

BRNO UNIVERSITY OF TECHNOLOGY
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**THE EFFECT OF SYNOVIAL FLUID
CONSTITUENTS ON LUBRICATION OF HIP JOINT
REPLACEMENTS**

**VLIV SLOŽEK SYNOVIÁLNÍ KAPALINY NA MAZÁNÍ
NÁHRAD KYČELNÍHO KLOUBU**

Shortened version of PhD Thesis

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1 INTRODUCTION

Total hip replacement is recognized to be one of the most successful and most applied surgical treatment of modern medicine. According to Health at a Glance 2015: OECD indicators [1], 161 operations per 100 000 inhabitants were conducted in OECD countries in 2013. Moreover, the number of operations still increases. Despite a rapid improvement of implant materials, hip replacements still suffer from limited longevity which is estimated to be between 10 – 20 years [2]. Since the need of revising operations substantially affects the life quality of patients, it is strongly desired to extend the durability of replacements.

The main cause of implant failure is aseptic loosening as a consequence of osteolysis [3]. During the articulation of the components, wear particles are released from the surfaces, interacting with the surrounding hard and soft tissues, leading to inflammation reactions and degradation of the tissue eventually. Therefore, recently the authors focused on in vitro testing of wear rate dependently on materials, geometry, or operating conditions [4]. It was revealed that the fundamental parameter influencing the wear of rubbing surfaces is implant material. In general, two different combinations are being implanted nowadays; hard-on-soft combination presented by very stiff femoral head (CoCr alloys, ceramic) and compliant acetabular cup (ultra-high molecular weight polyethylene - UHMWPE, highly cross-linked polyethylene - HXPE) and hard-on-hard combination where both components are made from metal or ceramic. From the performed studies, it is apparent that ceramic-on-ceramic implants exhibit the lowest wear rate. On the contrary, the highest wear occurs in the case when the cup is made from polymer [5].

Although the information about wear rate might be very important in relation to implant longevity, so far, little is known about the interfacial lubricating processes inside the contact. Even though, such a knowledge can lead to further development in the area of implants design or material towards the extension of the service life of replacements eventually.

The tribological performance of contact pair is substantially influenced by the prevailing lubrication regime. Sufficient separation of rubbing surfaces by fluid film can help to protect the surfaces against mutual contact potentially minimizing wear. However, it was discussed in literature that hip implants usually operate under boundary or mixed lubrication regime [6]. In terms of lubrication, one of the crucial parameters is the lubricant film thickness. In general, two different approaches can be employed for film thickness determination; numerical simulations and experimental measurements. Several studies have been conducted focusing on the numerical predictions of film thickness in hip replacements [7]. However, it must be highlighted that human synovial joints are lubricated by synovial fluid (SF) which is non-Newtonian liquid and corresponds to shear thinning behaviour [8]. Moreover, it is well known that protein adsorption onto rubbing surfaces, whose simulation is particularly complicated, substantially influences film thickness and tribochemical layers [9].

2 STATE OF THE ART

2.1 Experimental methods for film thickness investigation

Elastohydrodynamic experimental investigation in tribology experienced a rapid improvement during the last few decades. Summary of the experimental methods enabling film thickness measurements inside the contact of two bodies was provided in several references [10],[11]. Neglecting the unique approaches, often developed for specialized particular investigations, two groups of methods can be identified, in general.

The first group is represented by the electrical techniques based on the change of electrical quantity, i.e. resistance, voltage, or capacitance. The use of electrical methods in the area of hip biotribology was introduced by Dowson et al. [12] and Smith et al. [13], who performed qualitative analysis of surface separation over the gait cycle in metal [12] and ceramic [13] rubbing pairs using an electrical resistivity method. One of the main drawbacks of the described approach is that the studied materials have to be conductive. Therefore, in the case of ceramic, the base material had to be coated with thin conductive layer [13] which could influence the character of film development. Although the electrical methods provide the information about the surface separation, it does not allow to observe the contact in situ disabling to describe the character of protein film formation.

