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RESEARCH

Experimental Comparison of the Behavior between Base Oil and Grease Starvation Based on Inlet Film Thickness

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A B S T R A C T

This paper deals with the experimental study of an elastohydrodynamic contact under conditions of insufficient lubricant supply. Starvation level of this type of the contact may be experimentally determined based on the position of the meniscus, but this way can't determine all levels of starvation. Consequent development in the field of tribology achieved theoretical model that can determine all levels of starvation by dependency on the thickness of the lubricant film entering the contact, but it is difficult for experimental verification. The main goal of this work is an experimental study and description of the behavior of the elastohydrodynamic contact with controlled thickness of the lubricant film at the contact input. Contact was lubricated by the base oil and the grease and compared. Results were surprising because the only differences between oil and grease were observed for more viscous lubricants at thicker film layer entering to the contact.

1. INTRODUCTION

Rolling bearings, gears and cams are among the most commonly used mechanical parts at the present and it is necessary to ensure the correct function for all period of their predicted lifetime. Therefore, designers have to consider the impact of friction and wear during the design. Surfaces of the contact bodies are separated by a thin film of lubricant which reduces friction and prevents damage of components. The contact, formed by the thin film of lubricant under high pressure between non-conformal surfaces where the elastic deformation of the lubricated surfaces is of the same order of magnitude as the thickness of the lubricant film, is called Elastohydrodynamic (EHD) contact. The biggest influence on EHD contact has the volume of lubricant supplied to contact and the operating conditions. These factors define properties of the lubricant film inside the contact, which can be divided into two types: fully flooded and starved. Fully flooded contact film thickness can be calculated by formula according to Hamrock-Dowson [1], which indicates that film thickness increases with increasing speed. The opposite case is the formula applied for starved contact which indicates that film thickness starts to decrease with increasing speed from certain point as shown by Guangteng [2]. Starvation may not only be caused by increasing speed but also by other factors as lubricant supply, the operating conditions (e.g. the size of the load), change of lubricant properties or by a combination of these which was presented by Pemberton and Cameron [3]. A frequent reason, for the contact starvation is the failure of the lubricant supply. The lubricant in front of the contact is partially pushed out of the contact area by the contact pressure. The rest of lubricant remains in the contact inlet and passes through the contact and subsequently leaves the contact at the outlet. The lubricant is returned to the track of the contact by replenishment phenomena behind the contact area. In case that time period between overrollings is too short, replenishment is not sufficient and the contact becomes starving due to insufficient lubricant supply. This situation occurs for example in the rolling bearings.

Replenishment mechanism of the oil and its flow around EHD point contact have been investigated by Pemberton and Cameron [4] as mentioned previously and the first experimental study which dealt with the effect of the starvation on film thickness in EHL contact was published by the Wedeven et al. [5]. They provided information about the connection between the position of the inlet meniscus relative to the Hertzian zone and other features relating the starvation. The description of the starving contact depending on the position of the air-oil meniscus is very limited because the meniscus is very close to the Hertzian contact zone in case of small amount of lubricant at the inlet of the contact. Sometimes the situation occurs, that the distance between boundary meniscus and Hertzian contact is not visible because meniscus is intersecting with the contact zone. This type of starvation is called heavy or severe starvation or parched lubrication. Another disadvantage of this approach is, that inlet meniscus position is not a practical to measure in real applications. Therefore, it was necessary to suggest different way how to describe starvation level. In more recent studies presented by Chevalier et. al. [6] or Damiens et. al. [7] an alternative approach that defines the degree of starvation by using the amount of oil present on the surfaces was published. These studies contain theoretical models suitable for circular and elliptical contacts and other information that were also suitable in severely starved regime. The one of the most important parameters defining the formation of a lubricant film thickness is the thickness of the oil layer available in the contact inlet.

The works mentioned in the previous text have dealt only with contacts lubricated by oil, however, in many real applications the contacts are lubricated by greases. Basic frictional behavior of grease can be studied by laboratory devices such as four-ball apparatus [8] or pin-on disc apparatus [9], however these does not provide information about film formation. An example could be the contact lubricated by grease ca be rolling bearing. Most of them operating worldwide are lubricated by grease and better understanding of the processes going on inside them can help to design or estimate the life [10].

