EXPERIMENTAL INVESTIGATION OF LUBRICATION FILM FORMATION AT START-UP OF SMOOTH SURFACES

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Many machine components are operated under transient conditions that can cause the lubrication film breakdown. In such a case, surface interactions can lead to wear and significantly reduce life of these components. Start-up of the machine components to the relative motion is one of the transient phenomenon where surfaces are not fully separated by a continuous layer of lubricant. This article summaries relevant studies and extends it with experiments. The evaluation of the experiment was made by chromatic interferometry. This method is used to measure thin lubrication films. Measurements were carried out using an additive-free paraffinic base oil. An experimental study on lubrication film formation during start-up of smooth non-conformal contacts operated under pure rolling conditions was carried out. Experiments for different values of low acceleration quite good agree with theoretical and experimental results.

KEYWORDS
EHD lubrication, transient, film thickness, start-up non-conformal contact

1. INTRODUCTION

One of the most important parameters determining the performance and life of machine parts is a lubrication film thickness and its distribution. Gears, rolling bearings, cam and followers, etc. subjected to high loads and/or slow speeds are operated under conditions when lubrication film is not able to completely separate rubbing surfaces. The start-up operation represents one of the transient operation conditions that bring the risk of the surface damage because of surface interaction. The direct solid to solid contact is highly probable during the start-up. Compared to the large number of papers dealing with steady state conditions or surface effects of surface features [Krupka 2010, 2010/2], [Vrbka 2011, 2011/2], the most obvious cause for transient behaviour in elastohydrodynamic lubricated (EHL) contacts has received minor attention. The behaviour of transient processes in elastohydrodynamic (EHD) contacts attracted much attention of specialists dealing with the lubrication mechanism. It is due to the fact that most of lubricated machine parts operate under transient conditions when the speed as well as load or both at once are variable. Therefore, currently these phenomena have received particular attention. In the past decades, the experimental and theoretical tools to study the transient behaviour of EHL contacts have been improved and a couple of numerical and experimental studies have been presented also for the case of the start-up problem.

Detailed investigation on the effect of entrainment velocity variation upon EHD film thickness using the ultra-thin film interferometry technique presented Sugimura et al. [Sugimura 1998, 2010]. This studies deal with accelerating/decelerating, start–stop and reciprocating motions using low sampling speeds, which did not allow the study of very fast events. The behaviour of EHL line contact during start-up of motion has been modelled theoretically by Osborn and Sadeghi [Osborn 1992]. They predicted that the level of fluid entrainment and thus film thickness should rise smoothly with speed as the ball accelerates. This results are only for the case when the lubricant separates the surfaces of the bodies completely.

One of the first pioneers dealing with experimental study of lubrication film formation during start-up conditions was Kaneta [Kaneta 1999], who inserted the start-up conditions into the study of dimple phenomena occurring within EHD contact under specific sliding conditions. The build-up processes of the lubrication film were observed during a sudden start of the glass disc while permitting and preventing the rotation of the smooth steel ball. Chromatic interferograms were used for the qualitative description of lubrication film formation during start-up at slow acceleration conditions. Kaneta noted, what might be regarded as classical behaviour as predicted by Osborn and Sadeghi, with the generation of a wedge-shaped film as fluid entrainment increased with increasing speed.

A quantitative experimental study of the lubrication film formation within a smooth EHD contact during start-up was presented by Glovnea and Spikes [Glovnea 2001]. They also observed the lubricated contact formed between a glass disc and a steel ball under both pure sliding and pure rolling conditions; however, the acceleration was much more rapid when compared to Kaneta's work. Glovnea and Spikes found that the film thickness behaviour depends strongly upon acceleration and film thickness profiles exhibited two steps that travelled through the contact. They concluded that the majority of lubricating fluids form at the initial moment a front with an almost unchangeable shape propagating in the direction of movement of the surfaces.

