Vysoké učení technické v Brně
Brno University of Technology

Fakulta strojního inženýrství
Ústav konstruování / Odbor Kontrovaní strojů

Faculty of Mechanical Engineering
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Effect of surface texturing on friction under starved lubrication conditions

[Pojednání ke státní doktorské zkoušce]
[Discourse on the thesis]

Autor práce:Ing.Fadi Ali

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Autor práce: **Ing. Fadi Ali**
Author

Vedoucí práce: **prof. Ing. Martin Hartl, Ph.D.**
Supervisor

Brno 2012

ústav konstruování

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CONTENTS

1 INTRODUCTION

In industrial and economic applications the lubrication becomes necessary to extend the life cycle of machine components and to reduce the friction, wear and the loss of energy between rubbing surfaces. Non-conformal surfaces are common in machine components such as gears, rolling bearings, cams ... etc, the area of contact between non-conformal surfaces is very small (point or line contact) which results in a very high concentrated pressure, elastic deformations and contact fatigue even under low loads. In addition to the concentrated stress, a lot of machine components with non-conformal contacts work under starved lubrication especially in cases of high speeds and loads or in cases of using grease lubrication. Otherwise, the starvation has a significant effect on forming the film thickness between non-conformal EHL contacts and it is one of the most common reasons of fatigue failures.

It is well known that the elastohydrodynamic lubrication regime is dominated in non-conformal contacts. However, the theory of elastohydrodynamic lubrication (EHL) was clearly explained by Dawson and Higginson [1] which led to understand the behavior of elements with non-conformal surfaces in EHL contacts. In reality it is difficult to predict the value of friction coefficient due to the sensitivity of friction against many parameters such as operating conditions, roughness of mating surfaces and rheological properties of lubricants where almost all lubricants exhibit a non-Newtonian behavior under severe operating conditions. In addition, the value of friction coefficient changes substantially according to the regime of lubrication. Three typical regime of lubrication are distinguished in practice: 1- boundary lubrication 2- mixed lubrication (BL) 3- hydrodynamic lubrication (HL) or elastohydrodynamic lubrication (EHL). It is well known that using of lubrication leads to reduce the friction and wear between rubbing surfaces, but there is always a need to improve the performance and tribological properties of machine components to answer the request of severe operating conditions (high speeds, high loads and starvation).

Thesis focuses on measuring the coefficient of friction between lubricated non-conformal surfaces with artificial micro-features in sliding motion under starved lubrication conditions (the non-conformal contact is represented by a starved contact between a steel ball and flat disc). Torque sensor is used for measuring the friction force in the contact and the optical interferometric technique is simultaneously used for capturing interferometric images to observe the effects of starvation on the formation of lubricating film.

A lot of efforts and researches were carried out to study the effect of artificial micro-features on the film thickness profile and the pressure distribution under fully flooded and starved conditions in EHL contacts. But there is still a need to clarify and to observe the direct effect of surface textures in reducing the friction of non-conformal contacts and asperities interactions under starved lubrication. However, in this work, it is expected that shallow micro-dents could help in enhancing the film thickness under starved conditions by emitting the lubricant to the inlet of contact which results in reducing the coefficient of friction and minimizing the possibility of film collapse under starved conditions.

2 PRELIMINARY AIM OF THESIS

Thesis focuses on developing a traction machine to observe experimentally the coefficient of friction between smooth and textured non-conformal surfaces under starved and fully fooled conditions. Measurements are performed by using a torque sensor driven by the ball shaft and the system is integrated with computer through a Digital/Analog card. Because of research and projects requirements in the Institute of Machine and Industrial Design in Brno University of Technology, the subject of thesis was modified from “***Design of traction machine***” to the subject “***Effect of surface textures on friction under starved lubrication conditions***“. According to the previous change of thesis topic, the preliminary objective of thesis can be formulated by the following:

Experimental investigation on the effect of micro-dents on friction between sliding non-conformal surfaces under poor lubrication conditions by using a Tribometer equipped with a torque sensor.

3

3 LITERATURE REVIEW

3.1

3.1 Stribeck curve and lubrication regimes

The separation between lubricated surfaces in relative motion determines the value of friction and the role of asperities in carrying the load .Under low speeds the separation between surfaces is small and the nature of friction is nearly Colombian and the most part of load is carried by asperities resulting in high values of friction between rubbing surfaces, this regime of lubrication is called Boundary Lubrication (BL). Increasing the velocity increases the separation between lubricated surfaces in relative motion and the part of load which is carried by asperities becomes less while the hydrodynamic effect in the contact increases, this regime of lubrication is called Mixed Lubrication (ML). Under high velocities and low loads the separation in the contact becomes large enough to create a full film lubrication and the effect of asperities becomes negligible and the most part of load is carried by the hydrodynamic effect, this regime of lubrication is called the Hydrodynamic Lubrication (HL), when the contact between lubricated surfaces is non-conformal then there will be elastic deformations of surfaces, this regime is called the Elastohydrodynamic Lubrication (EHL). Figures 1-a and 1-b show a typical Stribeck curve and the coefficient of friction as a function of Hersey number ($\eta_0 u_s / p_{av}$).It is evident from Figure 1-b that the separation $\lambda_s = h_s/\sigma_s$ increases strongly with increasing the Hersey number, where σ_s is the standard deviation of roughness, $h_s$is the film thickness of lubrication.

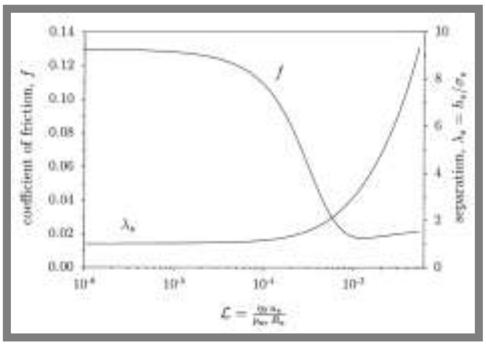

Fig. 1-a Stribeck curve and the separation $\lambda_s = h_s/\sigma_s$

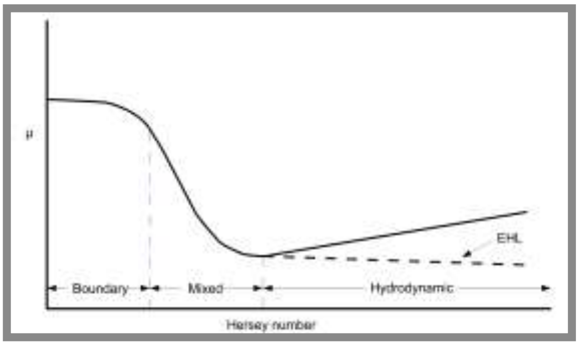

Fig. 1-b Stribeck curve and the distribution of lubrication regimes

3.2

3.2 Friction of smooth surfaces in fully flooded EHL contacts

The elastohydrodynamic lubrication is usually associated with non-conformal contacts where the film thickness can be less than 1μm. On the other hand, non-conformal contacts are subjected to high pressures which results in doubling the viscosity of lubricant passing through the contact leading to increase the shear stress especially in sliding motion. However, the friction in fully flooded EHL contacts is governed by many factors such as operating conditions, roughness and viscosity.

3.2.1

3.2.1 Effect of operating conditions, roughness and viscosity

Bassani et al. [2] measured the value of friction coefficient under different values of slide-to-roll ratio and results show that the friction of non-conformal contacts decreases with increasing the entraining velocity $u_e = \frac{u_1+u_2}{2}$ due to the increase of temperature in the contact which results in reducing the viscosity of lubricant. On the other hand, increasing the slide-to-roll ratio leads to higher values of friction coefficient because of the increase of shear rate. See Figure 2.

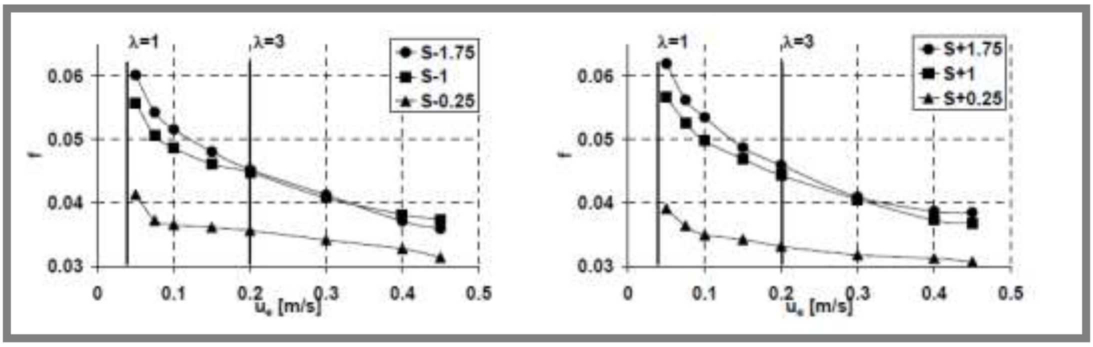

Fig. 2 Comparison of friction for negative and positive slide-to-roll ratio

The effect of roughness on friction coefficient was investigated by Wen-zhong Wang et al. [3-4]. Experiments were performed for ball on disk with different values of roughness R_a, see Figure 3, the study revealed that a higher friction coefficient is corresponded to the higher roughness regardless the regime of lubrication.

