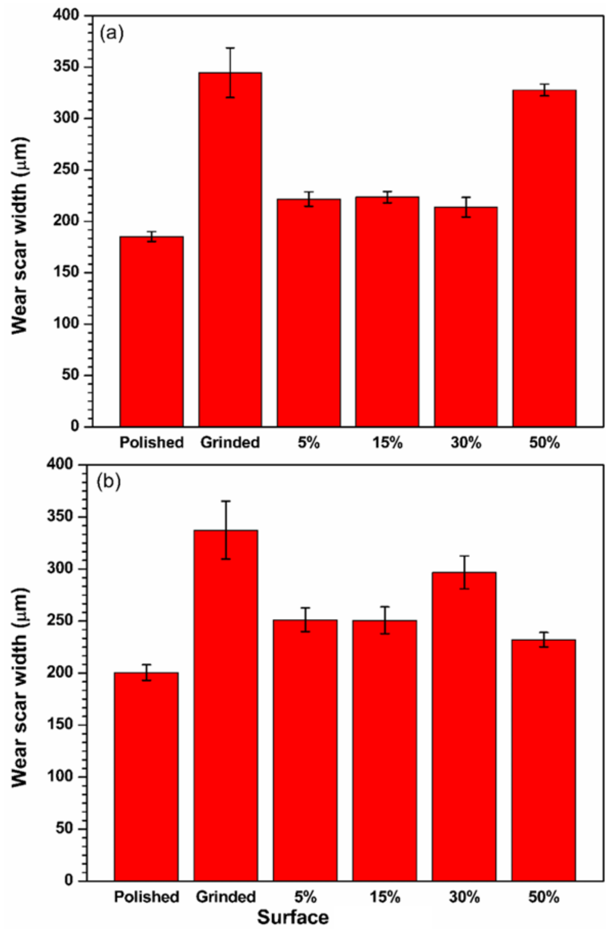

Fig. 4: Comparison of worn surfaces of the steel balls mated against specimens without and with LST at lubricated conditions under (a) 5W30 and (b) 15W50 oils, respecctively.

Fig. 4a shows the histogram showing the variation in wear scar width of balls slid againt the specimens in 5W30 oil. It showed that the wear scar size is highest of the ball slid against the ground specimen. The wear scar on the ball found to be decreased when it is slid against polised specimen. The wear on the balls is found to be decreased when slid against the dimpled specimens. The ball slid against the specimens with 5 to 30 % dimples exhibited similar wear scar diamteters, are much lower as compared to the ball slid against the polished specimen. As exception, the ball slid against the specimen with 50% dimples is found to have increased in wear compared to the balls slid against the polished and other dimpled specimens. Fig. 4b shows a histogram showing the variation on the wear scar width of the balls slid against the specimens under study in 15W50 oil. It can be seen from the figure that the wear scar width of the balls against dimpled specimens are found to decreased significantly compared to the ball slid against the ground specimen. It also explains the siginificane of dimples in decreasing the wear of the specimen.

4. DISCUSSION

Although the resistance to wear of some of the dimpled specimens is lower compared to the polished specimen, it can be explained due to the fact of occurrence a quick transition of lubrication from the boundary to mixed lubrication regime. The more wear particles collected on the surface helped to maintain the thickness of the lubricant between the surfaces. The increase of thickness of the lubricant comprises the appropriate condition for the transition of the lubrication regime explained by Stribeck curve [28, 34, 35]. As a result, the lowest coefficient of friction is observed for the surface with 15% dimples As the sliding occurs over the dimpled specimens, dimples may act multidimensionally according to the circumstance of the sliding environment. Dimples may act oil-reservoir pockets and traps to wear debris. They also uplift the specimens due to the micro-hydrodynamic bearing pressure and maintains the fluid films thickness avoiding or restricitng friction and wear. These dimples also reduces the area of contact between the sliding specimens. All these probable functionalities of the dimples actually decrease the friction and increase the resistance to wear. Also, our study and its outputs of low friction and wear of dimpled specimens compared to the polished specimen is in complete agreement with the literaures in this area of research of surface texturing and its impact on tribological behavior.

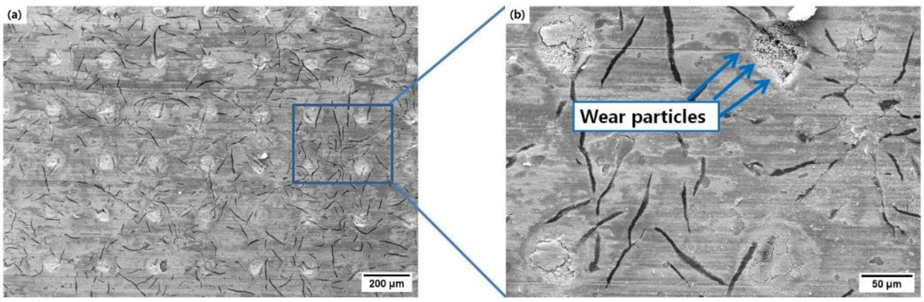

Fig. 5: SEM images worn surface with dimples of specimen (S3) with 15% dimples post friction test under the load of 5N and speed of 5cm/s in 5W30 oil: (a) Low and (b) high magnifications.

Fig. 5 shows SEM images of worn surface of 15% dimpled specimen post friction test using 5W30 oil at low and high magnification. Low magnification image (see Fig. 5a) shows the negligible wear of the dimpled specimen and the high magification image (see Fig. 5b) enlarges the dimples with its surrounding components and features. It showed that the dimples collected the wear debris or particles produced during the friction test under provided condition for this particular specimen. As seen from Fig. 5b, the worn particles are found to be remained inside a dimple indicating that the dimples act as wear traps. Similarly, those wear debris produced during sliding actually have capability to increase the fluid film thickness that the transition from complete fluid film lubrication to mixed fluid film lubrication regime was possible. It reduced the friction and wear of the dimpled specimen. Therefore, this investigation provides the significant proof of how the dimples play to reduce the friction and wear of the tribological components with the transition of lubrication regime at the sliding region.

5. CONCLUSION

From this study, it can be concluded that the coefficient of friction and wear of the ICE cylinder surface are reduced significantly at a load of 5N and speed of 5cm/s by using the LST process. The optimized dimple denisty for the significant reduction of coefficient of friction in both low and high viscous oil was found to of 15%. It was obtained that the coefficient of fricton of the specimen with 15% dimples was found to be decreased further in 15W50 oil compared to the specimen in 5W30 oil. An unmeasurable wear was noticed on the dimpled specimens due to load and low sliding speed. Therefore, the resistance to wear of dimpled specimen were found to be higher compared to polished specimen in low viscous oil but found to be lower in high viscous oil. The dimples created on the specimen are found to act as micro-traps for wear debris or particles produced during the friction tests.

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