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Experimental Investigation of Textured Surfaces in Line and Point Mixed Lubrication Contact

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Abstract

Finding a way to reduce the wear resulted from aperities interactions in mixed lubrication regime is an interesting area. One of the inspiring solution is surface texturing. Using a convenient laser, a textured surface with arbitrary micro cavity shape and size was prepared accurately. In this study, the effect of laser surface texture on the wear and friction behavior of discs in line and point contact in mixed lubrication regime was investigated. The effect of texturing area, linear velocity, and vertical load were examined. The friction coefficient variation reaches a narrow margin after an adequate distance. The results showed that wear decreases with increasing speed and decreasing the applied force. Comparing the results between plane and textured discs, it was found that the coefficient of friction was reduced between 12 and 19% and the amount of wear was reduced by almost more than 40%.

1. Introduction

Lubrication is defined as a way to prevent friction, abrasion, destruction, and wear on the mating surfaces using a fluid film. In hydrodynamic lubrication, the surfaces are completely separated by a layer of lubricant. In this method, the relative velocity between the surfaces causes the lubricant to be drawn into the convergent region. In non-conformal surfaces, the elastic deformation of surfaces is due to the order of thickness of the lubricant layer, therefore this must be considered in lubrication analysis. In this regime, as in the case of hydrodynamic lubrication regime, the sliding motion of convergent geometry as well as the viscosity of the lubricant have a significant effect on the performance of the lubrication. In the elastohydrodynamic regime, characteristics such as surface stiffness, degree of conformity, as well as the amount of increased viscosity of the lubricant with pressure are very important. If the load increases enough or the velocity decreases adequately, lubrication mechanism cannot maintain the required gap between the surfaces and some asperities interaction occurs. This is called mixed lubrication regime and it causes a jump in friction force and wear amount. Finding a way for keeping the lubricant in contact area is a challenging problem to improve the lubrication condition.

With the advancement of technology, textures, and patterns have been used on surfaces to improve their tribological performance. These patterns usually include holes with different geometric shapes. The size and geometry of the cavities are determined according to the characteristics of the contact surfaces (viscosity, pore geometry, contact speed, load pressure, etc.).

Surface textures can improve tribological behavior with oil content in the cavity and help withstand loads

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by creating hydrostatic pressure in the cavity. Micropores are also considered as a place to collect debris of wear of surfaces. On the other hand, micro-cavities are a small lubricant container. Although not much lubricant can be placed in these cavities, this small amount has a significant effect on reducing friction between contacting surfaces.

Qiu and Khansari investigated the tribological performance of laser surface texture of stainless steel rings [1]. The cavities were made in a circular and elliptical shape on the steel surface, which was elliptical in both radial and circumferential directions. It was observed that velocity plays a decisive role in the pressure on the cavities. For a given surface texturing density, the performance of the cavity depends on the depth to diameter ratio. If the density of cavities is constant, there is an optimal ratio. Finally, the results showed that elliptical cavities in the transverse direction perform better than the other cases. Kango et al. numerically investigated the effect of surface texture on the performance of a hydrodynamic journal bearing [2]. In this study, the effect of micro pores on the journal bearing was considered. The two-dimensional Reynolds equations were numerically solved in cylindrical coordinates by finite difference method to analyze the effect of texture on bearing characteristics. It was found that by creating small holes in different positions of the bearing surface, the bearing performance improved. Xiong et al. investigated the physiological properties of polytetrafluoroethylene with surface texture [3]. The results showed that the coefficient of friction of stainless steel decreases from 0.08 to 0.05 due to the surface texture. It was also found that there is the lowest coefficient of friction in the density of cavities between 7.9% to 8.8%. Braun et al. investigated the tribological effect of Polyalphaolefin [4]. It was found that friction reduction was not only dependent on the ratio of depth to the bore of the cavities, but a strong correlation between the pore diameter and friction reduction was also observed. Friction can be reduced by more than 80% if the texture is optimized. The desired diameter depends on the oil temperature and viscosity of the oil. Chaudhary et al. investigated the effect of surface texture on very high loads in reciprocating motion [5]. They examined dilute and viscous oils and showed the effect of micro cavities on improving tribological characteristics such as friction and wear. Etsion et al. conducted several research on textured surface developed by laser beam [6–8]. The performance of laser surface texturing on reciprocating automotive components, mechanical seals, parallel thrust bearing and some other applications was experimentally investigated and he found significant improvement in friction and wear reduction by using texturing surface in these application. The study of the friction and wear of non-conformal textured surface was recently considered by Cheng et al. [9], Niu et al. [10], and Long et al. [11]. The better performance of textured surface is the main finding of these studies. Using special alloy and composite in the material of samples with or without texture are other new field of study in finding a way to control the wear and friction [12, 13].

