FRICTION OF NON-CONFORMAL CONTACTS UNDER STARVED EHD LUBRICATION

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This paper presents experimental results of measuring the friction coefficient of smooth non-conformal surfaces (ball-on-disk test) in the range of elastohydrodynamic lubrication. The coefficient of friction under starved lubrication was observed under relative sliding motion by using a Tribometer and torque sensor. On the other hand, interferometric images were captured by a digital camera simultaneously with measuring the friction between the ball and disk to illustrate the influence of the air-oil meniscus position on the behavior of friction under the starved lubrication. The results show that the friction of starved contacts depends strongly on the distance of the air-oil meniscus from the Hertzian contact. However, the position of air-oil meniscus is basically related to the entraining velocity, the value of slide-to-roll ratio and the oil amount on the track.

Keywords
Friction, Starved lubrication, Non-conformal surfaces, EHD lubrication

1. Introduction

Non-conformal surfaces are common in machine components such as gears, rolling bearings, cams ... etc, where the area of contact between non-conformal surfaces is very small (point or line contact) which results in a high concentrated pressure and a contact fatigue even under low loads. 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 power between rubbing non-conformal surfaces. 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, the roughness of mating surfaces and rheological properties of lubricants where almost all lubricants exhibit a non-Newtonian behavior under severe operating conditions, see references [Jacod 2001], [Jacod 2003] and [Johnson 1993]. The traction of EHL contacts was studied by many researches, [De Vicente 2005] et al, introduced a numerical model to calculate the Couette friction of point contact and it was revealed that there is an acceptable agreement between the numerical solution and the experimental results. [Liu 2007] et al, studied numerically the shear thinning of elastohydrodynamic lubrication (EHL) in point contacts. The effect of roughness on the behavior of friction in point contacts was investigated by [Sojoudi 2010] et al. The phenomenon of 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 in EHL contacts [Hamrock 1976]. However, the starvation is attributed to the high viscosity of lubricants and high temperatures or to the lack of lubricant in the inlet of contact. Also, it is well known that the starvation is common in cases of grease lubricants or highly loaded bearings [Damiens 2004], [Olaru 1993] and [Chevalier 1993]. [Wedeven 1971] et al, studied the starvation of ball bearing by using the optical interferometry, results showed that pressure build-up will be delayed when the inlet region is insufficiently filled by the lubricant and that results in a 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 1987] et al, 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. A recent experimental study was carried out by [Querlioz 2007] et al, to investigate the effect of starved lubrication on the fatigue life of point contacts and it was observed that the starvation increases the thermal effects in the contact which leads to a scuffing failure. On the other hand, the friction depends strongly on the amount of lubricant and the operating conditions.

2. Methods and materials

A Tribometer modified by a torque sensor on the ball shaft was used for measuring the friction between the ball and disk in the presence of base oil, 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 loads can be varied in a wide range, see Fig.1 (a).

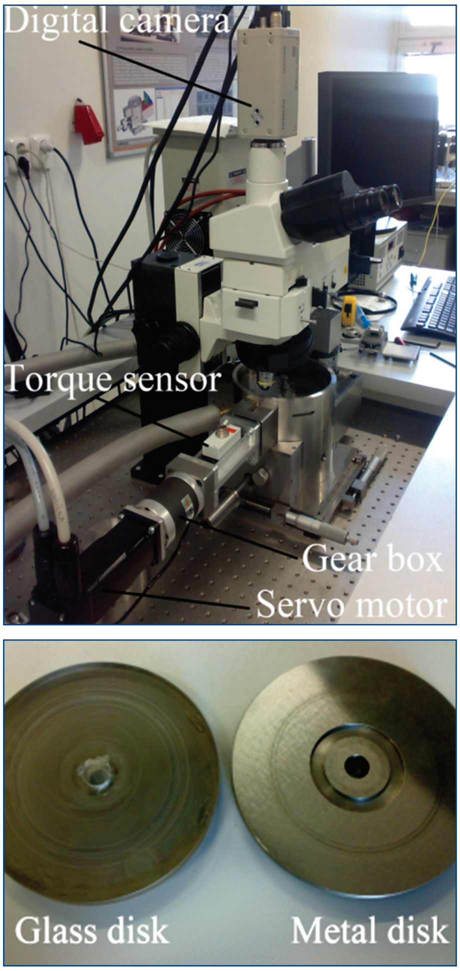

Figure 1. Tribometer (a), disks (b)