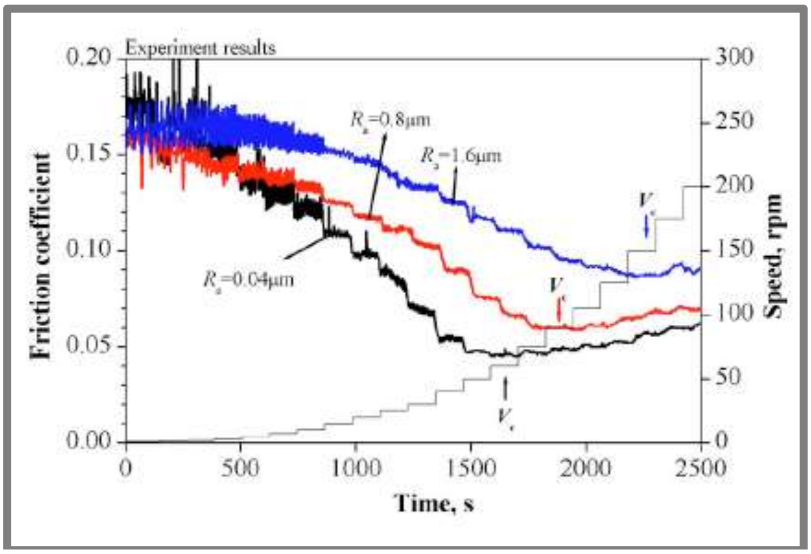

Fig. 3 Effect of roughness on Stribeck Curve

Sojoudi and Khonsari [5] studied the behavior of friction for lubricated point contact under sliding conditions and results show that the Stribeck curve is influenced by the physical properties of lubricant such as the viscosity and the effect of viscosity is clear particularly in the range of mixed lubrication, see Figure 4.

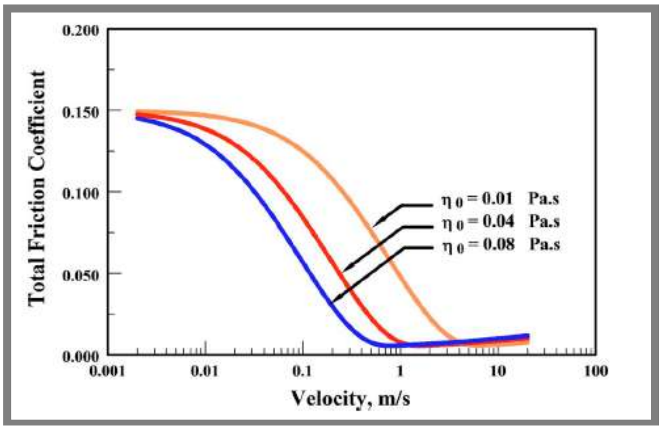

Fig. 4 Effect of viscosity on Stribeck Curve

3.3 Friction of textured surfaces

Microstructures have an influence on the coefficient of friction between contacting surfaces. Two opposing effects were observed by Geiger et al. [6]:

- Enhancement in the lubricant film thickness in the contact resulting in a better separation and less interaction between asperities and thus leads to a reduction in the coefficient of friction.
- In contrast, micro-dents cause a turbulent of lubricant flow, increasing the flow resistance and leading to an increase in the coefficient of friction.

Andersson et al. [7] revealed that a significant improvement in the tribological performance can be achieved with the low density of microstructures combined with an oil of high viscosity. Oils with a low viscosity are proper for lubricating surfaces with a high density of microstructures at low sliding velocities.

Wakada et al. [8] investigated frictional properties of textured ceramic surfaces through pin-on-disk tests under a very high contact pressure, see Figures 5 and 6. It was found that an appropriate surface modification can lead to significant reductions in friction under boundary and mixed lubrication conditions at the line contact in sliding motion, see Figure 7. The study revealed also that tribological characteristics depend strongly on the size and density of micro-dimples and the dimple size of approximately 100µm at a density of 5–20% is recommended.

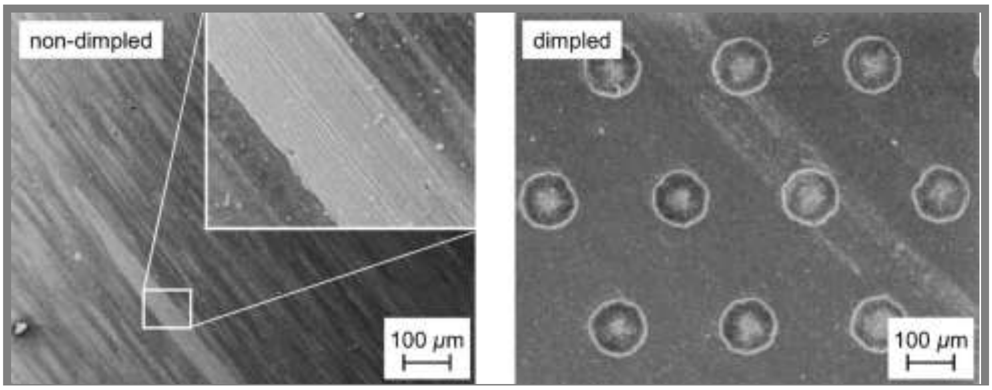

Fig. 5 Dimpled and non-dimpled surfaces

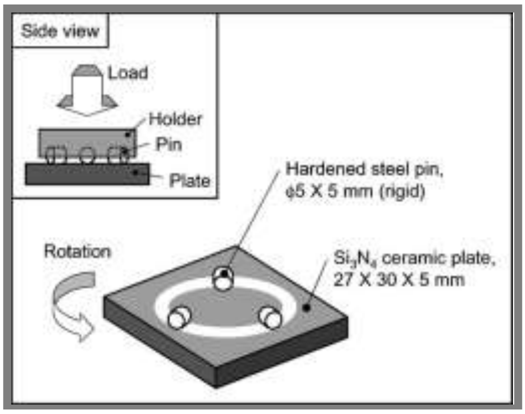

Fig. 6 Schematic diagram of pin-on-disk friction testing method

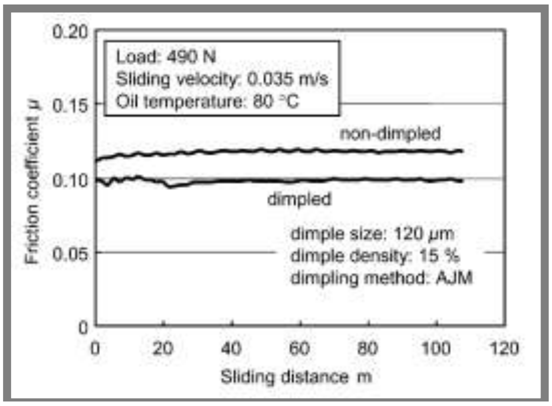

Fig. 7 Coefficient of friction of dimpled and non-dimpled surfaces

3.3.1 Effect of micro-textures orientation

Pettersson et al. [9-10] found that the ability of micro-textures to extract the lubricant into the interface of a sliding contact and to trap wear particles is related to the shape, size and orientation of the texture patterns. Under starved boundary lubrication conditions, surfaces with micro-textures showed very low and stable friction and much better wear resistance than non-textured surfaces, see Figures 8 and 9. The successful textures were those having the smallest tested grooves or squares and an orientation perpendicular to the sliding direction.

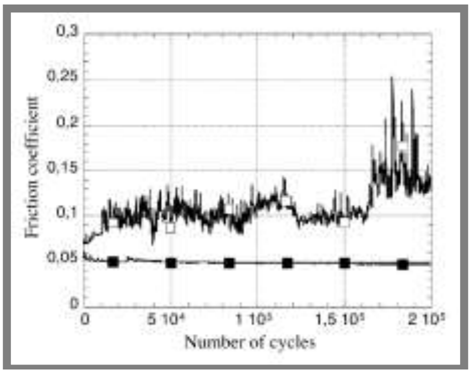

Fig. 8 The influence of texture orientation on the friction behaviour under starved boundary lubrication

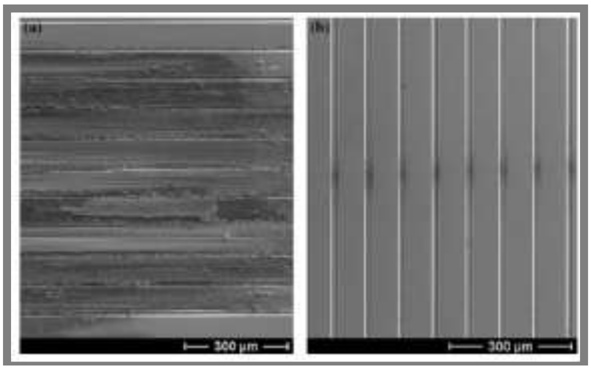

Fig. 9 The influence of orientation on wear under starved boundary lubrication

3.4 Effect of micro-textures on the pressure and film thickness

Implementation of surface texturing for some mechanical parts with parallel or conformal surfaces, for example, seals and thrust bearings, leads to decrease the friction and improve the lifetime of operating contacts. Etsion et al. [11-13] studied experimentally and theoretically the effect of surface texturing on the friction and it was proven that the application of laser surface texturing (LST) with piston rings provides benefits in reducing the friction about 30% in comparison with non-textured rings, also it was found that the performance of thrust bearings can be improved by using a proper micro-texturing because of the increasing of the hydrodynamic pressure, load capacity and wear resistance. Nanbu et al. [14] established a model-based virtual texturing for simulating the effects of textures bottom shape on the elastohydrodynamic lubrication contacts. The study provided an explanation of micro-texturing mechanisms in improving the performance of lubrication and film thickness, where cavitations prevent the increase of negative pressure at the edges of dimples and increase the lifting, which means that cavitations in the micro texturing create a net load capacity because of the drop of pressure in the inlet zone leading to increase the flow of lubrication to the contact. However, this mechanism works with other factors and other mechanisms to improve the performance of lubrication such as, the elastic deformation and the volume of dimples. The drop of pressure in the dimpled area causes a higher elastic deformation in the edges of dimples, then the volume of dimples becomes smaller and as result, the lubricant will be squeezed out to increase the supply of oil. Sliding speed determines the efficiency of micro-texturing where increasing the speed of textured surfaces leads to increase the supply of lubrication thus improving the film thickness and it is recommended to create micro-textures on faster moving surfaces because it results in more enhancement of film thickness in the contact.

3.4.1

3.4.1 Pressure distribution in dented non-conformal surfaces

The utilization of micro-textures to improve the tribological properties of surfaces is not limited for conformal surfaces, but also with non-conformal contacts some benefits can be obtained. Many papers were published about the effects of surfaces texturing on the film thickness and pressure profile for non-conformal contacts and it is stated that micro-textures with proper dimensions and operating conditions can enhance the film thickness. Nakatsuji et al. [15] evaluated the effects of micro-pockets on the lubrication by using a roller with a small number of micro-dents marked by a diamond pyramid; results revealed that micro-dents can prevent metal to metal contacts and scuffing under high load. S. Coulon et al. [16] studied a non-conformal dented contact under pure sliding conditions and it was observed a high value of pressure in the place where lubricant leaves the dent which results in very high pressure gradients .Figures 10-a and 10-b show the pressure profile for dented and smooth surfaces in dry contacts and under sliding motion.