Much research has been prepared in modeling the flow of lubricant on textures. Caramia et al. [14] obtained a two-dimensional model and Han et al. [15] a three-dimensional model of hydrodynamic lubrication with the cavity texture by solving the governing equations. The design and optimization of pore texture in recent years has continued to attract much attention and a lot of research is being done on it. These include the work of Gropper et al. [16, 17], Rahmani and Rahenajat [18], Meng et al. [19], Rom and Müller [20], and Taee et al. [21]. Yan et al. modeled the lubrication of the texture surface considering the effects of temperature and the surface roughness [22]. They provided a model for fatigue life and its relationship with contact conditions.

Torabi et al. [23] developed a transient numerical model to investigate the frictional behavior and formation of the lubricant layer on the textured surface. They also experimentally investigated the effect of laser texture on ST37 steel disc under line contact conditions in mixed lubrication regime. Comparing the results between textured and plane discs, it was found that the coefficient of friction was reduced between 12% and 23% in the experimental study, while the numerical estimate predicted a possibility of reduction between 25% and 40%. At high speeds, the estimates of the numerical model and the results of the experiment are very close.

In the present study, the effect of two dimensional surface texture on improving friction behavior of mechanical parts in line and point contact condition is considered. The purpose of these experiments is to obtain the coefficient of friction and wear amount in textured and plane discs to develop a more accurate model for real situation.

2. Experimental Study

2.1. Test Setup

Wear test apparatus is commonly used to investigate the friction and wear behavior of a material. Pin-on-disc test rig is a popular tribometer which can simulate the perfect point contact condition between a fixed pin and rotating disc. Fig. 1a shows the pin-on-disc test machine used in mechanical laboratory of Isfahan University of Technology. Furthermore, a close-up view of how it works is shown in this figure. This device is connected to a computer. It calculates and stores the amount of friction coefficient in terms of distance from the friction force data which comes from a load cell sensor.

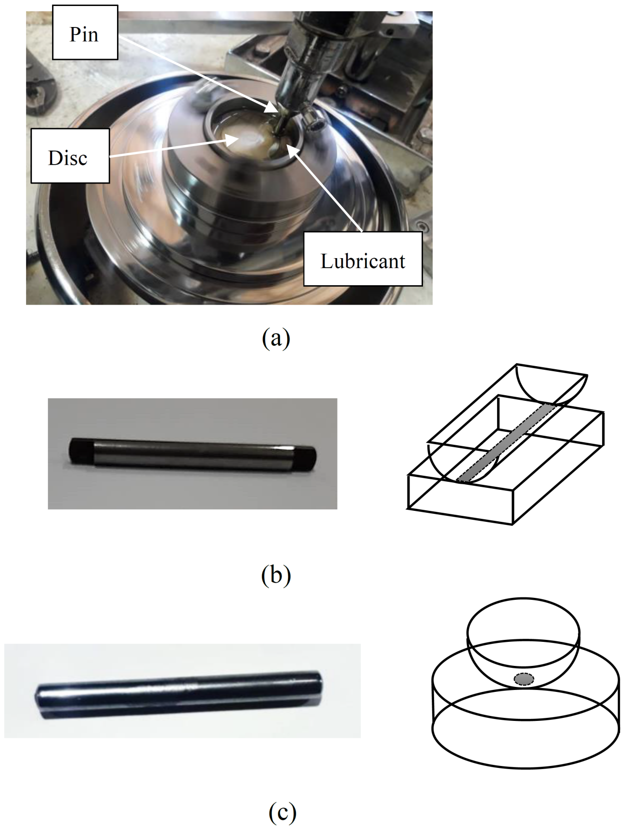


Fig. 1. a) Pin-on-Disc wear test apparatus: sample assembly with lubrication, b) Pin for line (left), and c) Pin for point (right) contact condition.

The ST37 steel was selected for the material of the disc, which has a hardness of 220 Vickers. The material of the pins used in the tests was 52100 bearing steel with a hardness of 800 Vickers. The pins for line and point contact condition are shown in Fig. 1b and 2b. The spherical shape of the pin was suitable for point contact, but for line contact, the end was cut and flattened on both sides to 2mm thick. The line contact pins have a radius of curvature 10mm in longitudinal direction.