Complex rheology of grease is the main difference from the liquid lubricants. The grease is commonly consisted of base oil, thickener and additives. The behavior of greases is similar with oils in certain situations. For example, Cann [11], investigated fully flooded and starved contacts lubricated by grease. Generally, the film thickness of fully flooded contact increases with increasing rolling speed. However, in case of greases the film thickness of fully flooded contact is thicker in the low speeds. This unusual effect is caused by thickener lumps, which pass through the contact and distorts the EHL film. The film thickness gradually decreases with increasing speed to a certain point. Then the film thickness starts to increase from this point. At higher rolling speed the film thickness is increasing with the exponent of 0.7. Viscosity of the base oil and the amount of thickener are two important parameters in lubricant that determinate the film thickness in the contact. The film thickness of fully flooded contact increases with the increasing viscosity of base oil and the thickener content. Opposite effects occurs in the starvation regime, where the increase of viscosity of base oil, thickener content and rolling speed increases the degree of starvation. The replenishment mechanism has also important influence on the degree of starvation of the EHL contact lubricated by grease similarly as in case of oil lubrication as shown by Astrom et. al. [12]. The degree of starvation is parameter, which determines transition point between fully flooded and starved contact and the severity of starvation of the contact. The parameter is defined by an amount of oil present near the track, surface tension, the base oil viscosity, the track width and the velocity [13].

This study extends the previous [14,15] and focuses on the behavior of the base oil and the grease made from the same base oil in the starved EHL contact. Aim is to compare the film thickness in the starving EHL contact as a function of the inlet film thickness for oils and greases.

2. EXPERIMENTAL METHOD

2.1 Experimental apparatus

The experimental apparatus was already in greater detail described in the previous study presented by Svoboda et. al. [14] and Kostal et. al. [15] and with small modification was also used for the purpose of this study. The apparatus allows forming and observing of a thin lubricating film due to relative movement of glass disc and two rolling elements. Two elements setup allows to control and measure inlet film thickness with sufficient precision. Svoboda et. al. [14] presented experimental approach based on the presumption of the pure rolling conditions of both elements. In case of this study the conditions of pure rolling were insufficient to achieve the larger set of experimental values. Therefore, this apparatus was modified as can be seen in Fig. 1. The modification consists of independently driven first rolling element.

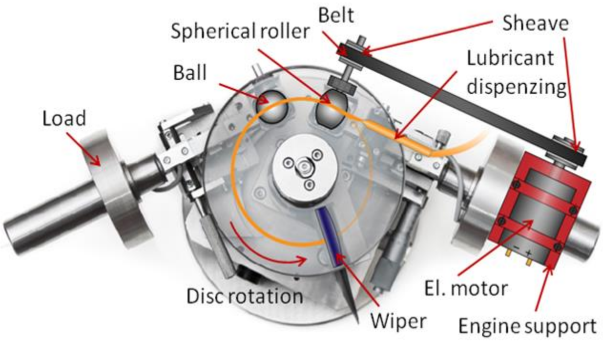

Fig. 1. The experimental apparatus.

Fig. 2. Detail of wiper directing lubricant back into the track of contact.

The basis of rig in Fig. 1 is almost common ball-on-disc apparatus. Enhancement consist of using two rolling elements. Both rolling elements were independently loaded at the bottom side of the disc by a lever system. The first element (spherical roller) and second element (ball) are made of the same steel and are in identical radial distance from axis of the rotation of the disc. Glass disc is driven by servomotor and drives the ball trough traction force in the loaded contact. Velocity of spherical roller is driven by el. motor and its torque is transmitted through the sheaves and belt. Electric motor is placed at a lever to prevent the unwanted forces created by belt acting in the contact area. Dispensing of the lubricant is secured by two methods. In first method the lubrication is continuously applied on the disc by lubricant dispenser and wiped out by a wiper which can be seen in Fig. 1 after passing through the contacts. This method was applied for experiments with base oils. Second method (most often applied for grease) consist in lubricant manually given onto the surface of the disc and after passing through the contacts, the displaced lubricant is directed back into the track of contacts by the wiper which can be seen in greater detail in Fig. 2.

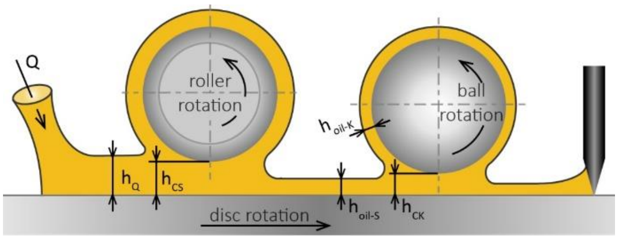

Fig. 3. Method of the controlling of the inlet film thickness.