Holmes et al. [Holmes 2002] presented numerical results for simple sliding conditions that corresponded to work presented by Glovnea and Spikes. The numerical simulation results presented in the theoretical studies show relatively smooth changes in the film profiles for start-up. This results obtained from a transient numerical analysis showed considerable differences in lubrication film profiles as to the damped oscillations observed during experiments carried out at the highest acceleration. Popovici et al. [Popovici 2004] numerically simulated the effects of the loading system on the contact dynamics during start-up to address this behaviour. They found a good agreement as to the overall start-up behaviour of the contact and concluded that it is unlikely that the oscillatory behaviour in experiments is only due to the dynamics of the loading system and suggested some other sources of stiffness or inertia (e.g. the driving system of the ball and the disk) that could play a role.

Recently Usov [Usov 2008] developed a mathematical model of the process of the lubricating layer formation. He compared experimental dependencies of the lubricating layer thickness on the coordinates at these moments of time from the data of [Glovnea 2001] in his study. The results of calculations were compared with the experimental results and they reveal good correlation proving the applicability of the proposed model of the process in question in pure rolling.

This paper focuses on the effects of optically smooth frictional surfaces on EHD film formation during a start-up of non-conformal contacts operated under pure rolling conditions and using an additive-free paraffinic base oil. The start-up case represents one of the transient conditions that bring the risk of the surface damage. The experimental study of the start-up will help to understand better the behaviour of lubricant film under the severe conditions.

2. EXPERIMENTAL APPARATUS AND CONDITIONS

Lubrication film formation was observed using a tribometer (Fig. 1) in ball-on-disc configuration in which a circular contact is formed between a glass disc and a steel ball. It is possible to simulate conditions that occur in real bearings with this tribometer.

The top side of the disc is covered with an anti-reflective layer and the lower surface of the disc is coated with a thin semi-reflective chromium layer. Both the glass disc and the steel ball are independently driven by servomotors. Contact is formed between the glass disc and the steel ball with perpendicular rotation axes. The load is applied in the contact through a glass disc which is connected with a weight by using a double-reversible lever. Contact is illuminated by a high-power xenon lamp. Obtained chromatic interferograms are recorded with a high-speed digital camera and evaluated with thin film colorimetric interferometry. It is based upon colorimetric analysis of chromatic interferograms using appropriate colour matching algorithm and colour/film thickness calibration curves [Hartl 2001]. Based on previously obtained results it is believed that the film thickness resolution is approximately 1 nm. Commercially provided balls of grade 100 were employed in this study. The ball had no preferential surface roughness pattern and its RMS roughness measured by 3D optical profilometer technique was about 1.5 nm. The glass disc had 150 mm in diameter and its surface was optically smooth. The elastic modulus of the steel ball was 212 GPa and that of the glass disc was 81 GPa. All measurements were carried out using an additive-free paraffinic base oil LSBS. The measurements were done at room temperature of 25 °C. At this temperature this oil has a dynamic viscosity of 0.69 Pa·s. The experiments were performed at a load of 36.5 N, corresponding to a maximum Hertz pressure of 0.552 GPa and a contact radius of 178 μm.

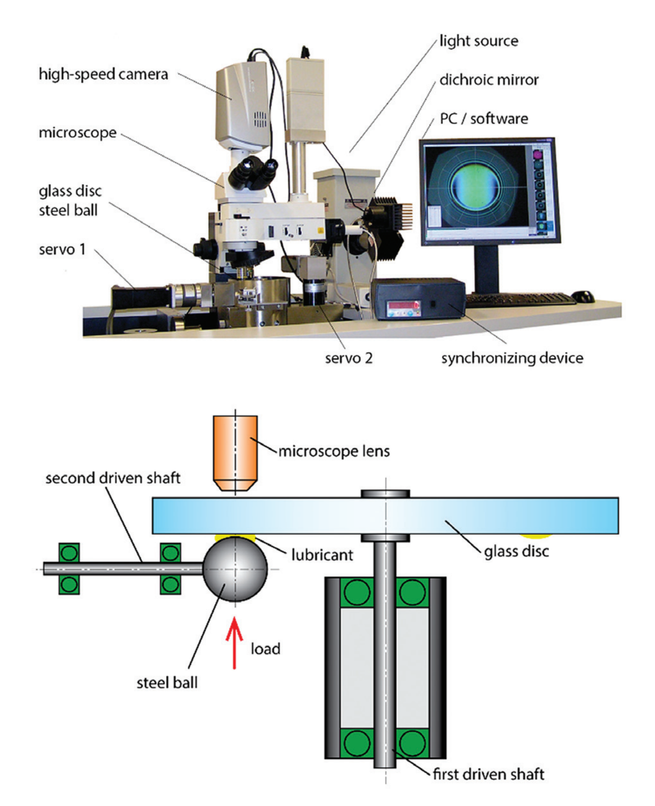

Figure 1. Optical test rig and its scheme

Start-up of friction surfaces under pure rolling conditions requires the precise control of the acceleration of both the ball and the disc. The ball is driven by AC servo motor through the planet gearbox while the disc is driven through multi-ribbed V belt that transmits the torque between the shaft of the gearbox and disc shaft.