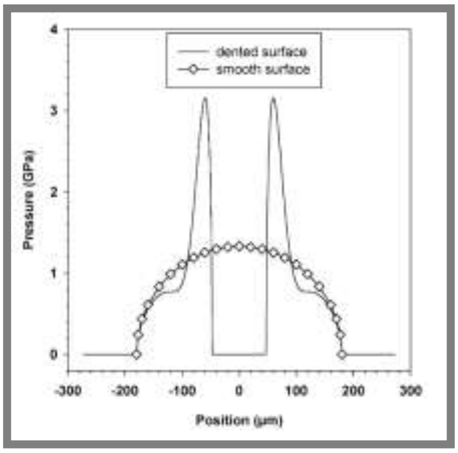

Fig. 10-a Pressure profiles for dented and smooth surfaces in dry contacts

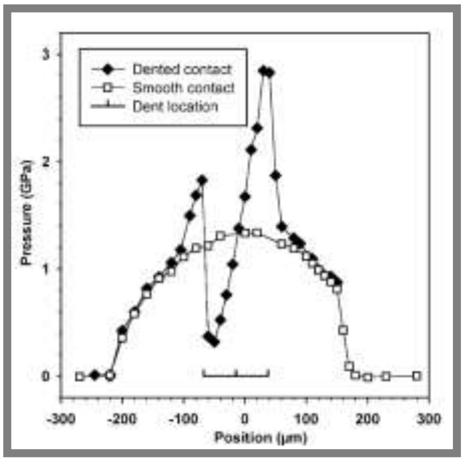

Fig. 10-b Pressure profiles for dented and smooth surfaces under sliding motion

Nélias et al. [17] studied the effects of debris dents on rolling contact fatigue**.** Results show that the dent (or bump) has effects on the pressure distribution and film thickness profile, only when the depth of dent is larger than the amplitude of surface roughness and the regime of lubrication becomes different according to the size of defects on the surface.

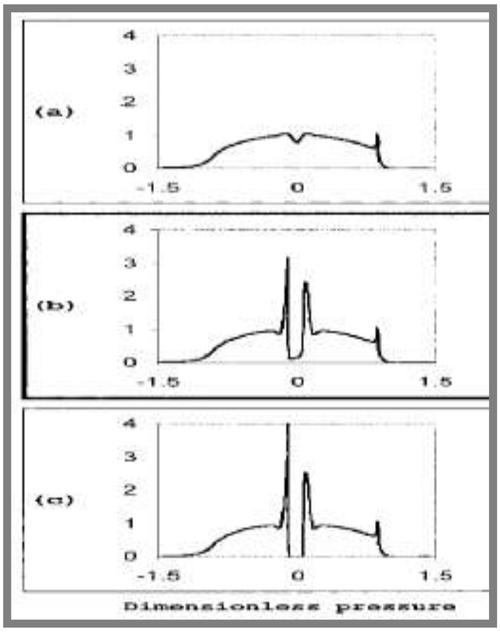

Fig. 11 Definition of three lubrication regimes corresponding to three typical sizes of dents

For small size, the dent will be totally absorbed by the elastic deformation and the film thickness of lubrication will be the same such as in the case of smooth surfaces and lubrication regime is the quasi-smooth EHL regime, Figure (11-a). Defects (dents) of intermediate size will be partially absorbed by the deformation and the micro-EHL regime without cavitation occurs, Figure (11-b). The large size of dent leads to create a zone of cavitation and the micro-EHL regime with cavitation occurs, Figure (11-c).The same study of Nélias referred to the effect of slide-to-roll ratio on the shear stress in the vicinity of the dent and it is evident from Figure 12 that the maximum shear stress increases for higher ratios of slide-to-roll.

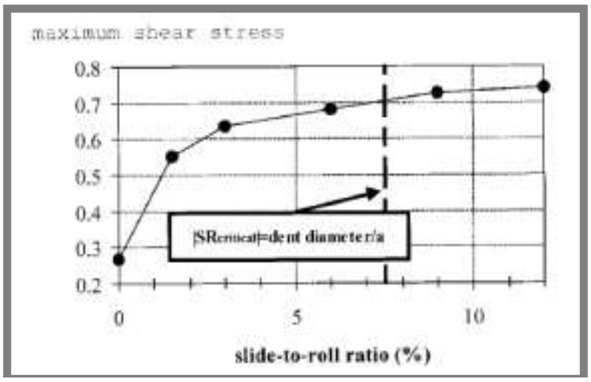

Fig. 12 Maximal local shear stress calculated in the vicinity of the dent (with shoulder) vs. slide-to-roll ratio

3.4.2 Film thickness profile in dented non-conformal surfaces

It was revealed in references [18-20] that for non-conformal contact (ball on disc) the emitted lubricant from the shallow dent improves the film thickness in case the disc moves faster than the dented ball at the same time the micro-cavities located around the border of contact had a negative effect on the film thickness and the hydrodynamic pressure because of the side leakage of lubricant .In addition to that, it was referred to the effect of surface texturing in case of reversal motion where the starvation of lubricant is dominated and results show that micro-textures help in reducing the negative influence of starvation by emitting additional lubricant from the dents which can lead to avoid the collapse of film thickness due to the starvation. Micro-dimples help in reducing the friction by playing a role of lubricant reservoir and by acting as a micro-trap for impurities in lubricant due to the wear, in addition to that, the film thickness of lubrication can be significantly influenced by the micro-dimples. Krupka and Hartl provided an experimental study for the effect of micro-dents on the thin EHD lubrication films for non-conformal surfaces; the study was performed by using the colorimetric interferometry. Results show that in case of positive slide-to-roll ratio, deep micro-dents can lead to reduce the lubricant film thickness, on the other hand minimizing the depth of micro-dents can improve the film thickness of lubrication (at slide-to-roll ratio $\sum=0.5$ minimizing the depth of micro-dents from 1180nm to 560 nm led to increase the film thickness from 20nm to 49 nm) .In case of the negative slide-to-roll the depth of micro-dents has not a significant effect in reducing the film thickness. When dents are on the slower moving surface push the lubricant in the direction of flow, otherwise dents on faster surface push the lubricant in the opposite direction of flow. Micro-dents improve the performance of lubrication and the tribological properties for the contacts between non-conformal surfaces, which lead to reduce the scuffing in high loads and metal-to-metal contacts, see Figures 13 and 14.

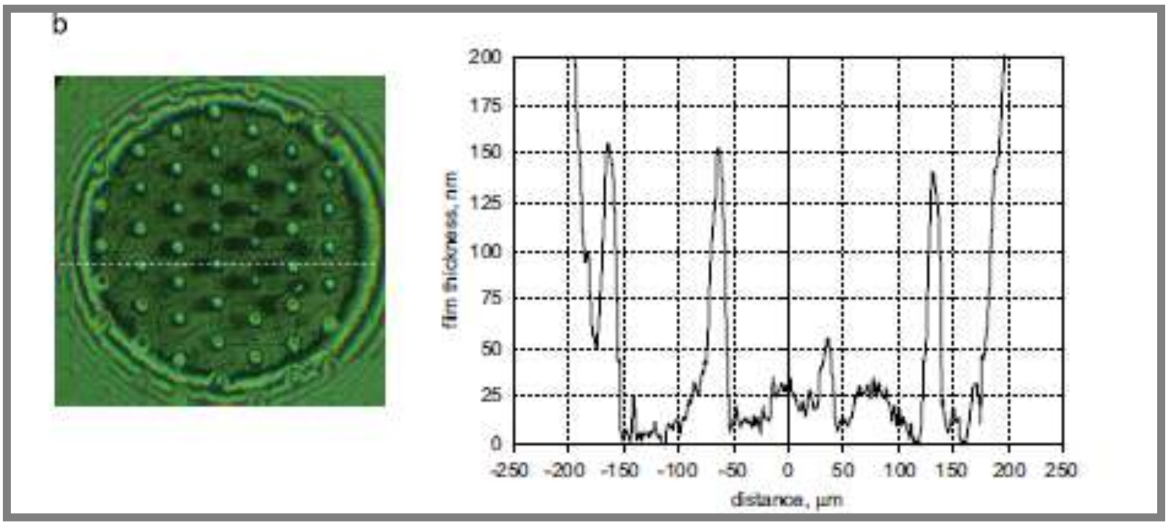

Fig. 13 Film thickness for non-conformal dented surfaces

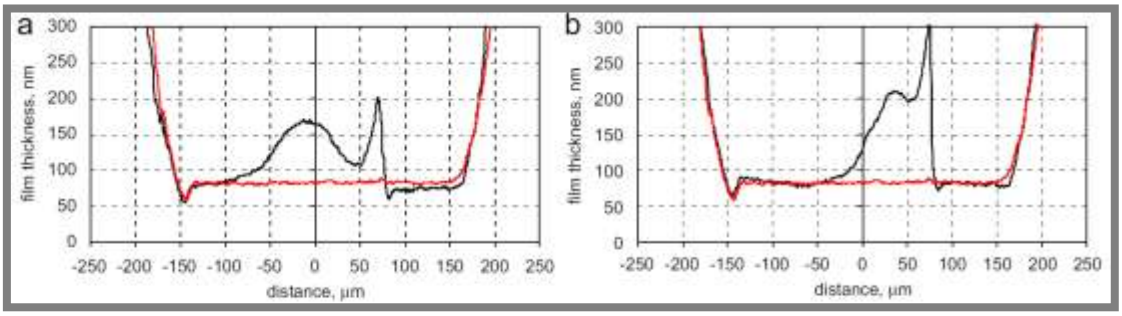

Fig. 13 Comparison of film thickness for smooth and dented non-conformal surfaces for ∑=0.5

3.4.3 Effect of micro-dent depth

Lubrecht .A [21] investigated the Influence of local and global features in EHL contacts, it was revealed that, the local features such as indentation influence noticeably the pressure contact when these local features have an amplitude (depth) larger than the global roughness. In concentrated contacts the pressure distribution can be approximated by the pressure distribution of the dry contact and results show that the difference in pressure and stress field is small for dry and lubricated contact with artificially-created dent. The dent geometry influences strongly the life reduction and as the dent dimensions increase the life tends to reduce.