Another experimental approach utilizes optical methods enabling direct contact observations. Based on the critical review, two different optical methods suitable for film thickness determination can be recognized; optical interferometry and fluorescent microscopy. As is discussed in the following chapter, optical interferometry is well-established routine technique for film thickness determination. It was proved by Hartl et al. [14] that the method provides very accurate results of the size of the gap between the two surfaces with the resolution down to 1 nm. However, due to the principle of the method, it is not possible to distinguish the individual components contained in the lubricant.

In an effort to be able to determine the role of particular constituents contained in model fluid, optical method based on the fluorescent microscopy may be a suitable solution. The results are expressed in terms of fluorescent intensity in this case [10]. By using appropriate fluorescent markers, it is possible to label the individual parts of the lubricant, so the qualitative information about the lubricant layer development can be obtained. Due to the principle of the method, fluorescent microscopy brings several advantages enhancing the measurement possibilities, such as:

- Measurement in a wide range of thicknesses from tens of nm to units of mm.
- Investigation of non-reflective, compliant materials (polymers, tissues).
- Measurement of contact bodies of high surface roughness.
- Determining of lubricant flow.

A detailed description of the mentioned experimental methods is provided in chapter 5. It should be highlighted, that the method based on fluorescent microscopy has never been used before for in-situ analysis of lubrication mechanisms in hip joint replacements. Therefore, the following part is focused on the review of the use of the method for tribological analyses.

2.2 Fluorescent microscopy in tribology

The first research work employing the fluorescent microscopy for the measurement of lubricant layer was given by Smart and Ford [15]. Mercury lamp induced fluorescence was used for the measurement of lubricant layer on rotating cylinder. It was discussed that the method enables to measure the lubricant film in the range from 0.1 μm to 1 mm dependently on calibration accuracy. In the paper, the authors detected the film thickness from 800 nm to 35 μm , according to the rotations of the steel cylinder. The knowledge was discussed in relation to starvation of rolling bearings.

The following paper was introduced by Ford and Foord [16], who replaced mercury lamp by the laser of a wavelength $\lambda = 441.6 \text{ nm}$. The consequence of the use of the laser as an excitation source is mainly a simpler design of the experimental setup. Publication dealt, among others, with the differences between lamp and laser excitation, while several points were highlighted. The authors also discussed a decay of fluorescence emission with time as a consequence of illumination. This phenomenon was observed even in the case of very stable lubricants after some time. The decay of fluorescence signal with time for gas turbine oil is shown in Fig. 2.1.

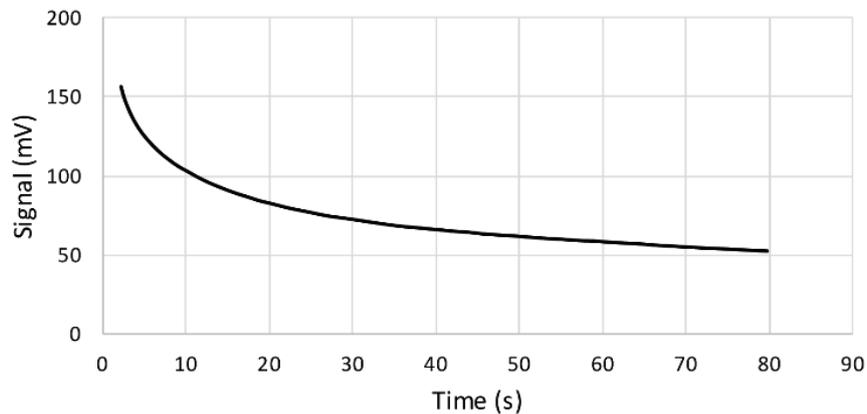


Fig. 2.1 Decay of the fluorescence emission as a function of time for turbine oil. The figure was reproduced based on [16].

For the purposes of laboratory investigations, ball-on-disc experimental device, introduced by Gohar [17], is extensively used in the area of tribology. The first combination of ball-on-disc device with the fluorescent method for film thickness measurement was introduced by Sugimura et al. [18]. Mineral oils were used as the test lubricants. Although the oils emit fluorescence naturally when illuminated in

UV, to enhance emission, base oils were doped by a Pyrene fluorophore, in addition. The experiments were realized under pure sliding condition, whilst the steel ball was stationary and the glass disc rotated. Two undesirable phenomena limiting the usage of the method were discussed by the authors. The first point was the interference of light beams arising at the interfaces disabling to process a precise calibration. The authors solved this issue by replacing the steel ball by glass lens for calibration. Although the interference disappeared, it must be taken into account that the calibration may be influenced by the different optical properties of calibration and test samples, potentially affecting results accuracy. Another point apparently influencing the results was background effect caused by cavities formed at the outlet zone. This problem was not completely solved in the study.