Experiments were performed under the pure rolling conditions (SRR = 0) for three different values of acceleration, namely 0.0887 m·s^{-2}; 0.1330 m·s^{-2} and 0.2660 m·s^{-2} see Tab. 1.

The final speeds of the ball and disc reached 0.2660 m·s^{-1} at 1000 RPM with the transmission 1:5. The pure rolling conditions and constant load were kept during the whole start-up. For each acceleration a speed ramp was set. In this case the ramp is plotted as the time at which the

Experiment No.:	Acceleration [m·s^{-2}]	Maximum speed [m·s^{-1}]	Time to maximum speed [s]
1	0.0887	0.2660	3
2	0.1330	0.2660	2
3	0.2660	0.2660	1

Table 1. Experimental conditions

servomotor reaches the set speed. The dependence of speed variation with time is shown in Fig. 2. For each acceleration the high-speed CMOS camera was set to capture the sequence of chromatic interferograms at a speed of 450 frames per second with exposure 2.22 ms. It is clear that both the speeds and accelerations are rather low, nevertheless it enabled observation of the film thickness formation in detail.

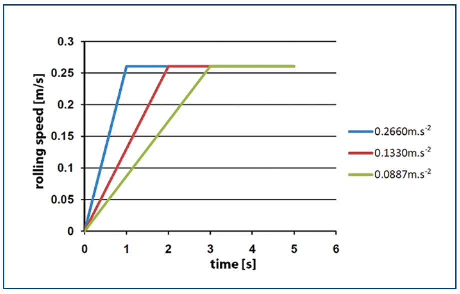

Figure 2. The ramp of the drive for three different values of acceleration

3. RESULTS AND DISCUSSION

Fig. 3 shows the sequence of chromatic interferograms at different moments and corresponding film thickness profiles taken along the centreline in the direction of motion. This series of experiments were realized for the value of the acceleration 0.0887 m·s^{-2} under pure rolling conditions.

The initial situation is a dry contact at zero speed. Subsequently, the speed is increased linearly with a certain rate of acceleration. First chromatic interferogram (Fig. 3a) was captured 26.7 ms after the beginning of the start-up motion when the speed of the disc as well as speed of the ball were 0.0024 m·s^{-1}. There is a big area of the contact without lubricant and frictional surfaces are in touch at this moment. The first step begins to form shortly after start-up of the motion. Furthermore, time t=48.9 ms and speed 0.0043 m·s^{-1} (Fig 3b)

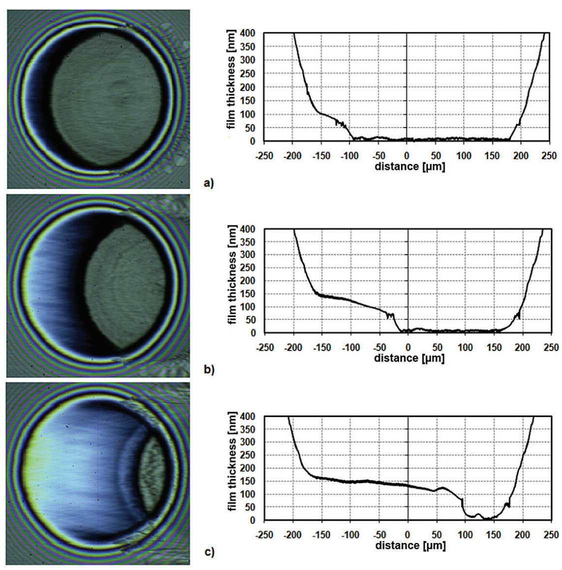

Figure 3. Series of chromatic interferograms during acceleration of 0.0887 m.s^{-2}