Mourier et al. [22-24] investigated experimentally and numerically the effect of micro-cavities on the film thickness for a contact between steel ball and silica disk. The conclusion of work showed that the micro-cavities do not significantly influence on the oil film thickness under pure rolling conditions. On the other hand, micro-cavities have a positive or a negative effect in case of sliding motion according to the depth of micro-cavities. Deep cavities cause a local decrease in film thickness Figure 14, while shallow micro-cavities increase significantly the film thickness Figure 15. The local lubricant film reinforcement is proportional to the slide-to-roll ratio, and to the time spent by the micro-dimple into the contact zone because the oil is pushed out from the micro-cavity under the combined effect of sliding motion and the elastic deformation of contacting surfaces.

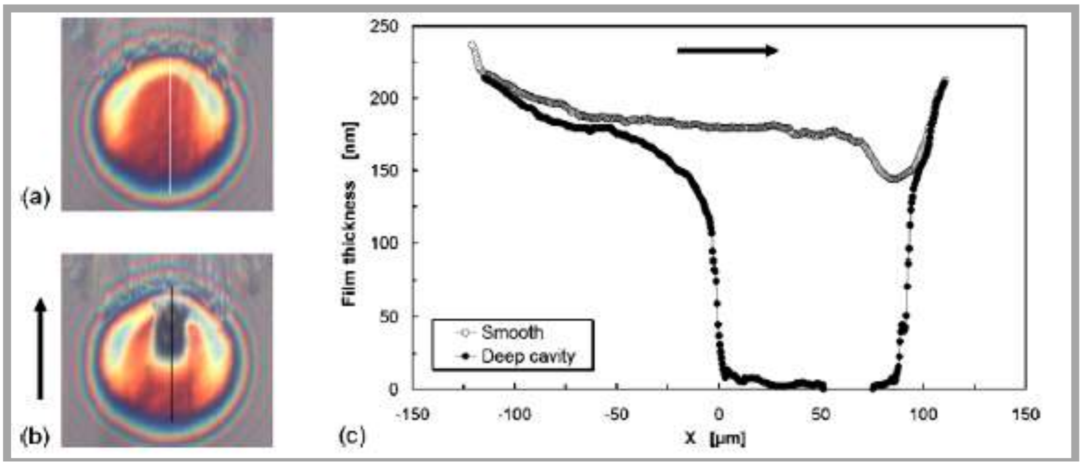

Fig. 14 Effect of deep micro-dimple on film thickness

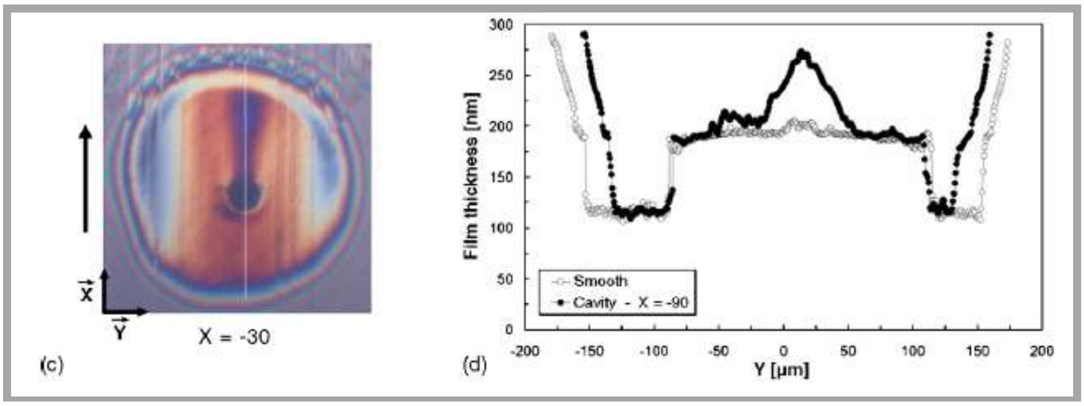

Fig. 15 Effect of shallow micro-dimple on film thickness

3.4.4

3.4.4 Effect of slide-to-roll ratio on the behavior of micro-dents

Figure 16-a shows that under pure rolling conditions the micro-cavity does not induce a significant film thickness variation and a small local pressure decrease accompanies the micro geometry during its passage. This pressure reduction increases with the depth of the micro-cavity, whereas it does not seem to depend on the diameter and profile of the micro-cavity.

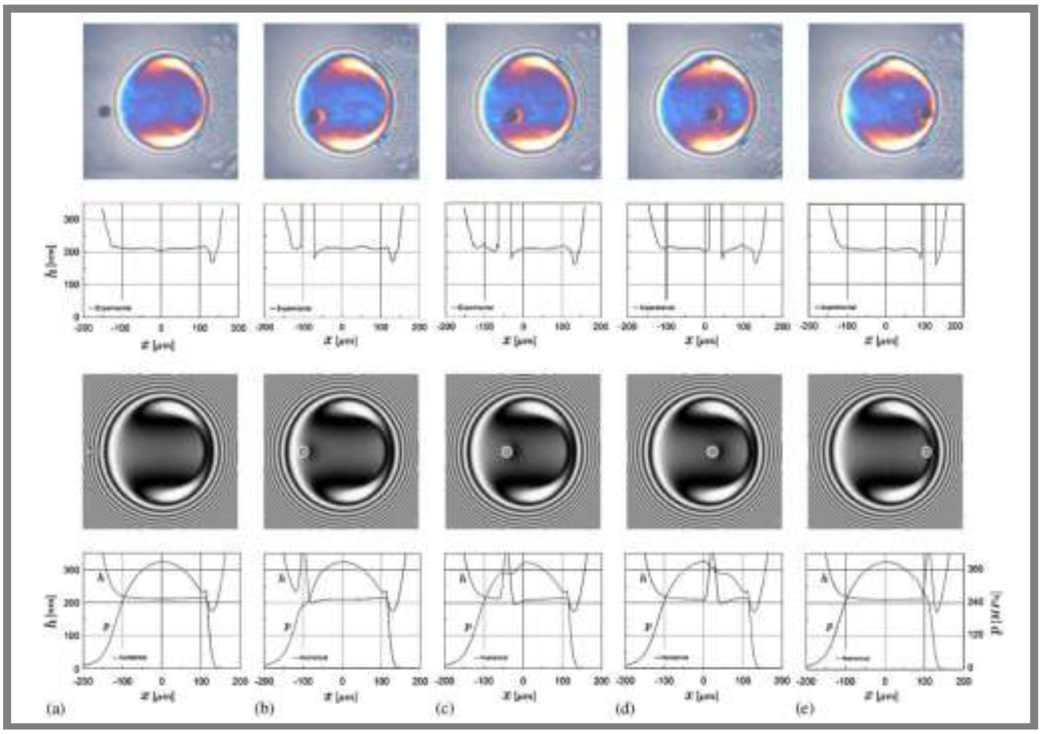

Fig. 16-a Micro-cavity passing through a circular EHL contact under pure rolling

When sliding is introduced in the elastohydrodynamic lubrication regime, two different types of film thickness distributions can be observed as a function of the micro-cavity depth:

- Local collapse of fluid film attributed to the deep micro-cavity
- Transient increase of lubricant film thickness accompanied to the shallow micro-cavity.

Figure 16-b shows the effect of passing micro-cavity through a circular EHL contact under rolling–sliding conditions and it can be stated that a significant increase in lubricant film thickness is induced by a shallow micro-cavity in the elastohydrodynamic lubrication regime.

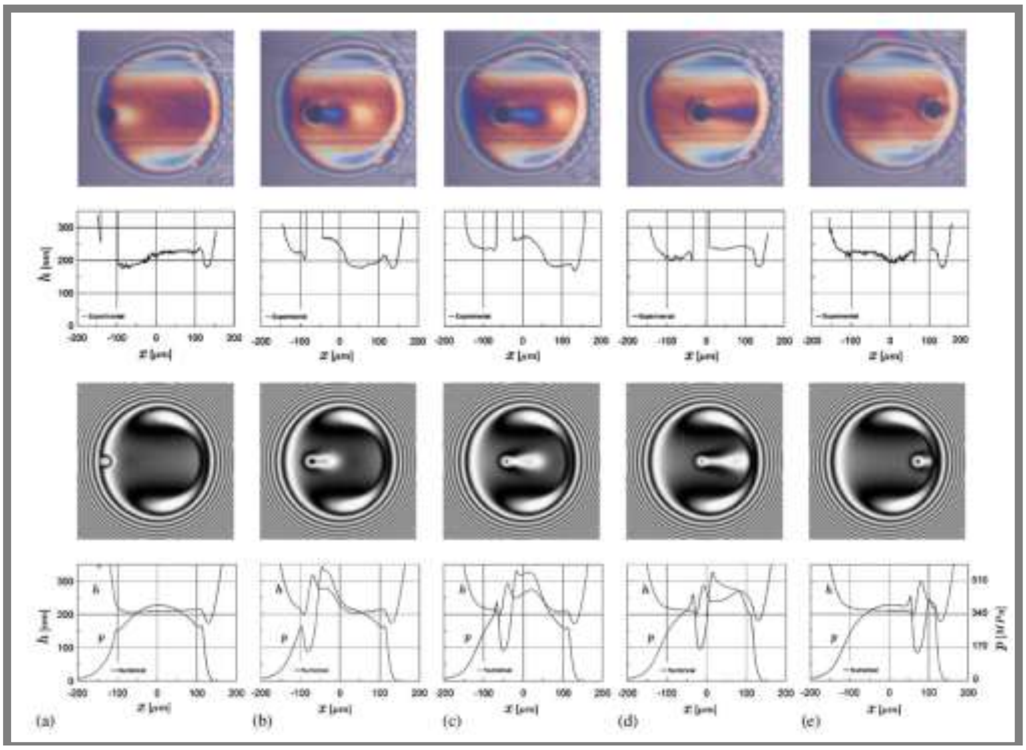

Fig. 16-b Micro-cavity passing through a circular EHL contact under rolling–sliding conditions

Wedeven et al. [25-26] used the optical interferometry to measure the film thickness associated with artificially produced dents and grooves under rolling and sliding conditions. A reduction in film thickness and pressure was observed at the leading edge of the dent due to the local modification of EHD pressure created by the dent through its passage in the contact .The noticeable increase of pressure and film occurred on the trailing edge of the dent. However, under pure rolling conditions, the film thickness distribution remained the same as the dent passed the Hertzian region. Micro-EHD pressures were observed as the dent passes the Hertzian region under sliding conditions. Grooves, which are perpendicularly oriented on the direction of flow, cause a substantial increase in film thickness , while the parallel grooves to the direction of flow have not a significant effect on the film thickness under pure rolling and pure sliding.