Substantial improvement of the fluorescent method was provided by Hidrovo and Hart, who introduced dual emission laser induced fluorescence (DELIF) [19] and emission reabsorption laser induced fluorescence (ERLIF) [20] principles. In the case of DELIF, the lubricant is doped by two fluorescent dyes with the similar excitation, but different emission wavelengths. The method is based on ratiometric principle allowing to normalize the emission of one dye against the emission of the second one, eliminating undesirable phenomena such as illumination intensity fluctuation or background effect pronounced by Sugimura et al. [18]. Despite a very good accuracy and system stability, it should be mentioned that both the approaches were no more applied for film thickness measurements by other authors, especially due to limitation of minimum detectable thickness and particularly complicated image processing based on the provided mathematical model.

Azushima measured the lubricant film thickness between the tool and the workpiece sheet during drawing process [21]. Topography of the surfaces after drawing was also investigated. The author clearly proved the principle of linearity between the fluorescence intensity and film thickness. The calibration consisted of the following steps. At the beginning, two glass sheets were weighted, while in a further step fluorescently doped lubricant was added between the sheets. The intensity was captured and the sheets were weighted again. From the change of the mass and the dimensions of the sheets, the thickness of the lubricant could be exactly determined. Several repetitions were conducted giving the dependence between the oil film thickness and light intensity, as is illustrated in Fig. 2.2.

The use of the laser induced fluorescence (LIF) for determination of lubricant film thickness in an elastohydrodynamic (EHD) contact was presented by Reddyhoff et al. [22]. It was discussed that the knowledge about the formation of film inside the contact can help to predict friction in EHD contact, which is beneficial, since it is known that friction determines power losses and; therefore, the efficiency of machines eventually. The contact was formed between the steel ball and the glass disc, while the contact operated under fully flooded conditions. Initially, the method was verified measuring the film intensity and comparing the results with those of quantitative film thickness obtained by optical interferometry. Subsequently, the lubricant flow was determined by adding fluorescently doped lubricant to the

contact drag, while the main attention was paid to the observation of the boundary between the stained and unstained lubricant entraining the contact.

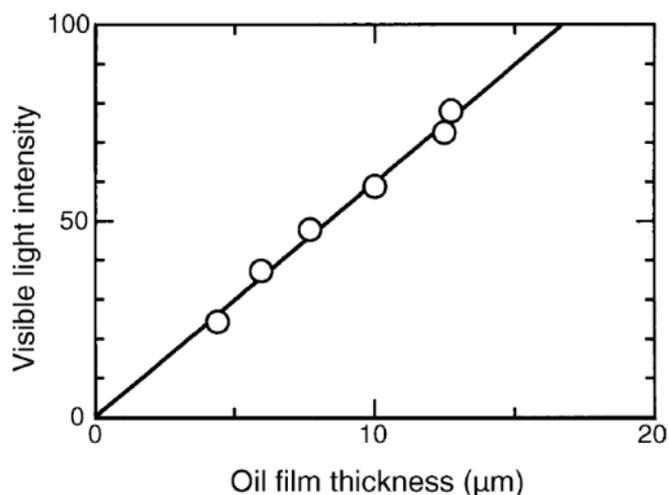


Fig. 2.2 Dependence between the oil film thickness and light intensity [21].