An Nd: YAG laser with a wavelength of 1064nm, and a power of 100 W with a pulse width of 100ns was used to create hemispherical holes on the surface of the disc. One of important parameters in caving the texture on the surface is the ratio of texturing area to the total area of surface. This parameter is called cavity density. There is an optimum cavity density in each contact condition [24].

After laser texturing, the samples were polished using sand paper No.1000. The disc samples had a diameter of 50mm and a thickness of 8mm. The surface roughness of the samples after sanding was 0.1μm. According to the radius of movement of the pin on the surface of the disc (0.016m) and the width of the contact area of the pin and disc, two pore densities were examined. The discs were textured in cases of 5 and 7 rows with different radial and circumferential distances, as follows:

5-rows: radial distance from the center to the center of the holes 1.4mm and 115 holes in each row

7-rows: radial distance from the center to the center 0.9mm and 79 holes in each row

According to these calculations, hemispherical holes with a diameter of 400μm and a depth of about 30 μm were created on the surface. Since the device had an eccentricity of approximately 2mm, the bandwidth of 6mm to the center of the radius of 16mm was considered. Fig. 2 shows the 5-row and 7-row discs.

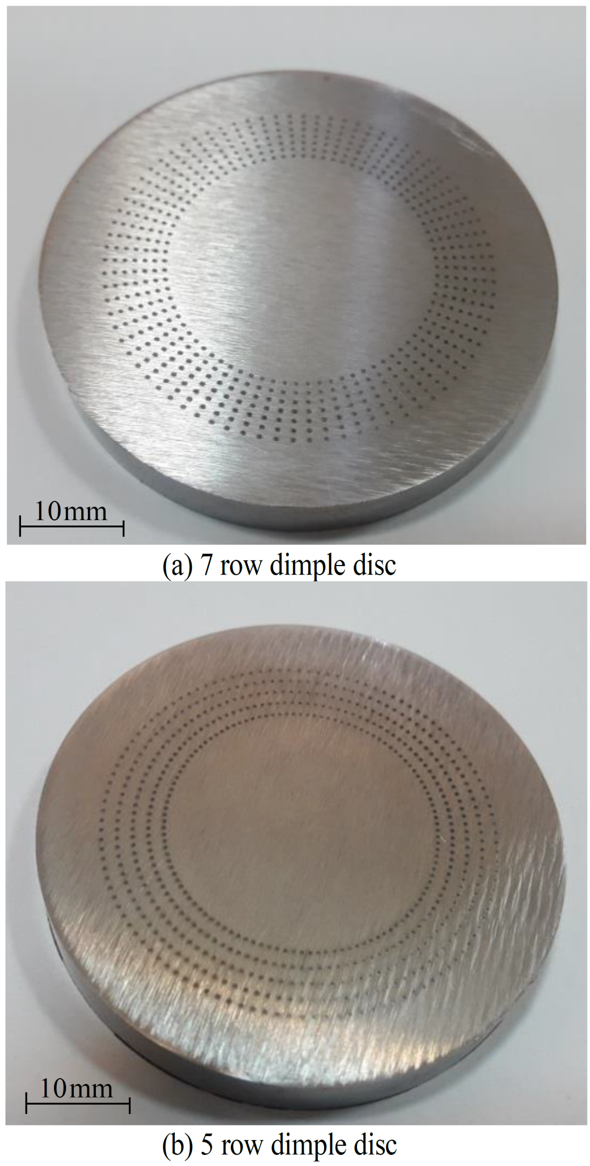


Fig. 2. Textured disc samples.

Before the experiment, the sample was carefully washed with acetone and the samples were weighed using the scale with a measurement accuracy of 0.0001g. After the test, the sample is washed again with acetone so that the effects of lubricant as well as the wear particles are completely eliminated. The difference between the primary and secondary weights will indicate the amount of weight loss of the sample. Due to the very low wear of the discs, they were weighed 10 times in each turn and their average was recorded. The weight of plane and textured samples was determined after a distance of 1000m. In this research, ISO VG-68 hydraulic oil with 68cSt viscosity was used.