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

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

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:

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

The sliding speed u_s [*m/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 and elastic module 210 GPa while the diameter of disk at the contact with the ball is 100 mm. Two disks were used in experiments, a glass disk and a metal disk; see Fig. 1(b). 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 which gives the possibility of capturing interferometric images of the contact simultaneously with measuring the friction by the torque sensor. Experiments were carried out by using a base oil (2400N) with a measured viscosity η = 0.383 Pa.s at 40C°.

3. Results and discusion

3.1. Effect of operating conditions

3.1.1. Effect of entraining velocity Ue

Figs. 2 and 3 show the measuring of friction coefficient under starved (14 μl) and fully flooded conditions with slide-to-roll ration SRR = 0.8. The entraining velocity was increased from 15.8 mm/s to 28.5 mm/s with keeping the other parameters constant. It is apparent from interferometric images that the increasing of entraining velocity under starved conditions makes the air-oil meniscus in interference with the Hertzian circle, which resulted in a higher friction due to the insufficient film thickness. As the air-oil meniscus is out of Hertzian contact, see Fig. 2, the friction under starved conditions is nearly similar to the friction under fully flooded. However, under fully flooded conditions, increasing the entraining velocity leads to reduce the friction, this is attributed to the enhancement of film thickness according to the Hamrock and Dowson theory. However, this experiment shows the noticeable effect of entraining velocity on the friction coefficient and the position of air-oil meniscus under starved lubrication.

3.1.2. Effect of slide-to-roll ratio SRR

To investigate the effect of effect of slide-to-roll ratio, the coefficient of friction was measured under a constant entraining velocity

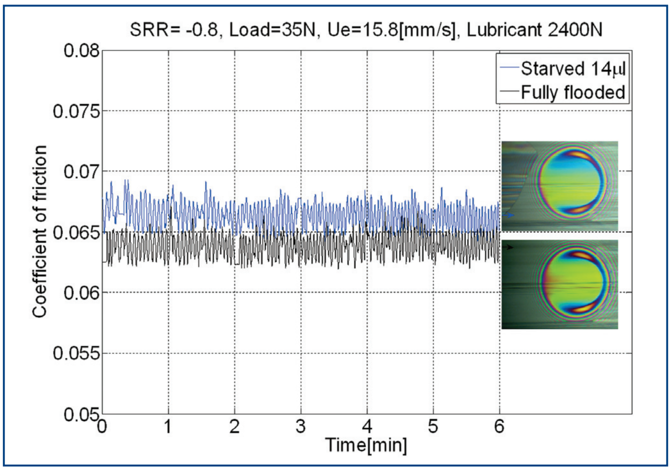

Figure 2. *Coefficient of friction under straved and fully flooded conditions with SRR = –0.8, Load = 35N, Ue = 15.8 mm/s*

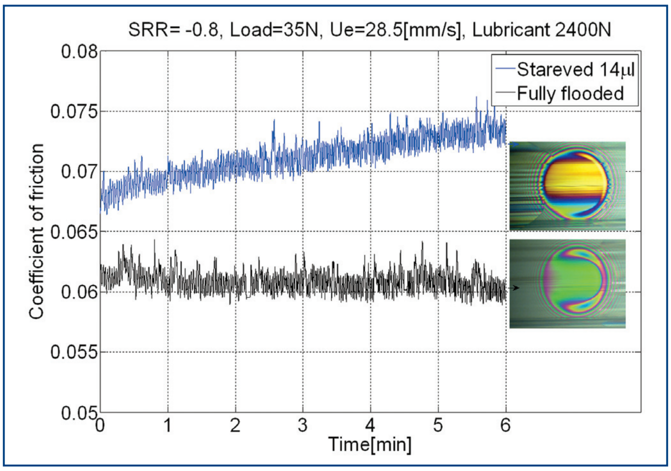

Figure 3. *Friction coefficient under straved and fully flooded conditions with SRR = –0.8, Load=35N, Ue = 28.5 mm/s*