The principle of the experimental measurements which is shown in Fig. 3 is based on supplying of lubricant film layer to second contact (h_{oil-S}). This lubricant film layer, entering to second contact, has to be well-defined and is formed by the first contact. The lubricant applied on the disc (Q) enters at first into the contact between the roller and the disc. The lubricant is distributed after passing through the contact to both contact surfaces. The thickness of the lubricant film on the glass disc in the outlet area of the first contact ($h_{\text{oil-S}}$) depends on the velocity of roller and disc. Lubricant film is ruptured at the first contact outlet into the two parts, each on individual surface. The lubricant film is then carried by the disc from the first contact to the second contact created between ball and the same glass disc. The carried thickness of the lubricant on the disc is joined with the rest of lubricant film thickness ($h_{\text{oil-k}}$), which is adhered on the surface of the ball, in the vicinity of the second contact inlet. The remaining thickness of the lubricant on the surface of ball is half of its central thickness ($h_{\text{CK/2}}$) assuming pure rolling conditions between the ball and the glass disc. The lubricant film layer entering to the second contact (h_{oil}) is composed partly of lubricant film thickness leaving from the first contact ($h_{\text{oil-S}}$) and the lubricant film thickness adhered on the surface of the ball ($h_{\text{oil-k}}$). This is described by the formula (1). Parameter h_{oil} cannot be pointed out in the Fig. 3 easily, because it is composition of two layers happening very close to the contact.

$$h_{oil} = h_{oil-S} + h_{oil-K} \tag{1}$$

The lubricant film thickness leaving the first contact ($h_{\text{oil-S}}$) is determined by the central thickness of the first contact and parameter of rupture ratio at EHL contact outlet (Δ). The values are multiplied by each other as shown in formula (2). Parameter of rupture ratio was introduced in earlier work [16].

$$h_{oil-S} = h_{CS} \cdot \Delta \tag{2}$$

Both lubricated contacts were investigated by microscope and images were recorded by CCD digital camera. The film thickness was evaluated by colorimetric interferometry from the captured images. The film thickness in EHL contacts can be evaluated in the range between 1 and 800 nm with an accuracy of ±1 nm by using thin film optical interferometry. See [16] for detailed description of the method. Results for base oil and grease are compared with the theoretical prediction published by Chevalier [6].

Whole process needs to be done quickly, because free layer of lubricant, which is being carried by disc from the first to the second contact, is changing in time due to out-of-contact replenishment. This process was already quantified by previously done study [17] and verified for the purpose of this study and current lubricants. Period of the measurements was kept under 1 second in all cases to avoid influence of the replenishment between contacts.

2.2 Experimental conditions

The steel ball and the spherical roller (spherical roller has a radius of curvature 106 mm in a direction perpendicular to the direction of rolling) with diameter of 25.4 mm in direction of rolling, were used for all experiments. The glass disc had a diameter of 150 mm. The contact pressure was determined by the load and contact size, which was different for each contact. The effect of compressibility of the lubricant was determined for each type of load and contact. The influence of difference of loads and contact shapes on the result values was included by the effect of compressibility of the lubricant. The temperatures during all experiments were about 23.5 °C ± 0.5 °C.

Table 1. Used samples.

Grease (Mogul)	Viscosity (mm^2/s)
LV 2-3	50
LA 2	130
LVT 2-EP	200

2.3 Lubricants

Three mineral type base oils and greases produced with the same oils were selected for the purpose of the study. The samples have the same type of thickener (Li-soap), same type of base oil (mineral) but different viscosity of the base oil which can be seen in Table 1. The set of the lubricants was selected to investigate the influence of the thickener on the behavior of the starving EHL contact. The rolling elements and the disc were always cleaned from impurities and lubricants by acetone before each measurement. The capture of the interferometric images started at the moment when the lubricant was equally distributed on the surface of the disc.

3. RESULTS

3.1 Theoretical model

Theoretical model introduced by Chevalier [6] describing the relationship between inlet film thickness and starvation level was used to create prediction for the operating conditions of the current experiments. Parameters of the base oil entering the model and its following calculation revealed very little differences between types of lubricants. The results of the adjusted theoretical model are drawn in Fig. 4 and the detail of these curves is shown in the right part in Fig. 4.

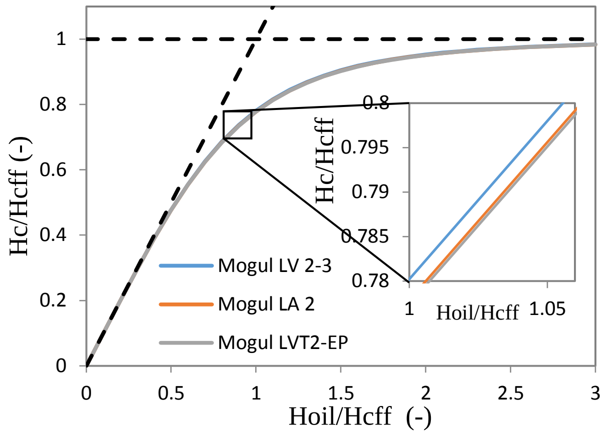

Fig. 4. Theoretical model of base oils.