The effect of operating conditions was investigated by Kaneta et al. [27-28]. It is revealed that the film thickness distribution or the elastic deformation of the bump is influenced significantly by the surface kinematic conditions and the orientation of the bump and under simple sliding conditions, surface irregularity has a negative effect on the film thickness.

Ai et al. [29-30] studied numerically the influence of moving dent on point EHL contacts and results show that under pure rolling conditions, the effect of dents on the pressure distribution is very limited and localized in the vicinity of dent. See figure 17.On the other hand, the presence of sliding motion results in a pressure ridge at the trailing edge as the dent moves faster than the opposite surface and at the leading edge as the dent is slower than the opposite surface and as the slide-to-roll ratio increases, the pressure and film thickness profile become more influenced by the dent. Increasing the slide-to-roll ratio and the depth of dent is generally associated with increasing the fluctuation of fluid in the vicinity of dent and the pressure fluctuation becomes larger when the dent is localized on the slower or stationary surface. Otherwise, increasing the dent width in x and y direction reduces the fluctuation. Figure 18-a and Figure 18-b show a numerical simulation of pressure distribution and film thickness in the vicinity of micro-dimple under positive and negative slide-to-roll ratio (SRR).

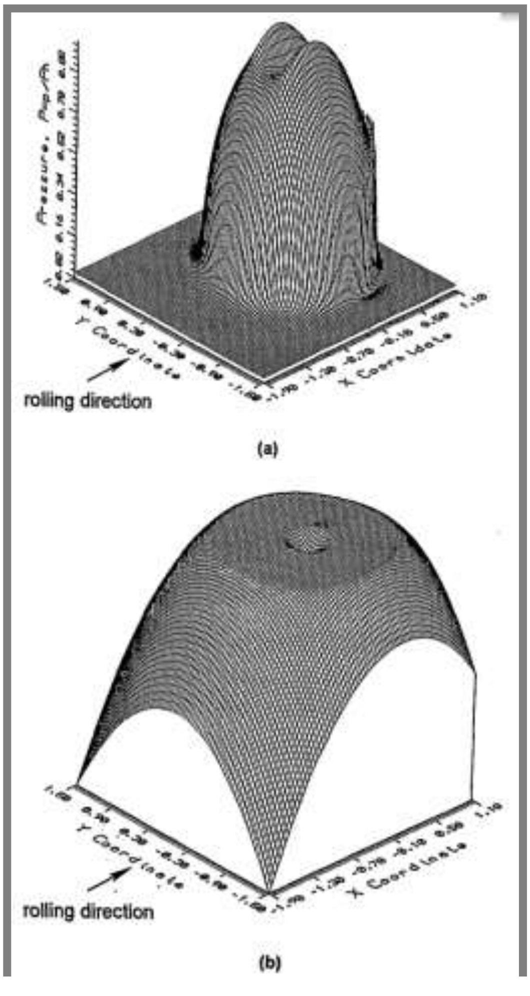

Fig. 17 Effect of micro-dent on pressure distribution (a) and film thickness profile (b) under pure rolling conditions SRR=0

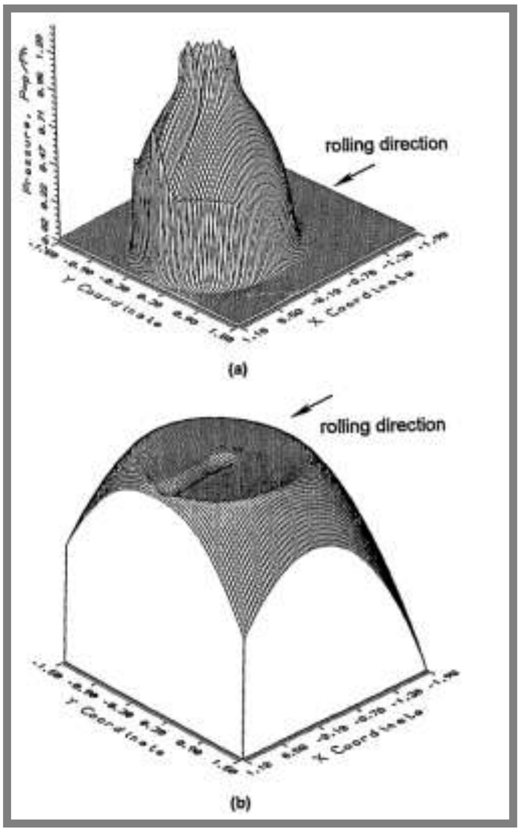

Fig. 18-a Effect of micro-dent on pressure distribution (a) and film thickness profile (b) under sliding conditions SRR= -2

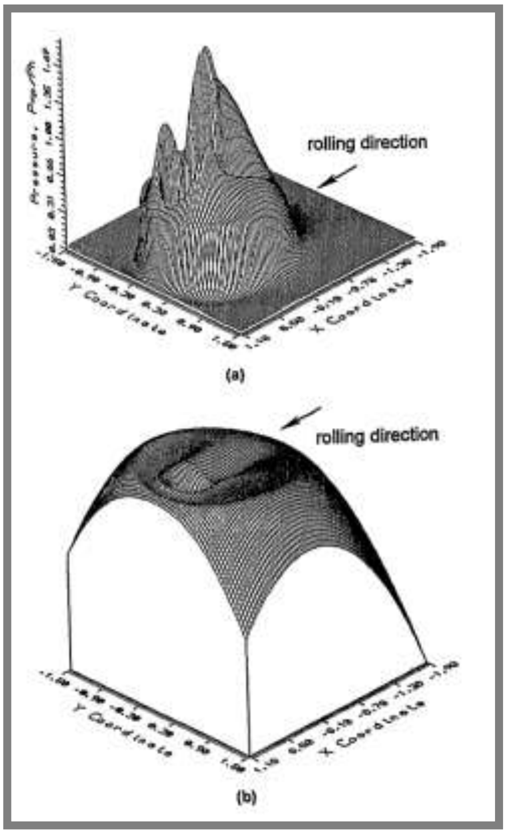

Fig. 18-b Effect of micro-dent on pressure distribution (a) and film thickness profile (b) under sliding conditions SRR= +2

3.5 Surface texturing under starved lubrication

3.5.1 Definition of starvation in EHL contacts

Starvation occurs in case of insufficient amount of lubricant in the inlet region of contact and results in a thinner film thickness in comparison with the fully flooded lubrication. Figure 19 shows that both surfaces 1 and 2 bring a thin layer of lubricant, $h_{\infty 1}$and $h_{\infty 2}$ respectively, into the contact.

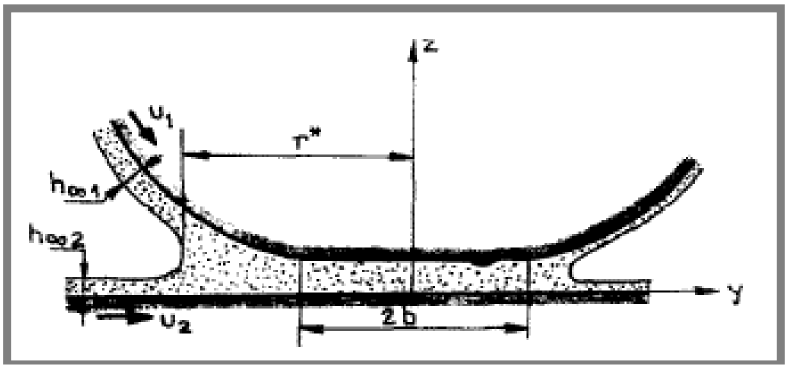

Fig. 19 Illustration diagram of a starved EHL contact

The starvation can be encountered under severe or non-steady state operating conditions where the behavior of film thickness cannot be predicted by Hamrock and Dowson formula .See Figure 20. In addition to that the starvation can be attributed to high speeds, high viscosity and high temperatures of lubricant or due to the lack of lubricant and it is well known that the starvation is common in cases of grease lubricants or highly loaded bearings [31-33].