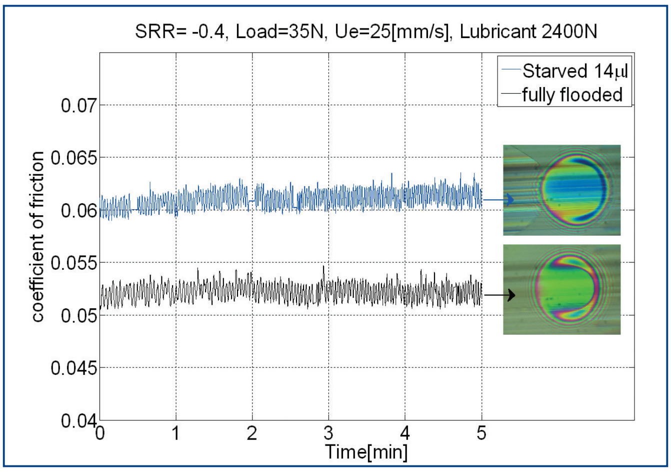

Figure 4. *Friction coefficient under straved and fully flooded conditions with Ue = 25 mm/s and SRR = -0.4*

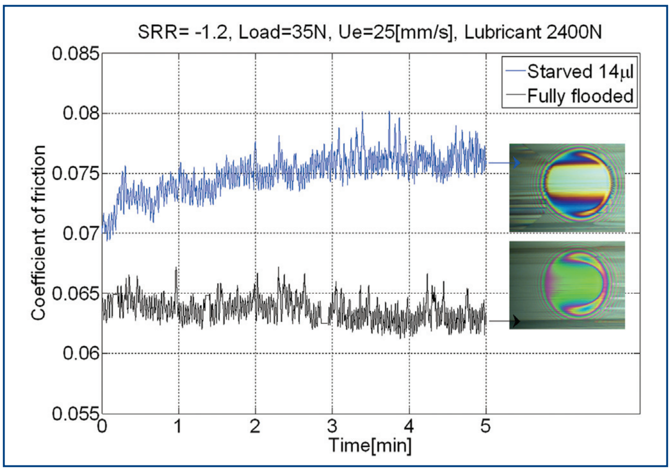

Figure 5. *Friction coefficient under straved and fully flooded conditions with Ue = 25 mm/s, SRR = –1.2*

Ue = 25 mm/s. Figs. 4 and 5 show that the increase of slide-to-roll ratio increases the coefficient of friction under both of starved (14 µl) and fully flooded conditions, this act is attributed to the increase of sliding velocity (note that the entraining velocity is constant) which results in increasing the Couette flow in the contact and consequently the shear stress which results in a higher coefficient of friction. Otherwise, it is clear from the interferometric images that the increase of slide-to-roll ratio leads to a higher degree of starvation in the contact due to the reduction of film replenishment time particularly on the faster surface. The less time of film replenishment on the track results in more insufficient film thickness in the contact.

3.2 Effect of oil amount

3.2.1 Metal-to-metal contact

The effect of oil amount on the coefficient of friction was investigated by measuring the friction versus sliding speed, the lubricant 2400 N was used in the experiment because the starvation is common with high viscosities; in addition to that, the contact was highly loaded by 40 N to ensure the occurrence of starvation. The slide-to-roll ratio was kept at and the experiment was carried out in ambient temperature 24 C°. The contact between the ball and metal disk was lubricated by a little amount of oil (only 20 µl) and the same experiment was repeated with a fully flooded contact. Fig. 6 shows that the friction coefficient has a larger value at all sliding speeds under the conditions of starvation in comparison with the fully flooded conditions. The difference in friction coefficient between the starved and fully flooded lubrication becomes larger as the severity of operation conditions increases, particularly the sliding speed.