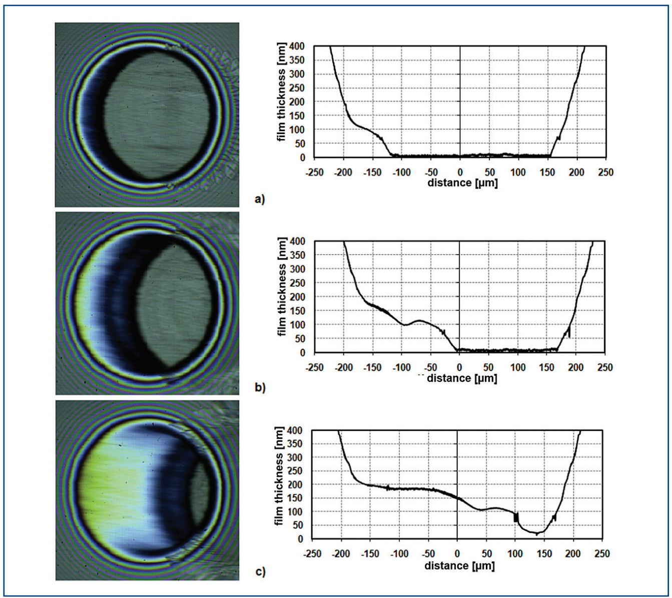

Figure 4. Series of chromatic interferograms during acceleration of 0.1330 m·s^{-2}

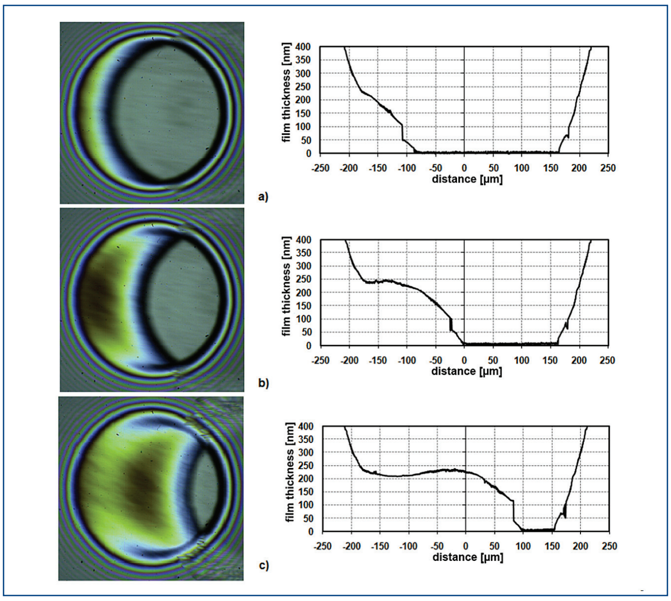

Figure 5. Series of chromatic interferograms during acceleration of 0.2660 m·s^{-2}

is immediately followed by area of wedge with increased volume of lubricant which could be interpreted also as a second step, which has already been described in the work of Glovnea and Spikes [Glovnea 2001]. This step follows the first step across the width of the contact at time t=66.7 ms and speed 0.0059 m·s^{-1} (Fig. 3c) at an approximately constant distance until complete flooding of the contact with lubricant.

There is a part of contact where the lubricant continuously do not separates the friction surfaces throughout the acceleration and can be concluded that after a certain number of starts, there is a real risk of damaging the machine components. The generation of a wedge-shaped film as lubricant entrainment increases with increasing mean surface velocity can be clearly seen. Nevertheless, one can also notice the presence of certain step in film thickness that is formed just from the beginning of the start-up motion.

The same sequence of chromatic interferograms for acceleration 0.1330 m·s^{-2} is shown in Fig. 4. Approximately at the same locations as in the previous series of interferograms of acceleration, but at another times, some differences can be seen in the thickness profile of the lubricating film. The first step is again formed immediately after the start-up of the frictional surfaces. Furthermore, lubricant creates a steep wedge lubricating film which could be interpreted as a second step, described by Glovnea and Spikes [Glovnea 2001]. This second step passes through the entire width of the contact at a constant distance from the first step. As in the previous case, there can be seen no continuous layer of lubricant in the contact during acceleration time as in the previous case.