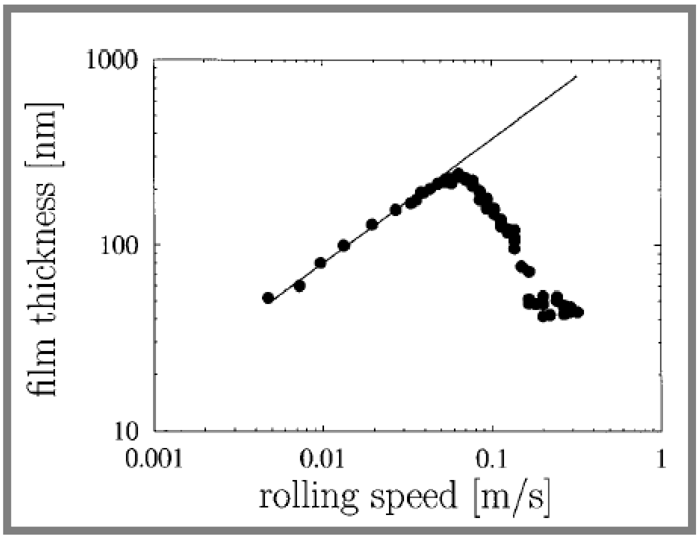

Fig. 20 Film thickness under starved conditions

Wedeven et al. [34] studied the starvation of ball bearing by using of optical interferometry and results showed that pressure build-up will be delayed when the inlet region is insufficiently filled by lubricant resulting in failure of developing the film thickness. On the other hand the reduction in pressure build-up for EHD contacts leads to reduce the rolling friction and to increase the sliding friction. The results showed also that the film thickness diminishes to zero in the region of Hertzian pressure under starved conditions. The effect of starvation on the lubrication of rigid non-conformal contacts was studied by Ghosh et al. [35] and it was revealed that the dynamic load capacity of the contact reduces with the increase of starvation in comparison with the fully flooded dynamic load capacity and the starvation has not a valuable effect on the peak of pressure in the contact.

3.5.2 Effect of starvation on the friction of smooth surfaces

D.J. Schipper et al. [36- 38] introduced a theoretical model supported by experiments to predict the friction; the model depends on the fact that the friction of lubricated contacts is the sum of asperities friction and the hydrodynamic action as the following:

$$f = \frac{F_f}{F_T} = \frac{f_c F_c + \iint_{AH} \tau_H(\dot{\gamma})\, dA_H}{F_T} \qquad (1)$$

Where f *is* the coefficient of friction, F_f is the friction force in the contact, F_T is the normal load, F_c is the load carried by asperities, f_c is the coefficient of friction of asperities, τ_H is the shear stress, $\dot{\gamma}$ is the shear rate, A_H is the area of contact.

Figure 21 shows the effect of starvation on the coefficient of friction and the separation. As the degree of starvation is low the coefficient of friction does not change strongly in comparison with the fully flooded condition. Otherwise, the friction starts to increase when the separation between mating surfaces becomes lower and the oil amount on the track is little.

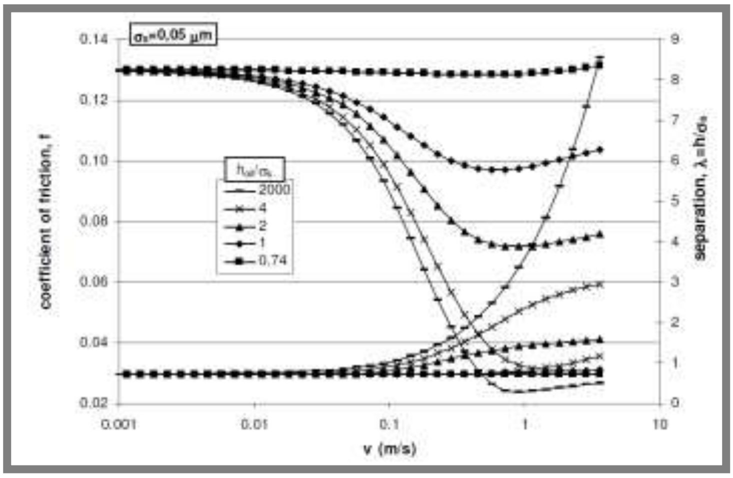

Fig. 21 Effect of starvation on the coefficient of friction and the separation of line contact

Querlioz et al. [39] studied the influence of starvation on the traction coefficient using Mini Traction Machine (MTM). The study proved that the traction depends strongly on the amount of lubricant and operating conditions. Figure 22 shows the effect of oil amount on the traction coefficient.

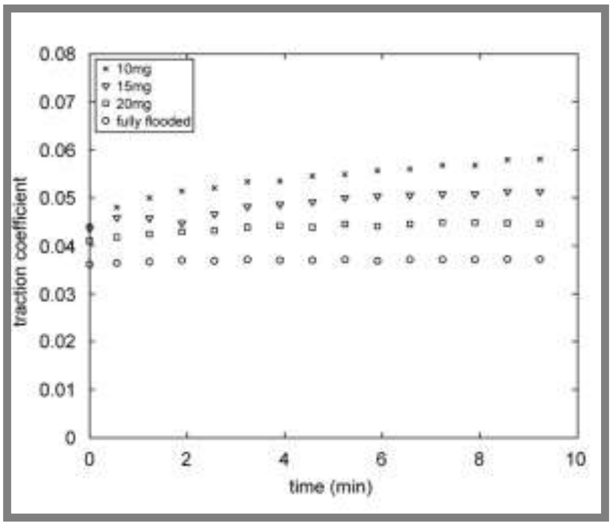

Fig. 22 Traction coefficient versus time for different amounts of lubricant

3.5.3 Effect of micro-dents under starved lubrication

Dumont et al. [40] described numerically the behavior of pits in fully flooded and starved ball-on-disc contact and it was found that for fully flooded conditions the film profile around the pit is similar to the smooth film profile but for starved conditions there is a change in film profile on the sides and behind the pit and in the starved case the height of the film behind the pit is almost 3 times higher than the height in front of the pit and the benefits of pits decreases as the degree of starvation decreases because the film thickness becomes larger and the amount of emitted oil from the pits becomes less see, Figure 23.

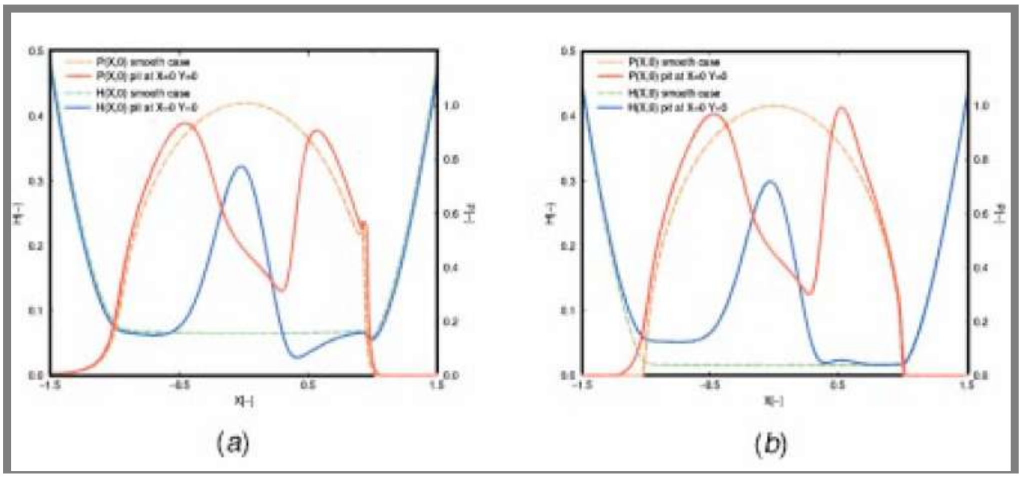

Fig. 23 Gap and pressure profiles along the X axis for fully flooded and starved contacts

3.6

3.6 Effect of surface texturing on the contact fatigue

Contact fatigue is a major reason of machine components failure. The initiation of fatigue is usually induced by micro-cracks and the propagation of cracks which leads later to the fracture. Cheng et al. [41] investigated experimentally the contact fatigue crack initiation with artificial defects; it was revealed by the study that the direction of friction force determines the position of cracks initiation. In addition to that, the propagation of crack is strongly influenced by the roughness hardness and temperature.

Enhancing the fatigue life of rolling line contacts was investigated by Zhai et al. [42], the significant of the study shows that the effect of micro-dents on the fatigue life depends on the lubrication regime; micro-dents are more efficient to enhance the fatigue life under severe lubrication conditions than under fully flooded lubrication.

Ai et al. [43-45] revealed that under the pure sliding the effect of micro-dents on the stress is quite negligible and there are not noticeable benefits of using micro-dents to reduce the contact fatigue life under good lubrication conditions. When sliding is introduced the effect of micro-dent becomes clear and a significant pressure spike is generated which leads to a severe stress concentration on the edge of micro-dent. The location of concentrated pressure depends on the direction of sliding, see Figure 24.

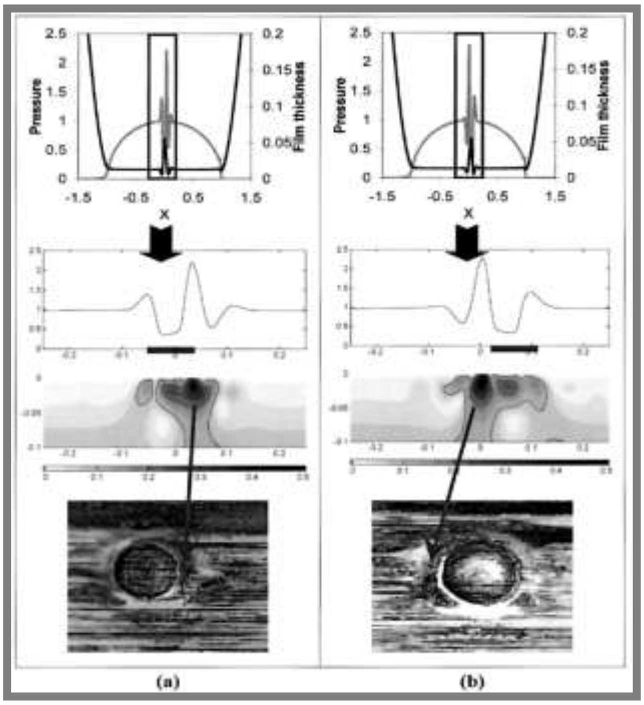

Fig. 24 stress field in the vicinity of micro-dent

4 ANALYSES AND INTERPRETATION OF LITERATURE

The behavior of friction for lubricated non-conformal contact is studied by many researchers and it was proven experimentally and theoretically that the friction is affected by many factors such as speed, load, viscosity, temperature …etc. recent researches were carried out to investigate effect of surface modification on reducing the friction coefficient, results revealed that surface texturing has benefits in reducing the friction and increases the load capacity for conformal surfaces. On the other hand, a lot of effort was done to investigate the benefits of surface texturing for non-conformal surface during the different regime of lubrication and the results showed that there are advantages of surface texturing if dimensions of dents were properly designed. In general, surface texturing leads to increase the film thickness and the maximum pressure in the contact between non-conformal surfaces because the micro dents play the role of micro reservoirs which emit the lubricant to the area of contact. Some experimental results recorded a negative effect of deep micro-dented surfaces such as reducing the film thickness. The effect of slide-to-roll ratio on dented surfaces was studied by many researchers and it was proven that when slide-to-roll ratio increases, the pressure and film thickness are significantly modified, while the effect of dimples becomes negligible under conditions of pure rolling. Dumont et al. [28] investigated numerically the effect of micro pits under starved condition on the film thickness and pressure contact and the results revealed that pits can improve the film thickness under starved lubrication.