Another experimental approach for lubricant flow investigation, based on fluorescent method, is known as fluorescence recovery after photobleaching (FRAP). Ponjavic et al. [23] employed FRAP to investigate through-thickness velocity profiles and slip length in elastohydrodynamic lubricated (EHL) contact. Initially, the methodology was validated by spatiotemporal intensity distribution of plane Couette flow in a 1 μm polybutene film between two slides, while the bottom slide was stationary and the top slide velocity was 26.3 μm/s. Bleaching and exposure time were 25 ms and 180 ms, respectively. The photobleached plug initial diameter was 20 μm. Comparison of the experimental and numerical data is shown in Fig. 2.3. Subsequently, an EHD contact between the steel ball loaded against the glass slide was studied. Applied load of 5 N resulted to a theoretical Hertzian pressure of 315 MPa. Sliding speed was 360 μm/s leading to the expected film thickness of 170 nm.

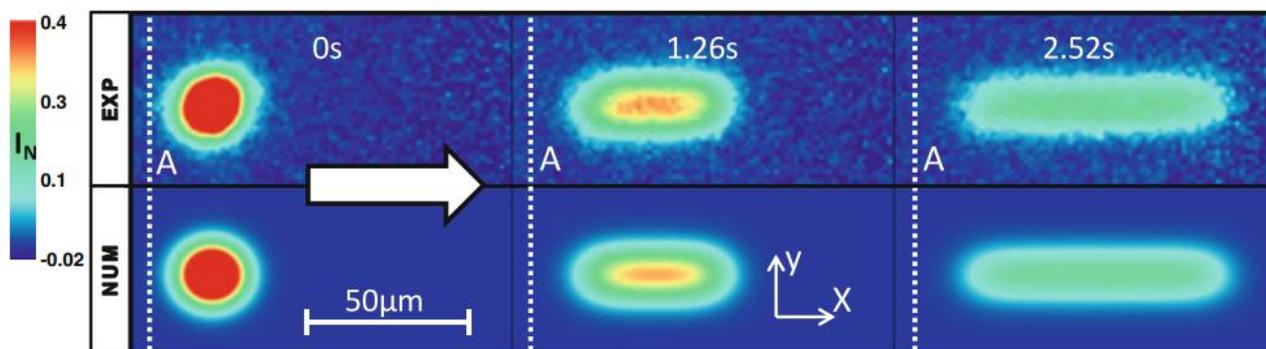


Fig. 2.3 Validation of the methodological approach; comparison of the experimental (top) and numerical (bottom) spatiotemporal intensity distribution. White arrow indicates the shearing direction of the fluid [23].

Due to limitations in relation to measurement accuracy and minimum measurable film thickness, fluorescent microscopy was also successfully combined with optical interferometry several times. Qian et al. [42] investigated the lubrication failure of oil film in point EHL ball-on-disc contact at high slide-to-roll ratios (SRR). Central film thickness was measured by optical interferometry and the pool shape was observed using fluorescent microscopy. The authors concluded that at high SRRs, the transition from EHL to mixed or boundary lubrication regime occurs. The problem of starvation was discussed in the study as well. Due to starvation occurring in the inlet zone of the contact, thermal effects play a dominant role in the lubricated contact region, resulting to disc wear and subsequent lubricant failure.

LIF was later employed for direct measurement of film thickness in compliant contact [24]. Glass disc was sliding against polydimethylsiloxane (PDMS) pin with the radius of curvature of 12.7 mm. The experiments were realized under fully flooded and starved lubrication conditions. Three various lubricants were used; pure glycerol, glycerol with distilled water in a ratio 1:1, and pure distilled water. As a fluorophore, Eosin was added to the base lubricant as in the case of the previous study [22]. A measurement range in the performed study was from 200 nm to 25 μm .

In the consequence paper, Myant et al. [25] applied LIF investigating the effect of transient start-up and sudden halting conditions on lubricant film. The same experimental configuration (stationary PDMS pin vs. rotating glass disc), as in the previous study, was employed, and the contact was lubricated by the mixture of glycerol (90 wt%) and water (10 wt%) doped by Sulforhodamine G of an approximate concentration of 0.05 wt%.

The study was followed by Fowell et al. [40], who measured the lubricant film thickness in the compliant contact in various configurations. Two non-conformal contacts were investigated; PDMS hemisphere vs. glass disc and fluorocarbon rubber (FKM) O-ring sealing vs. glass disc, respectively. Finally, the disc was substituted by concave glass lens, so the conformal setup of sealing and lens could be studied as well. As a test lubricant, mixture of glycerol (75 wt%) and water (25 wt%) doped by 0.01 wt% of Rhodamine 6G was used. Bottom part of the disc was immersed in the lubricant. Then, the lubricant is entrained to the contact as a consequence of disc/seal rotation.