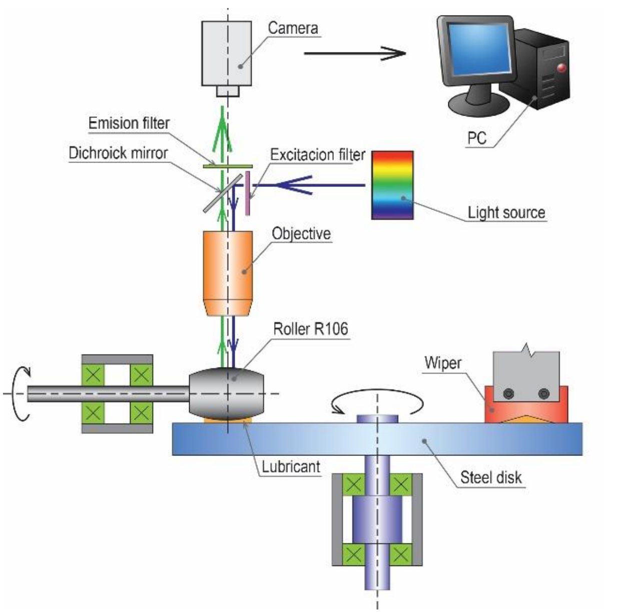

Fig. 5. Apparatus modified to investigate rupture ratio.

The main difference in the lubricant properties is the viscosity. The different viscosity causes a different flow of lubricant around and through the contact but in the case of theoretical model the change of viscosity does not take effect because the values of thicknesses are in ratio h_c/h_{cff} on the vertical axis and h_{oil}/h_{cff} on the horizontal axis and viscosity influences each of these parameters similarly, therefore, ratio is similar. The published theoretical model is valid only for base oils but the goal of this study is to compare oil and grease behavior, not oils between each other. Therefore, the same behavior of oils does not necessarily mean the same behavior of greases.

3.2 Parameter lubricant rupture ratio

Parameter describing lubricant rupture ratio at EHL contact outlet was investigated in earlier work [16]. Authors described experimental device and method how to obtain this parameter for oils. Parameter of the lubricant rupture ratio for base oils and greases in case of this study was investigated on the same apparatus which was slightly modified for measuring greases. After passing through the contact a wiper that was located on top side of a steel disc was used to return the displaced grease back into the track of the rolling element. The apparatus is shown in Fig. 5. Detailed description of the experimental procedure can be found in the previously mentioned article [16].

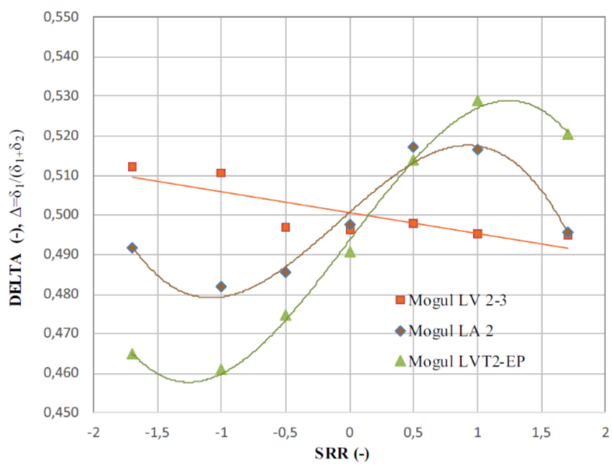

Fig. 6. Parameters of the rupture ratio for base oils.

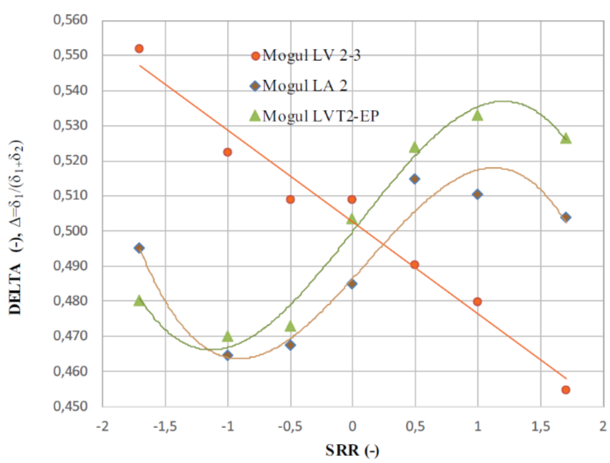

Fig. 7. Parameters of the rupture ratio for greases.