The literature can be summarized by the following points:

- The coefficient of friction in EHL contacts is strongly influenced by the operating condition and the physical properties of lubricant.
- The effect of surface roughness on the friction is negligible when the separation is larger than the height of roughness.
- Micro-dents with proper dimensions and orientation could reduce the coefficient of friction between rubbing surfaces.
- Micro-dimples with a small size (in the scale of roughness) have a little effect on the pressure distribution and the film thickness profile in EHL contacts, because the micro-dimples will be completely absorbed by the elastic deformation.
- Micro-dimples with a large size cause a reduction in the film thickness in EHL contacts due to the cavitation.
- Micro –dimples with proper dimensions enhance the film thickness in non-conformal contacts.
- There is a very high concentrated stress around the edges of micro-dimples in the EHD Hertzian contact.
- The effect of micro-dimples under pure rolling conditions is very little in comparison with the effect of same micro-dimples under pure sliding conditions.
- Micro-dimples are more efficient in enhancing the film thickness under starved conditions than under fully flooded conditions.

- Shallow micro-dents are recommended. On the contrary, deep micro-dents can cause negative effects on the film thickness

One of the most important parameters that describes the efficiency of surface texturing is the friction because the friction determines the amount of wear and the loss of energy between rubbing surfaces. A lot of machine components have a non-conformal contact working under starved condition due to the severity of operating conditions and the increase of using the grease lubricants, for this reasons it is necessary to find a method to prevent the metal-to-metal contact and reducing the friction. Surface texturing can offer the solution to avoid the failure of components under starved conditions, at the same time it is necessary to take into account the possible negative effects accompanied with the modification of surface topography such as the cavitation, the fluctuation of pressure around dents and the concentration of pressure on the edges of micro-dimples in the EHD Hertzian contact. Otherwise, the measuring of friction coefficient represents a valuable method to estimate the efficiency of surface texturing.

5 AIM OF THESIS

On the basis of the profound study of the literature and published papers, the aim of thesis can be formulated by the flowing:

The main objective of thesis is to investigate experimentally the effects of shallow micro-dents on the coefficient of friction between non-conformal surfaces (ball on disk) under starved lubrication conditions in the presence of sliding.

It is important to understand the combined effect of starvation and surface modification on the friction in lubricated contacts. However, the aim of thesis is based on the hypothesis that, if the contact between starved lubricated non-conformal surfaces was modified by shallow micro textures then the friction between these surfaces will be less because micro textures work as lubricant reservoirs which support the film of lubrication in the contact and prevent the collapse of film lubrication. In addition, it is expected that micro-dents to be more effective under starved conditions than under fully flooded conditions since the micro-amount of oil emitted from micro-dents can be more helpful in enhancing the starved thin film in comparison with enhancing the thick fully-flooded film. On the other hand, there is a possibility that micro textures lead to reduce the amount of lubricant in the contact under starved condition because the lubricant will be trapped in the micro textures resulting in reducing the feed rate of lubricant which leads to high friction and wear.

Basic Aims of dissertation:

- Studying experimentally the effect of artificial micro-dents on reducing the coefficient of friction in sliding motion between non-conformal surfaces under starved lubrication.
- Observing the optimum distribution of shallow micro-dents on matting surfaces.
- Comparing results with fully flooded conditions to ensure whether micro-dents are more effective under starved or fully flooded conditions.

6 METHODS

The nature of research is quantitative and deductive. The approach of acquiring data depends on the experimental measuring and analyzing results.

6.1 Methods and materials

A tribometer modified by adding a torque sensor on the ball shaft is used for measuring the friction between ball and disk in presence of different lubricants, where the contact between the ball and disk represents a non-conformal contact. Speed of ball and disk can be changed in the range (-100 to +100 rpm) and for loads can be varied for a wide range, see figure 25.

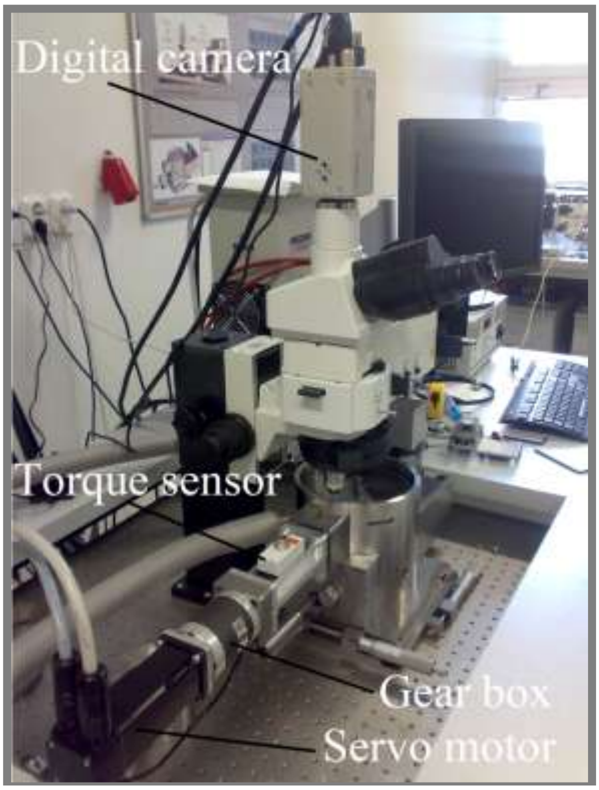

Fig. 25 Tribometer equipped by a torque sensor and a digital camera

Fig. 26 Glass and metal disk for experiments

When the surfaces of ball and disk are in relative motion, the entrainment speed u_m is given by:

$$u_m = (u_{disk} + u_{ball})/2 \tag{1}$$

where u_{ball} [*m/s*]and u_{disk}[*m/s*] are the linear speed of the ball and disk respectively. The slide-to-roll ratio SRR is given by the following formula:

$$SRR = (u_{disk} - u_{ball})/u_m \tag{2}$$

The sliding speed u_s is given by:

$$u_s = |u_{disk} - u_{ball}| \tag{3}$$

The diameter of ball is 25.4 [mm] and it is made of steel AISI 52100 with a measured roughness (RMS) about 15 nm with elastic module 210 GPa while the diameter of the disk at the contact with the ball is 100 [mm]. Two disks are used in the experiments, a glass disk and a metal disk, see Figure 26. The apparatus is integrated with a computer for acquiring data, where a sensor torque is installed to measure the traction between the ball and disk then the software shows the results on graph and saves the results. The apparatus is equipped by a digital camera and the contact between the ball and disc is illuminated by a high-power source of light to improve the resolution of images, which gives the possibility of capturing interferometric images of the contact simultaneously with the measuring of friction by the torque sensor. Figure 27 shows the type of results which can be obtained from the combination between the torque sensor and the optical interferometry. In all experiments the base oil (2400N) with a dynamic viscosity h = 0.38[Pas] at 40 °c is used to lubricat the non conformal contact. Experiments were conducted in the ambient temperature 24°c.

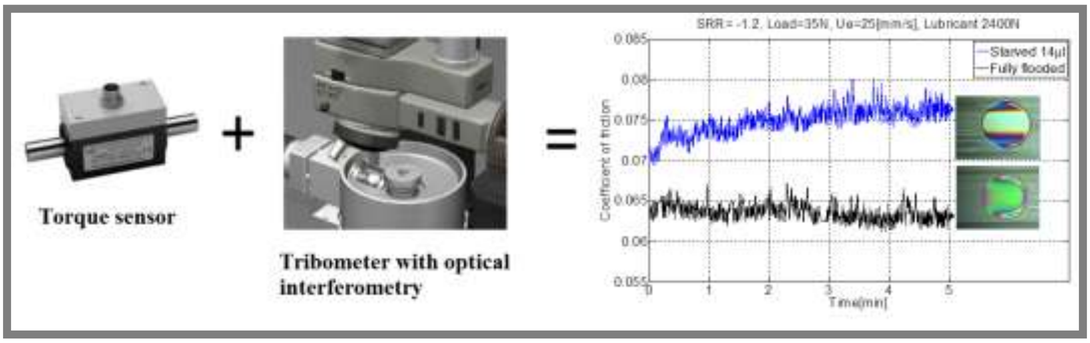

Fig. 27 type of results which can be obtained from the combination between the torque sensor and the optical interferometry

Another instrument can be use in the context of measuring the coefficient of friction, MTM (Mini Traction Machine) is a flexible instrument for measuring the coefficient of friction of lubricated contacts under a wide range of slide-to-roll ratio, and the process of test is automated with MTM and the results are reliable. See Figures 28 and 29.