2.2. Test Design

The velocity is restricted to the apparatus rotational speed and the radius of pin position from the center of disc. Moreover, the force is not limited, but when high load is used at such velocity, the strong asperities interaction will not be avoidable. The distance for the wear test is an important parameter. The rate of wear becomes constant after a while and it is possible to compare the several different situations at a same long enough distance, such as 1000m which is chosen in this study.

To investigate the effect of surface texture on the wear and friction behavior of contacting surfaces, for both five and seven rows textured surface samples, five different load i.e. 1, 3, 5, 8 and 10kg and five speeds of 0.027, 0.0535, 0.081, 0.107, and 0.135m/s were adopted. Each test was repeated three times and the results averaged to reduce the fluctuation error. The resulting friction coefficient was obtained from these 25 states.

The better pore density is chosen from five and seven row texture and then adequate number of samples (50 discs) were prepared. A new set of experiments were conducted under three different loads of 50, 100, and 140N and two different speeds of 0.085 and 0.215m/s to investigate the effects of speed change at constant load and load change at constant speed in both line and point contact condition. For each test, the experiment continued to 1000m of sliding distance. Each test was repeated three times to assure repeatability of the results. If the results have an agreement with 5 percent deviation, the median of three experiments is reported. Otherwise, the unreasonable data are omitted and the median of other data is calculated.

3. Results

At the constant load, as the speed increases the lubricant film thickness increases and therefore the portion of load carried by asperities decreases. Therefore, the friction coefficient decreases. Additionally, in the mixed lubrication regime, at constant linear velocity, increasing vertical load decreases coefficient of friction, although the effect of the load is much less than the linear velocity. As the load increases, the thickness of the lubricant film decreases and the surfaces get close to each other, resulting in a decrease in the share of force that the lubricant bears and an increase in the share of force borne by the roughness. In fact, the load endured by the roughness always increases with the increase of the applied load and the reason is the decrease of the separation gap between the surfaces, but this increase is often less than the increase of the total load, which shows a nonlinear share of roughness.

The presence of a pressure spike at the outlet of the elastohydrodynamic lubrication regime creates large shear stresses near the surface. Increased pressure may halve the life of a heterogeneous contact. For different loads, velocities, and material parameters, the amplitude of the pressure increase is completely different. At the inlet point, the convergence of the flow and the increase in viscosity, and at the outlet point, the divergence of the flow, and consequently the decrease in viscosity, is seen to increase the pressure at the outlet; as the load increases, this pressure also increases. As the dimensionless load increases, the location of the pressure spike is transferred to the outlet.

As the speed at constant load increases, the thickness of the oil film increases and more load is borne by the lubricant. Therefore, the force of the roughness is reduced and with this reduction, the contribution of the roughness in the load bearing of the total friction coefficient decreases until it enters the hydrodynamic lubrication regime, in which the increase in velocity at constant load results in an increase in the coefficient of friction. In the elastohydrodynamic lubrication regime, with increasing speed, a significant increase in pressure spike is observed.

Figs. 3a and 3b shows the results of different linear velocity and load for 5 and 7 row disc test data. According to the results, the same concept described in previous paragraphs is validated. By increasing load and decreasing velocity, a rise in friction coefficient was observed. Consider the velocity of 0.0535m/s, when the load is doubled from 5 to 10 kg, the friction coefficient increases about 7.7 percent for 5 row and 7.5 percent for 7-row disc. Meanwhile, if load is considered 5kg and velocity is almost halved from 0.107 to 0.0535m/s, the friction coefficient increases about 5.5 and 4.5 percent, respectively.

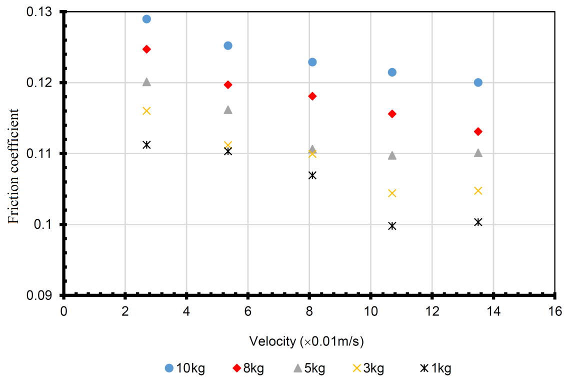
To investigate the effect of pore density, the results of 5 and 7 row in comparison to each other are shown in Fig. 3c. In this figure the ratio of difference friction coefficient of 7-row from 5-row disc to the friction coefficient of 7 row is reported. From the results, it is concluded that the 5-row disc has better results, because with increasing speed, the coefficient of friction decreases and with increasing load at constant speed, de the coefficient of friction decreases.