The lubricant rupture ratio at EHL contact outlet had to be investigated because first contact was not always operated under pure rolling conditions. Rupture ratio is equal to 0.5 under pure rolling conditions but this does not apply with sliding conditions. Therefore, it was investigated how the parameter which determines how the lubricant is distributed onto the contacting surfaces changes for each lubricant for rolling and different sliding conditions. The lubricant rupture ratio is labeled as Δ and is composed of two values of lubricant thickness. A first value is thickness in the center of the track behind contact on disc (δ_1). A second value is thickness on the highest point of roller (δ_2).

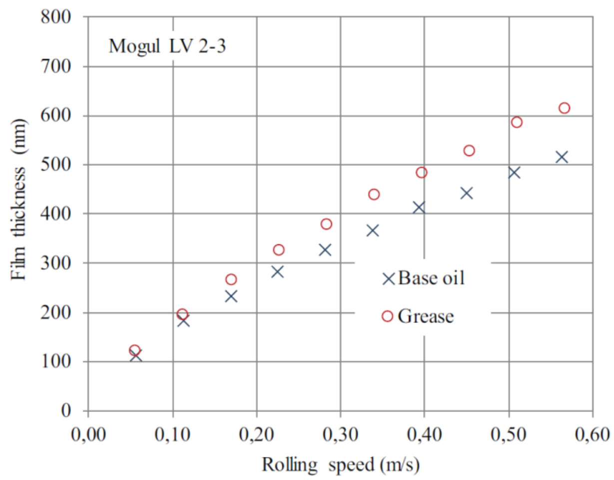

Fig. 8. The fully flooded contact lubricated by Mogul LV 2-3.

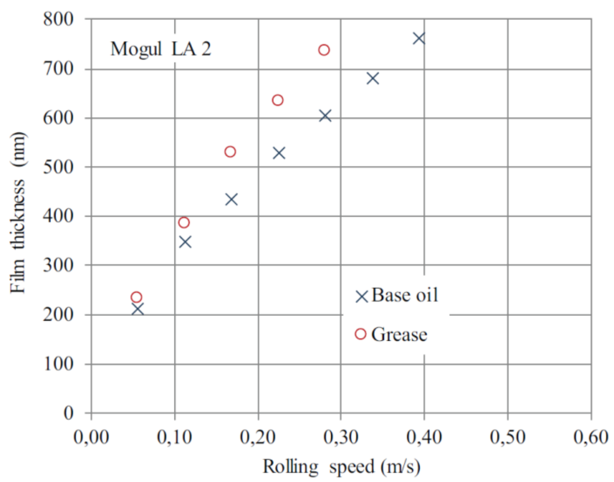

Fig. 9. The fully flooded contact lubricated by Mogul LA 2.

The results of rupture ratio for all types of lubricants are plotted in two figures. Figure 6 shows the results of base oils and plot in Fig. 7 shows the results for greases. These all parameters were measured for same mean speed u_m=200 mm/s.

3.3 Grease behaviour under fully flooded conditions

The results of central film thickness for the fully flooded contact created between ball and disc are shown in the Fig. 8 to Fig. 10. The contact lubricated by Mogul LV 2-3 (Fig. 8) and Mogul LA 2 (Fig. 9) had thicker lubricant film in the case of lubrication greases compared with its base oil. But the thickness of the film created with Mogul LVT2-EP (Fig. 10) had very similar values for base oil and grease. The thickener in the grease Mogul LVT2-EP did not cause a change of central film thickness compared to values of central film thickness of its base oil.

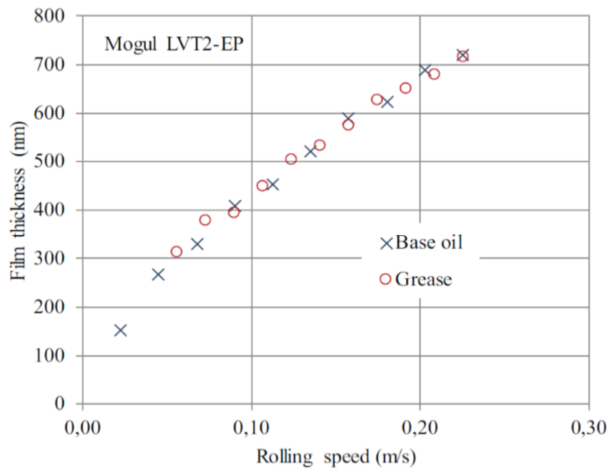

Fig. 10. The fully flooded contact lubricated by Mogul LVT2-EP.

3.4 The influence of the inlet film thickness to the starvation level

Figures 11-13 show data already including the effect of lubricant compressibility and rupture ratio for base oils and greases produced with the same base oil. These plots show the dependency between starvation severity of the EHL contact and inlet lubricant film thickness. The obtained data are compared with the theoretical model in each figure. All theoretical curves are almost in all cases above the experimental results. Measured data are approaching closer to the theoretical curve with gradually increasing values of hoil. The biggest difference between the theoretical curve and experimental data is in the location of the lowest values of hoil.