2.3 Film thickness measurement in hip joint replacements

Initial study focused on the film thickness measurement in hip joint replacements was introduced by Mavraki and Cann [27]. The paper dealt with the fundamental aspects of implants lubrication, while the main interest was focused on the influence of proteins on coefficient of friction (COF) and film thickness. As a reference lubricant, bovine serum (BS) of various protein concentrations (25%, 50%, 100%) was used, while the results were compared with those for healthy and periprosthetic SF. Healthy fluid was represented by the solution of phosphate-

buffered saline (PBS) with added albumin (A) and γ -globulin (G) in a ratio A:G = 2:1. In the case of periprosthetic fluid, the same amount of proteins was solved in 2-amino-2-(hydroxymethyl)-1,3-propanediol (Tris). To be able to determine the effect of proteins, both lubricants with the interchanged protein concentrations were also investigated. The authors employed simplified ball-on-disc configuration while COF was measured on commercial mini traction machine (MTM) and lubricant film thickness on optical tribometer. For the evaluation of film thickness, optical interferometry method was used. The graph in Fig. 2.4 shows the dependence of film thickness on mean speed for 50% BS.

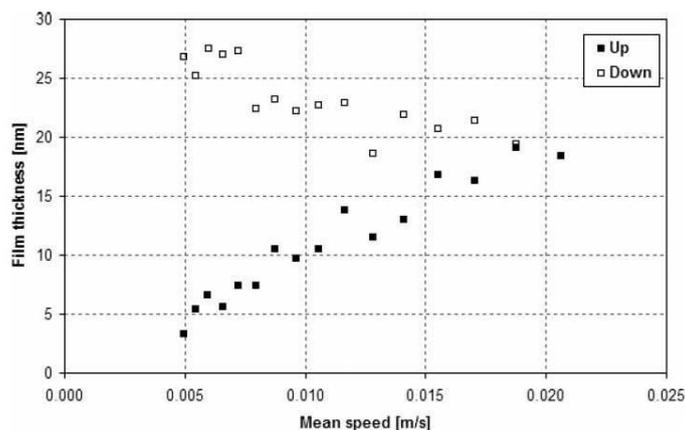


Fig. 2.4 Development of film thickness as a function of mean speed for 50% BS [27].

The study was later extended by the same authors [8] considering the effect of high (200 MPa) and low (30 MPa) contact pressure on film thickness. For this purpose, two different configurations were investigated; ball-on-disc and lens-on-disc. The radius of the ball and the lens was 9.5 and 50 mm, respectively. Experiments were realized under pure rolling (ball-on-disc) and pure sliding (stationary ball; lens) conditions. The contact was lubricated by BS. According to significant variance of results, the authors emphasized that the SF, as well as BS, which is often used as its model, is the non-Newtonian fluid. Due to this fact, it is very complicated to derive predictions for film thickness estimation. It was found that the change of the experimental conditions from pure rolling to pure sliding caused a substantial reduction of film thickness for around 70% – 80%. In general, protein film was higher at lower contact pressure. The film thickness at lower contact pressure was also very sensitive to concentration of BS

The following paper, pronounced by Fan et al. [28], provided an extensive analysis of the effect of model fluid composition on lubricant film formation. The same experimental approach consisting of the ball-on-disc device and optical interferometry, introduced in previous studies [8],[27], was employed. For the first time, real femoral component from CoCrMo alloy was used as one of the contact bodies. The experiments were performed under pure sliding conditions with stationary ball, considering the speeds from 2 to 60 mm/s and body temperature. Several lubricants were tested, finding that in the case of BS, there was no

significant influence of protein concentration on film thickness. However, complex protein solutions exhibited approximately two times higher values of protein film.