As a result, the other tests were performed on 5-row discs to investigate the effect of texturing surface of line and point contact conditions.

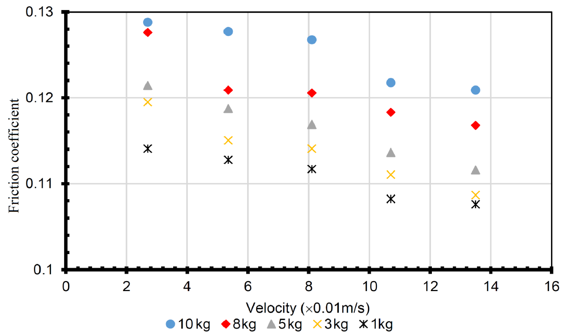
To compare the effect of surface texture, two speeds and three loads were selected. Five row textured disc was used for comparison with plane disc.

Table 1
Friction results for plane and textured discs.

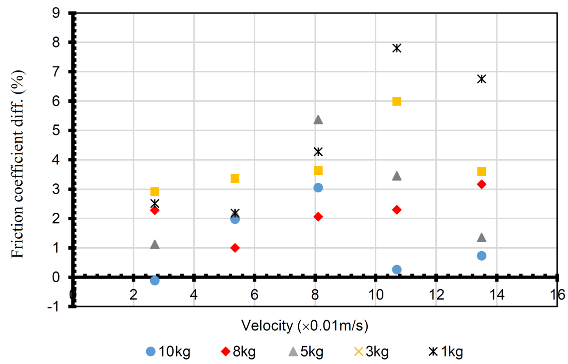
Velocity (m/s)	Load (N)	Friction coefficient			
		Plane-line	Plane-point	Textured-line	Textured-point
0.085	50	0.215±0.007	0.235±0.001	0.189±0.001	0.201±0.003
	100	0.171±0.001	0.198±0.003	0.143±0.004	0.160±0.002
	140	0.116±0.001	0.145±0.006	0.095±0.005	0.125±0.004
0.215	50	0.189±0.002	0.206±0.007	0.152±0.003	0.168±0.006
	100	0.155±0.004	0.180±0.001	0.130±0.002	0.155±0.003
	140	0.108±0.002	0.150±0.002	0.091±0.001	0.122±0.003



(a) Five-row textured disk



(b) Seven-row textures disk



(c) Friction coefficient difference= (Friction$_{5\text{-row}}$−Friction$_{7\text{-row}}$)/ Friction$_{7\text{-row}}$ (%)

Fig. 3. Comparison of frictional behavior between 5 and 7 row textured discs.

The line and point contact condition were also compared with each other. In point condition the contact area was smaller than line contact, so load was distributed on a smaller area, higher pressure was produced and thinner lubricant film thickness was formed. Therefore, the friction force in point contact was much more than line contact due to thinner film thickness. Table 1 shows the average value of friction coefficient which is an average of several repeated experiments.

As shown in Table 1, in both line and point contact condition, the highest coefficient of friction is related to lower velocity and lower load and appositely the lowest coefficient of friction is related to higher velocity and highest load. Moreover, at constant load, increasing the velocity increases the thickness of the lubricating layer and thus reduces the coefficient of friction. Furthermore, as can be seen in this case, at a constant speed, with decreasing load, the coefficient of friction decreases and the amount of wear increases.

The wear amount in line and point contact condition for plane and textured disc is shown in Table 2. A textured surface form a thicker lubricant film and asperities contact is reduced considerably. The lowest amount of wear is related to higher speed and lower load, while the highest amount of wear is related to lower speed and higher load. As expected, with increasing speed at constant load, the amount of wear is reduced and with increasing load, the increase in wear is determined.

It is shown in both Tables 1 and 2 that for friction coefficient the error is less than 5 percent and for wear amount the error is between 2 and 11 percent.

Fig. 4 shows the value of the coefficient of friction reduction and Fig. 5 shows the amount of wear reduction after texturing the surface. It is seen that a significant reduction in the amount of wear in textured compared to plane disc, which indicates the effect of micro pores on the surface of the disc. Comparing the results with each other, it was found that the coefficient of friction for textured discs decreased by about 13 to 19% discs and the amount of wear reduction was more than 40% compared to plain discs. According to the results in some situation, the point contact results improvement is better than line contact and in other situation the line contact friction coefficient improves much more than point contact condition. A definitive result is friction improvement in both condition after texturing the surface. But Fig. 5 results show that wear amount in point contact improves much more than line contact condition, especially in higher velocities.