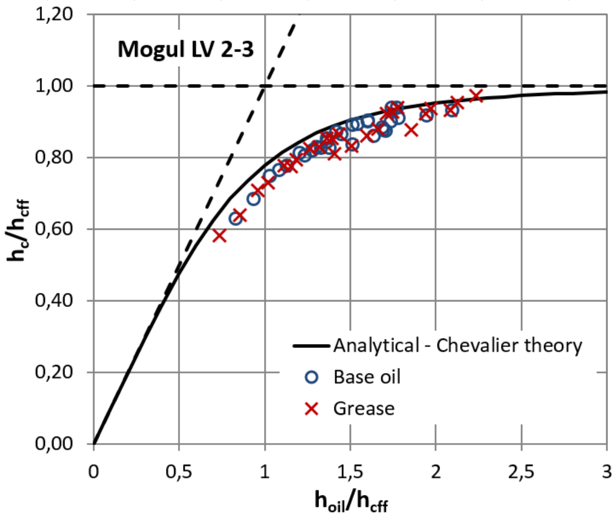

Fig. 11. Experimental data of Mogul LV 2-3 and comparison with theoretical model.

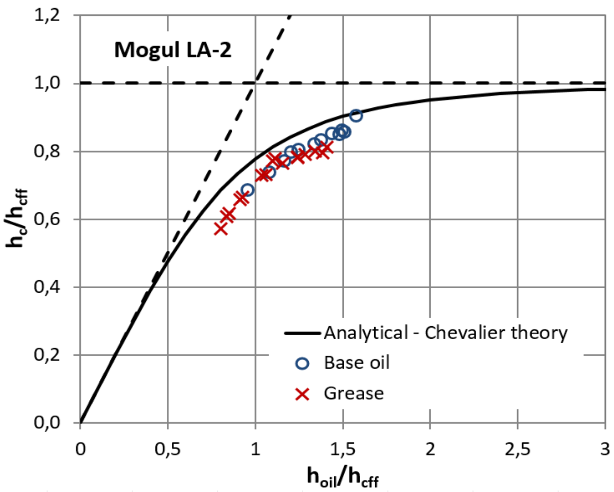

Fig. 12. Experimental data of Mogul LA-2 and comparison with theoretical model.

In Figs. 11 and 13 the axis of graphs are described with lowercase h. The lowercase h represents a specific value of lubricant film thickness, but mostly the theoretical model is shown with an uppercase H, which represents the dimensionless thickness values. The conversion into the dimensionless values is not necessary, because the thickness is in ratio h_c/h_{cff} and h_{oil}/h_{cff} on the both of axes. In case of transferring the specific values to dimensionless values will occur reduction of the reduced curvature parameter, by which would be the values of the film thickness divided.

4. DISCUSSION

Two different measuring methods were used in this study. The optical interferometry was used for almost all performed experiments except of the measuring of which was investigated by a method of fluorescence.

Optical interferometry is one of the most frequently used methods for measuring thin film thickness in the concentrated contacts. Hartl [18] presented and confirmed the accuracy of optical interferometry that achieves 1nm for measuring thickness in the contact. This measuring method is sufficiently accurate so it was not necessary to verify the correct operation of measuring method itself. On the other hand, the second method of fluorescence is currently not as well verified method as optical interferometry. For this reason, the correctness of measuring method of fluorescence was verified so that was possible to demonstrate the validation of the results. Experiments ensuring the accuracy of measurements by fluorescence are presented and commented further.

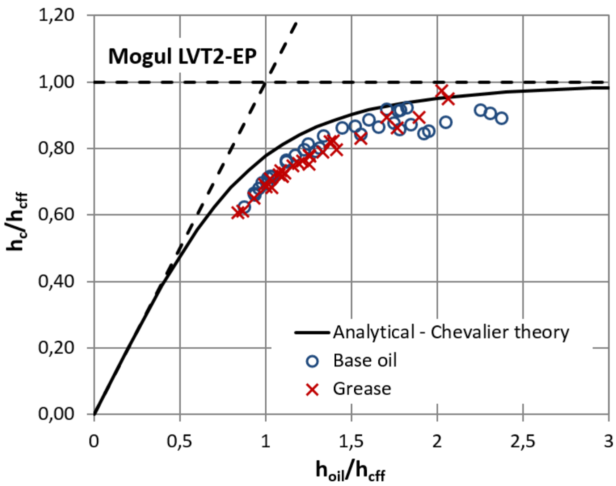

Fig. 13. Experimental data of Mogul LVT2-EP and comparison with theoretical model.