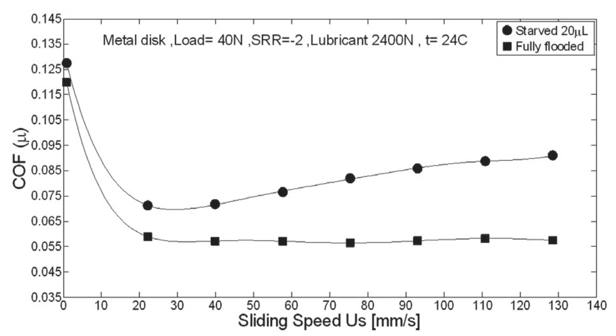

***Figure 6.** The friction coefficient of point contact under starved and fully flooded lubrication*

3.2.2 Metal-to-glass contact

The use of transparent glass disk enables the capturing of interferometric images by a digital camera simultaneously with the measuring of friction, see Fig. 7, The advantage of this process is the possibility of following the position of air-oil meniscus under starved conditions where it is well known that the starved lubrication is usually accompanied by the rise of a region with a mixture of air and oil which is called the air-oil meniscus. The effect of air-oil meniscus position on the friction is observed under a load 24N and a slide-to-roll ratio (). The period of measuring lasted 4 minutes and the interferometric images have been captured in the 2nd minute of measuring.

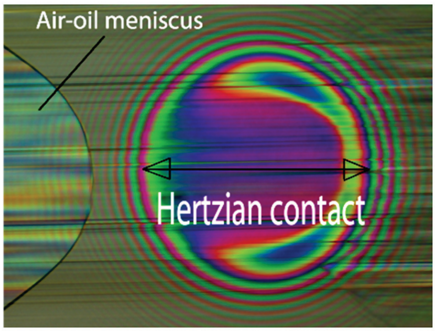

***Figure 7.** Interferometric image of a typical starved contact with load = 24N.*

Results in Fig. 8 show how the air-oil meniscus approaches to the Hertzian contact with increasing the degree of starvation, this action is accompanied with increasing the value of friction coefficient. For oil amount 16 µl the air-oil meniscus becomes in interference with the Hertzian contact which results in a higher friction in comparison with the friction for oil amount 20 µl. However it is clear that the appearance of the air-oil meniscus next to Hertzian contact increases the friction in the contact and the value of friction coefficient depends on the distance of air-oil meniscus from the Hertzian contact.