Table 2
Wear amount results for plane and textured discs.

Velocity (m/s)	Load (N)	Wear amount (mg)			
		Plane-line	Plane-point	Textured-line	Textured-point
0.085	50	6.93±0.15	7.67±0.15	3.87±0.15	3.70±0.15
	100	8.37±0.15	9.05±0.15	4.60±0.15	5.10±0.15
	140	9.5±0.150	9.57±0.15	5.10±0.15	5.20±0.15
0.215	50	6.37±0.15	7.37±0.15	3.43±0.15	3.17±0.15
	100	7.70±0.15	7.85±0.15	4.23±0.15	3.45±0.15
	140	7.97±0.15	9.27±0.15	4.90±0.15	4.13±0.15

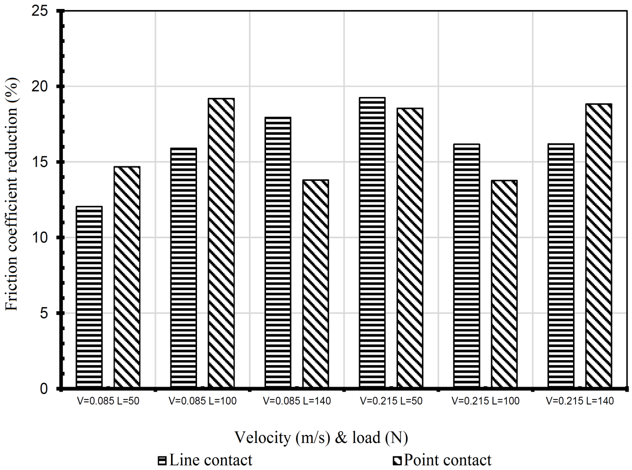


Fig. 4. Friction Coefficient Reduction in line and point contact condition after texturing the surface.

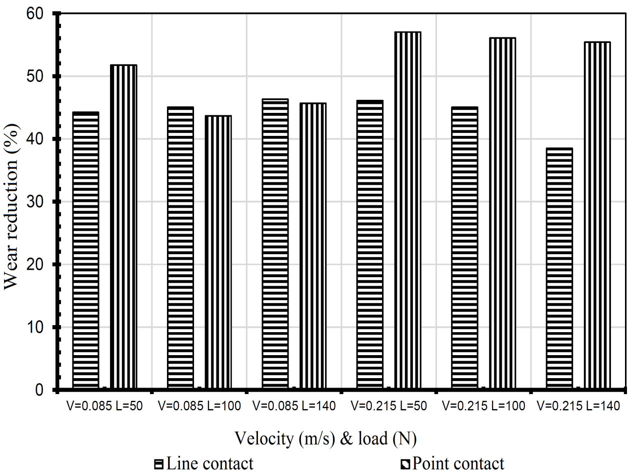


Fig. 5. Wear amount Reduction in line and point contact condition after texturing the surface.

The smaller area in point contact versus line contact condition results in higher pressure, thinner lubricant film, and asperities interaction probability. These phenomena can cause more friction and wear amount in the point contact condition. The textured cavities which provide reservoir for lubricant can effectively help to reduce the friction and wear in this situation by assisting to preserve the lubricant film. The results show the better efficacy of dimples in point contact with respect to line contact condition.

4. Conclusions

In this study the changes of the coefficient of friction and the amount of wear was investigated between the plane and textured surfaces under line and points contact mixed lubrication. The changes of friction coefficient and wear rate in mixed lubrication regime with linear velocity and load were investigated experimentally using a pin-on-disc device. The textured discs were first examined in two modes of 5- and 7-row. Since the 5-row disc showed better results for the mixed lubrication regime, it was selected for the experiments. The results show that in both line and point contact for plane and textured surfaces, with increasing load at constant speed, the coefficient of friction decreases and the amount of wear increases, also with increasing speed at constant load, the coefficient of friction and the wear amount decrease. The result of comparing planed and textured surface in linear and point contacts showed the role of micro pores in reducing the coefficient of friction and the wear amount, by 12 to 19 percent and more than 40%, respectively.

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