The results obtained on the apparatus (Fig. 1) could be influenced by contact simulator itself, calibration or by deviation of the measuring method. Applied measuring method on this apparatus was the optical interferometry therefore the errors of method were neglected. The influences of device and calibration were investigated in the earlier study [15]. The published results of standard deviation of calibration were approximately 1.6 %. The main mechanical factors affecting results are throwing rolling elements, due to their imprecise positioning. Other factors are for instance the unstable operation of servo-motor and surface aberrations such as small roughness features on the rolling elements. In case of thinner lubricant film thickness (average 93 nm) was standard deviation almost 4.5 %. This can already be considered as significant, therefore, the experimental values were obtained from statistically processed data. It means that for every data point were recorded two pictures under same conditions and then values from these were averaged. Also difference between them was evaluated and in the case of increased difference, data were recorded again. At first two pictures of the first contact was recorded then two pictures of the second contact and in the end two picture of the first contact again to exclude any change in time and therefore, ensure stable conditions. data evaluated by this method are shown in Fig. 11 to Fig. 13.

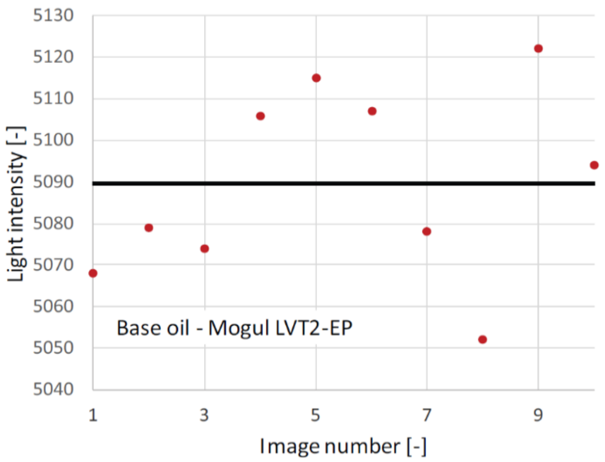

Fig. 14. The repeatability of measurement base oil Mogul LVT2-EP.

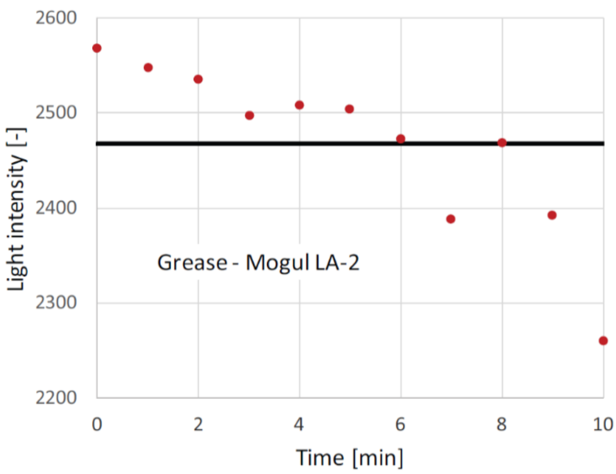

Fig. 15. Verification of the stability of the lubricant film thickness distribution

Results in Fig. 11 to Fig. 13 are quite surprising because the values of the base oil and the grease are characterized by only slight differences which on the top of it can be noticed only with use of the more viscous lubricants at higher values of the parameter hoil. It can be seen that the result values for the base oil and grease Mogul LV 2 3 are closer than the values of other lubricants. This slight difference is especially visible in higher values of the parameter hoil. Difference could be caused by different behavior in the higher mean speeds for each lubricant. Higher values of hoil were achieved by increasing the mean speed in the first contact. More viscous lubricant behaves differently under these conditions (i.e. higher speeds and increased sliding) which causes that data are more scattered in this area and it prevents correct evaluation.

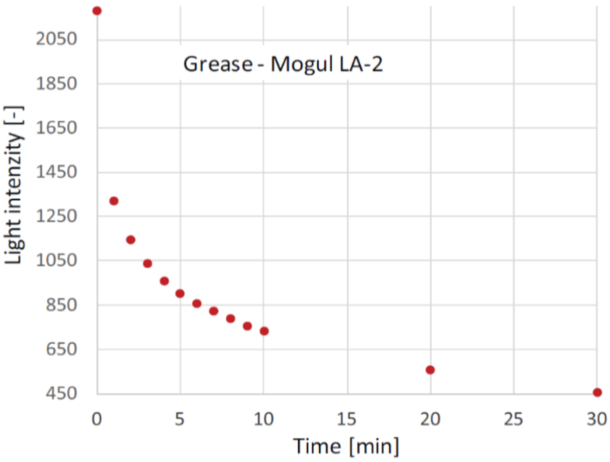

Fig. 16. Dependence of light intensity against time for statically sensed area.