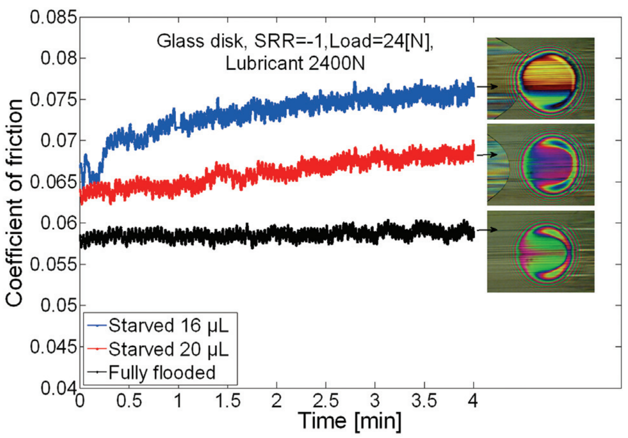

***Figure 8.** Effect of air-oil meniscus distance from the Hertzian contact on the coefficient of friction*

4. Conclusions

The coefficient of friction between non-conformal point contacts was measured under different operating conditions. Under fully flooded conditions, increasing the entraining velocity leads to reduce the friction between the mating surfaces because of enhancing the film thickness and the separation. On the other hand, increasing the slide-to-roll ratio for fully flooded contacts, results in a higher friction. The effect of starved conditions on the friction of non-conformal surfaces becomes larger for high entraining velocities and high slide-to-roll ratios. It was observed that as the entraining velocity increases, the air-oil meniscus becomes closer to the center of Hertzian contact which results in a reduction of film thickness and a higher friction. In addition to that, increasing the slide-to-roll ratio reduces the time of film replenishment on the track under starved conditions and increases the shear stress which results in a higher friction. However, the effect of slide-to-roll ratio is attributed substantially to the change form Poiseuille flow to Couette flow.

References

[Chevalier 1993] Chevalier, F., Lubrecht, A.A., Cann, P.M.E., Colin, F. and Dalmaz G. Film thickness in starved EHL point contacts. *Journal of Tribology-Transactions of the Asme*, Jan 1998, vol. 120, no. 1, pp 126–133.

[Damiens 2004] Damiens, B., Venner, C.H., Cann,, P.M.E. and Lubrecht, A.A. Starved lubrication of elliptical EHD contacts. *Journal of Tribology-Transactions of the Asme,* 2004, vol. 126, no. 1, pp 105–111.

[De Vicente 2005] De Vicente, J., Stokes, JR. and Spikes, HA. The frictional properties of Newtonian fluids in rolling-sliding soft EHL contact. *Tribology Letters*, 2005, Vol.20, pp 273–86.

[Ghosh 1987] Ghosh, M. K., Hamrock, B. J. and Brewe, D. E. Starvation effects on the hydrodynamic lubrication of rigid nonconformal contacts in combined rolling and normal motion. *Asle Transactions,* Jan 1987, vol. 30, no. 1, pp 91-99.

[Hamrock 1976] Hamrock BJ. and Dowson, D. Isothermal elastohydrodynamic lubrication of point contacts. Part I: Theoretical formulation. *ASME J. Lubr. Technol,* 1976, Vol.98, pp 223–228.

[Jacod 2001] Jacod, B., Venner, CH. and Lugt, PM. A generalized traction curve for EHL contacts. *Transactions of the ASME Journal of Tribology,* 2001, Vol.123, pp 248–53.

[Jacod 2003] Jacod, B., Venner, CH. and Lugt, PM. Extension of the friction mastercurve to limiting shearstress models. *Transactions of the ASME Journal of Tribology,* 2003, Vol.125, pp 739–46.

[Johnson 1993] Johnson, KL. Non-Newtonian effects in elastohydrodynamic lubrication. *In:* D. Dowson, et al, ed. *Thin films in Tribology, Proceedings of the 19th Leeds-Lyon symposium on Tribology,* New-York, 1993, Elsevier Science Publishers B, pp. 15–26.

[Liu 2007] Liu, Y., Wang, QJ., Bair, S. and Vergne, P. A quantitative solution for the full shear- thinning EHL point contact problem including traction. *Tribol Letters,* 2007, Vol.28, pp 171–81.

[Olaru 1993] Olaru, D.N. and Gaftanu M.D. Starvation in ball-bearings. *Wear*, Dec 1993, vol. 170, no. 2, pp 219–234.

[Querlioz 2007] Querlioz, E., Ville, F., Lenon, H. and Lubrecht, T. Experimental investigations on the contact fatigue life under starved conditions. *Tribol Int*, 2007, Vol.40, pp1619–26.

[Sojoudi 2010] Sojoudi, H. and Khonsari, MM. On the Behavior of Friction in Lubricated Point Contact With Provision for Surface Roughness. *Journal of Tribology-Transactions of the Asme,* 2010, Vol.132. *DOI:* 10.1115/1.4000306.

[Wedeven 1971] Wedeven, L. D., Evans, D. and Cameron, A. Optical analysis of ball bearing starvation. *Journal of Lubrication Technology*, 1971, vol. 93, no. 3, pp 349-&.

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