Fig. 28 MTM (Mini Traction Machine)

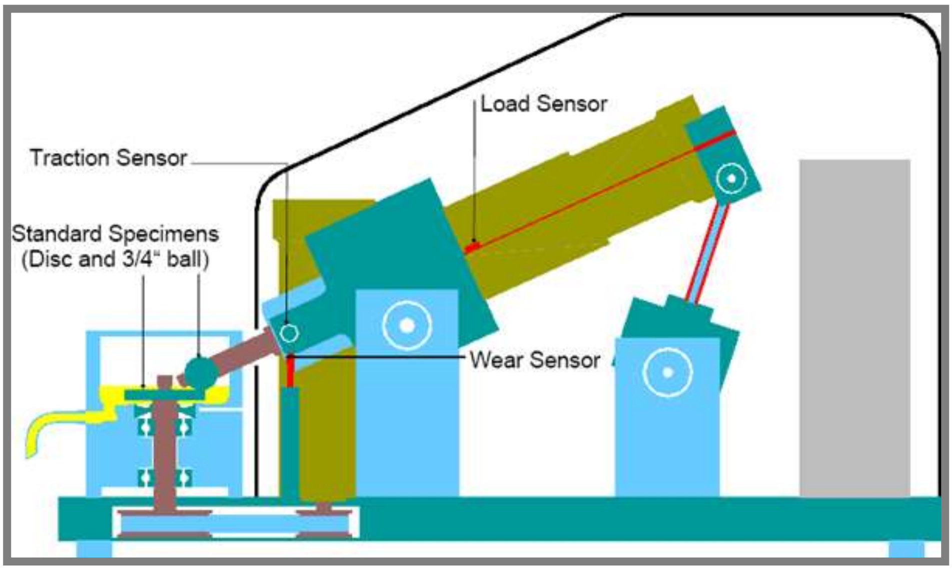

Fig. 29 Schematic of MTM

To investigate the effect of micro-dents on the coefficient of friction under starved conditions, the surface of the ball can be indented by a Rockwell indenter integrated with a load cell. Proposed dimensions of dents are 35 μm for the diameter and 0.6 μm for the depth. These dimensions can be made by applying a load of 8N on the Rockwell indenter.

7
7.1
7.1.1

7 CURRENT STATE OF THESIS

7.1 Preliminary results

7.1.1 Effect of starvation on the friction coefficient

The effect of starvation degree was observed under steady state operating conditions of the sliding velocity and load (SRR=-1 , entraining velocity $u_e = 60[mm/s]$, load=32N) where the degree of starvation was modified by changing the oil amount on the track , see Figure 30 and please note that the images were captured in the 5th minute. Interferometric images show that the coefficient of friction increases largely under starved conditions when the air-oil meniscus starts to touch the Hertzian contact with a little amount of lubrication (18μl) on the track. Otherwise, the coefficient of friction of starved and fully flooded contact is nearly the same for a sufficient amount of oil (42μl) on the track. The sudden rise of friction coefficient is attributed to the insufficient replenishment of fluid on the track for low amount of lubricant which results in reducing the distance between the air-oil meniscus and the center of Hertzian contact.

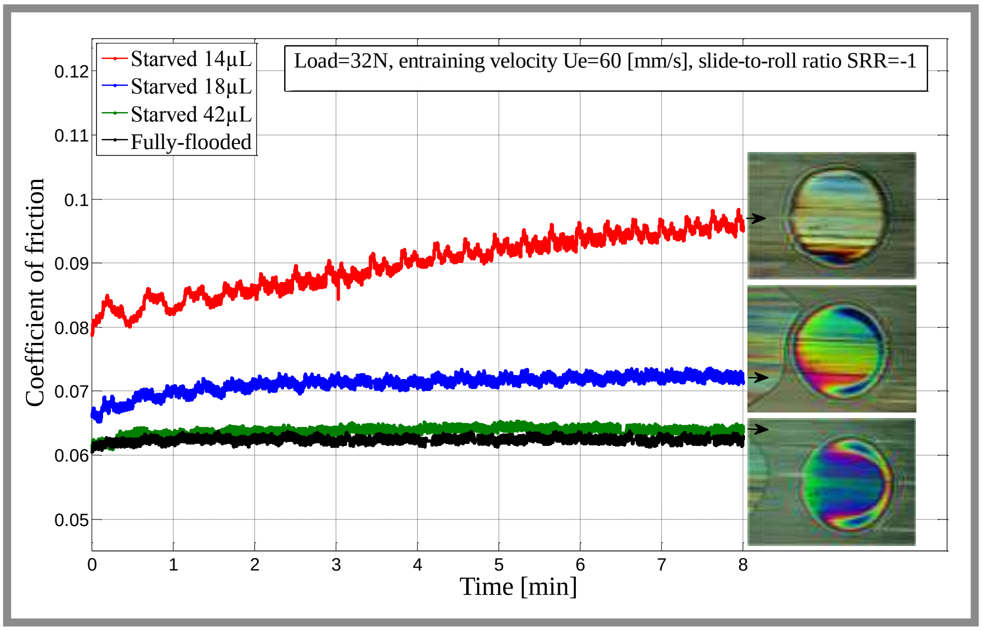

Fig. 30 Effect of oil amount on the coefficient of friction and the position of air-oil meniscus

7.1.2

7.1.2 Friction of textured surfaces

I

of ball was artificially modified by 4 rows of shallow micro-dents, see Figure 31. The average diameter of dent is about 35μm with depth about 0.6μm. Figures 32 and 33 show a comparison of friction coefficient for smooth and textured surface under starved and fully flooded lubrication. The results show that the benefits of micro-dents under starved lubrication are proportionally considered where the reduction of friction is about 9%. On the other hand, the benefits of micro-dents under fully flooded condition is negligible and the value of average friction of smooth and textured surfaces is nearly the same, this is justified by that, the amount of emitted fluid from the micro-dent doesn't make a noticeable difference in enhancing the film thickness under fully flooded lubrication where the film is originally large enough.

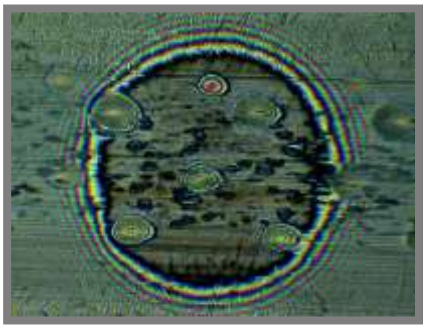

Fig. 31 Micro-dents on the ball surface

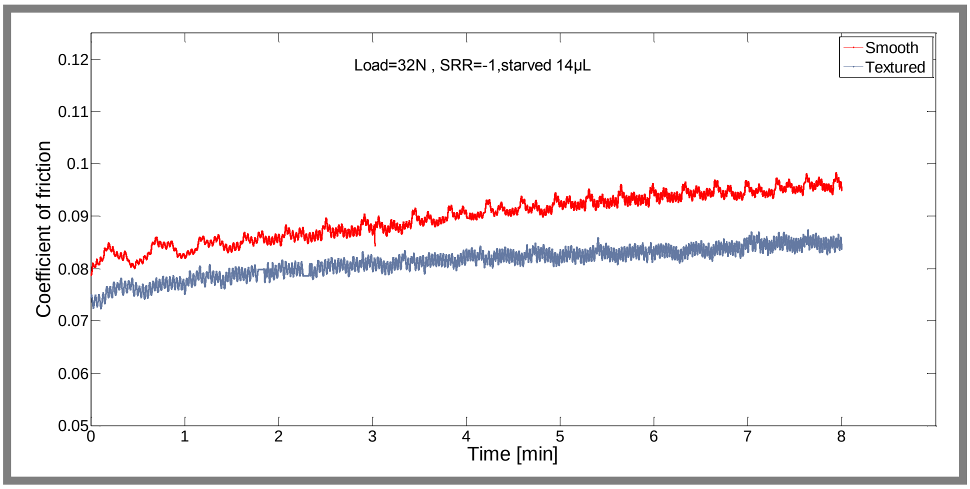

Fig. 32 Coefficient of friction for smooth and textured surfaces under starved conditions

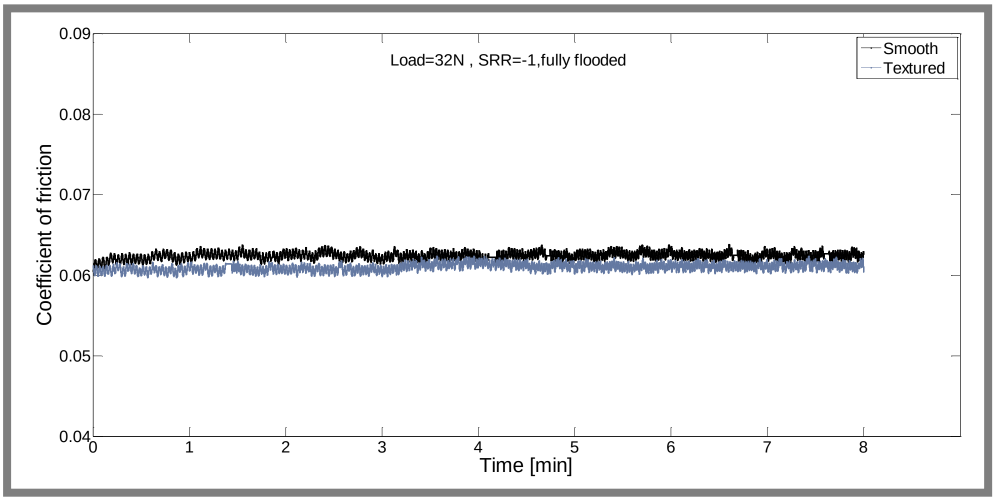

Fig. 33 Coefficient of friction for smooth and textured surfaces under fully flooded conditions

8 CONCLUSIONS

The loss of power due to the friction in some machines can reach high levels (30-40% in engines), in addition to that, the most of wear is caused by friction between contacting surfaces, for these reasons the reduction of friction is considered to be an engineering and economic requirement. This research can be included in the context of improving the tribological characteristics of rubbing surfaces by using the method of surface modification which provides the possibility of enhancing the film of lubrication in the contact. There are many examples of successful application of micro-dimples for mechanical components operating under hydrodynamic conditions such as seals, rings and bearings .This research is a serious attempt to test the ability of surface texturing in reducing the friction between lubricated non-conformal surfaces under starved conditions.

Results will support the researches concerning the improving of tribological properties to reduce the loss of power due to the friction between rubbing surfaces in relative motion under severe operating conditions. Otherwise, results can be published in scientific journals which are relevant to the field of Tribology such as TRIBOLOGY INTERNATIONAL, TRIBOLOGY LETTERS, TRIBOLOGY & LUBRICATION TECHNOLOGY, JOURNAL TRIBOLOGY and TRIBOLOGY TRANSACTIONS.

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