The parameter of lubricant rupture ratio was investigated on the apparatus in the Fig. 5 by fluorescence method. Values were influenced by the same factors as values measured on previous apparatus (Fig. 1) by optical interferometry. The fluorescence method is however very sensitive to reflectivity of the surfaces, that is why both the disc and the ball were made from the same type of the bearing steel to prevent the error caused by different reflectivity of each surface. The first test verified repeatability of measurements acquired by fluorescence method. The experimental results are shown in the Fig. 14 where results of the base oil Mogul LVT2-EP was chosen because it had the biggest standard deviation of size 21.6 luminance levels between the all used lubricants. The deviation is 0.5 % which is considered as negligible value.

Next test verified the stability of light intensity (quenching) of greases in the track on the disc behind the contact during motion. The operating conditions were stable during the experiment. The grease Mogul LA-2 is shown in the results in Fig. 15 due to the biggest standard deviation and also that it was hardest to channel it back into the track so it is the most problematic lubricant from the all used samples. The value of the light intensity was recorded in the period of one minute. From Fig. 15 is clear that the light intensity of the lubricant is gradually decreasing. The standard deviation for the ten-minute test corresponds to a value 3.5 %. This value seems to be high but one need to realize that all measurements of parameter of lubricant rupture ratio run for maximum four minutes. Standard deviation of the values (Fig. 15) for four minutes corresponds to only 1 %, which is considered negligible.

The final test was focused on quantifying of the pure quenching of motionless lubricant on the disc surface in dependence on time. The pictures of the observed area were taken at certain intervals during the thirty minutes. A decrease of fluorescence intensity under continuous excitation was defined assuming unchanged constant volume of lubricant. Assuming constant thickness of the lubricant a gradual decrease of emitted intensity occurs due to the effect of energy loss in the lubricant. The results of this dependence are shown in Fig. 16. The results presented in this paper should not be influenced by a phenomenon of the quenching of lubricant during measurement, because illuminated volume of lubricant is much smaller compared with a total track length and lubricant is continuously changed in the illuminated section. Specifically, the observed (excited) area is around 0.2 mm^2 while total track area on the disc is equal to 188 mm^2 which makes it almost one thousand times bigger. Moreover, already excited lubricant is mixed with unexcited lubricant after passing through the wiper. When one considers the values of quenching from Fig. 16 divided by one thousand the influence of the quenching of the lubricant is negligible for mentioned timescales. This statement confirms Fig. 15 that includes the effects of the quenching of lubricants and continuous supply of lubricant to contact but there could be also another influence, so it is not proportional.

It could be said that all experiments with the use of fluorescence method are valid in terms of repeatability of experiments. Overall influence of previously mentioned aspects on the results is about 1.5 % which is considered as acceptable.

5. CONCLUSION

The behavior of h_c on h_{oil} for base oil and grease can be considered as identical based on the presented experimental results. The contact pressure influences the base oil and the grease in the vicinity of the starving EHD contact similarly. This contact pressure produces a shear stress in the lubricant which causes the same ow of grease around the starving EHD contact as in the case of movement of the base oils itself. Thickener is the only difference between composition of the base oils and greases used in this work. Based on this data can be said that thickener causes no difference in the ow of lubricant under increased pressure in the contact inlet region.

The results of this study showed that grease behave like base oil in very close area to the starving contact and side ow of lubricant causes starvation in the same scale. In case of multiple contacts, the lubricant film thickness leaving contact becomes input thickness of the following contact. This information is important because it shows that the multiple contacts (e.g. rolling bearing) can be treated equally from the point of inlet film thickness whether it is lubricated by oil or by grease.

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Nomenclature

1	Relation to the disc
2	Relation to the ball
h_c	Central film thickness
h_{cff}	Central film thickness of the fully flooded contact

h_{oil}	Inlet film thickness
$u_{1;2}$	Entrainment speeds of surfaces
u_m	Mean speed; $(u_1 + u_2)/2$
SRR	Slide-to-roll ratio; $2(u_1-u_2)/(u_1+u_2)$
k	Ellipticity of the element $k = 1.0339((R_y)/(R_x))^{0.636}$
R_x	Radius of the curvature in the x direction
R_y	Radius of the curvature in the y direction
x	Coordinate in the rolling direction
y	Coordinate perpendicular to the rolling direction
p	Pressure in the contact
η	Viscosity at atmospheric pressure
1	Dimensionless film thickness on the disc
2	Dimensionless film thickness on the ball
Δ	Rupture ratio parameter; $\delta_1/(\delta_1+\delta_2)$
γ	Resistance to the side-flow
ρ_1	Relative density of the pressurized lubricant in the first contact
ρ_2	Relative density of the pressurized lubricant in the second contact

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