The third series of interferograms (Fig. 4) were measured within the experiment with the highest acceleration value at 0.2660 m·s^{-2}. A several times higher film thickness of lubricant can be seen in contrast with the both first and second measurements at the highest value of the acceleration. The first clearly evident step is starting to build immediately after start-up. Again, as in the second series, the build-up is followed by the wedge of lubricating film, which is however clearly steeper than in both the first and second series of interferograms. This slope gradually decreases during acceleration of the frictional surfaces, but the wedge layer as such is very well visible also just before flooding of the whole contact.

Holmes et al. [Holmes 2002] have shown that the central film thickness increases with time from the moment the front part of the film reaches the centre of the contact for higher accelerations. This position of the separation point between the dry and lubricated part of the contact is seen to move ahead at the average speed, and its position as a function of time can be well predicted from the entrainment speed versus time curve.

Although that the rate of speed increases linearly the thickness of the lubricating film can exhibits a nonlinear behaviour. During a higher acceleration the film thickness may even exceed the value of the film under stable conditions (Fig. 5c) in a short time period and then shortly stabilize. This behaviour of lubricant film noted also Sugimura [Sugimura 2010] during sudden acceleration followed by rapid stop. A representative of these operational conditions is e.g. a step motor. The start phase is basically a high acceleration to a certain value, therefore we can find some similarity in the experiments.

Glovnea and Spikes [Glovnea 2001] presented the experimental dependencies of the lubricating layer thickness on the coordinates at these moments of time. It is apparent at first glance, that the film thickness within the first moments of movement increases very slightly in all the levels of acceleration. The film thickness starts to significantly change and the wedge step is forming when speed of movement reaches a value about 0.01 m·s^{-1}. This shape is forming progressively. The first edge is formed as step change in thickness of the lubricating film and the film thickness is further almost unchanged. Another edge is abruptly formed later. Delay in the forming of the second edge is heavily dependent on value of acceleration. Oscillations, as described in this experiment, may arise probably from the high accelerations and it has two reasons. The first is the static friction between the ball and the disk when the contact is not yet fully flooded by lubricant. The second, more likely possibility is a delay of transmission of force in the lubricating film, which subsequently leads to a dynamic response of the system to sudden imbalances. Similar oscillations were observed in the experiment for low acceleration values. The film thickness profile differs when comparing the numerical and experimental results. There are no step-shape profiles in the numerical model but this step-shape profiles are visible in the experiment.

Afterwards, Usov followed the work of Glovnea and Spikes [Glovnea 2001] and compared experimental dependencies of the lubricating layer thickness using numerical analysis of the EHD film formation at start-up. The rheological model of the lubricating fluid behaviour within the transient region is determined by the type of the fluid front and its speed of propagation. But it weakly influences the dependence of the lubricating layer thickness on the time in the process of separation of the surfaces one from the other after the contact between them disappears. Results were as expected for low rate of acceleration: the central film thickness increases with time until the steady state value is reached and the agreement between theoretical and experimental results is quite good. The lubricating fluid front appears a certain time after the motion starts and it propagates through the clearance while the front shape remains unchanged. Similar results were obtained experimentally also for lower acceleration values.

4. CONCLUSIONS

The experimental results of lubrication film formation at start-up of smooth surfaces for non-conformal contacts operated under pure rolling conditions is reported in this article. Some important experimental results and inferences are as follows:

– Film thickness profile is strongly depend on the acceleration during start-up of smooth frictional surfaces.
– The wedge-shape lubricant film is formed rapidly as step change in the thickness of the lubricating film with an almost unchangeable shape propagating in the direction of movement of the surfaces.
– The step-shape profile that passes through the contact at lower acceleration was observed, but only one input step followed by wedge layer of lubricant was visible at higher acceleration.
– The film thickness may even exceed the value of the film thickness under stable conditions in a short time period during a higher acceleration.
– Typical wedge-shaped film was generated from the contact entrance with increasing mean surface velocity while there were solid to solid interactions within the remaining part of the contact.

It is clear that both the speeds and accelerations are rather low than in previous studies [Glovnea 2001], [Usov 2008], nevertheless it enabled observation of the film thickness formation in detail.

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