Previous studies focused mainly on the effect of mean speed, contact pressure, model fluid composition, or temperature on protein film formation. Myant et al. [29] focused on the influence of load and time on lubricant film thickness. Moreover, static test at zero speed was conducted allowing to study protein adsorption onto surfaces. Applied load in the case of static test was 5 N. Five different test lubricants were investigated, 25% BS, three albumin saline solutions (and γ -globulin saline solution. From the results of the static test (Fig. 2.5), it is apparent that the thickest film (≈ 30 nm) was formed by γ -globulin solution, even the protein concentration was the lowest. On the contrary, lubricant containing albumin led to very thin protein film just in the range of units of nm with negligible effect of protein concentration. Thickness of BS was somewhere between the simple protein solutions and the film at the end reached around 10 nm.

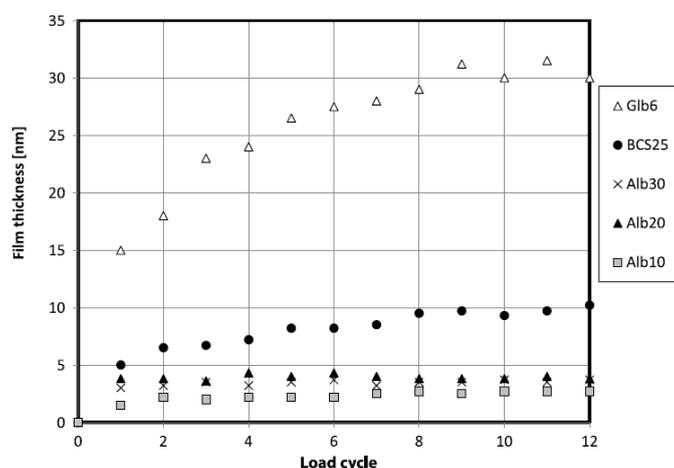


Fig. 2.5 Development of adsorbed protein film as a function of load cycle for various lubricants [29].

Following experiment lasted 12 minutes (the same like in the case of static test), while it was carried out under constant sliding speed of 10 mm/s. Corresponding sliding distance was approximately 14.4 m. The load resulted to a mean contact pressure equal to 113 MPa. The results showed that the film thickness was the highest for γ -globulin solution, while the maximum at the end of the test was around 230 nm. Independently of protein concentration, lubricants containing albumin formed films thinner than 50 nm.

A detailed observation of the contact lubricated by 25% BS was provided by Myant and Cann [30]. The authors observed the protein agglomerations in front of the contact while they called this gel-like suspension as a “inlet phase”, see the left part of Fig. 2.6. As can be seen in the graph displayed on the right of Fig. 2.6, very good correlation between the length of the inlet phase and the central film thickness was found. Therefore, it can be concluded that film thickness is strongly influenced by the agglomerated proteins.

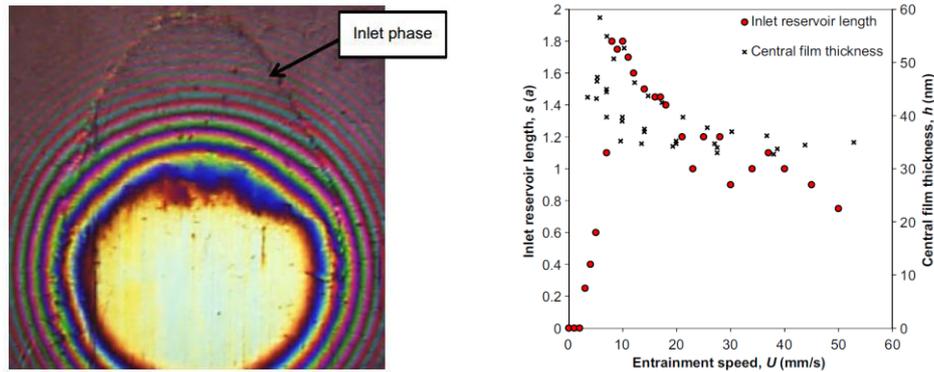


Fig. 2.6 Left: Inlet gel-like phase of proteins in front of the contact zone. Right: Development of film thickness and inlet reservoir length as a function of sliding speed [30].

The above references focused on several factors apparently influencing the protein film formation in hip replacements. Theoretical knowledge was summarized by Myant and Cann [31]. The authors defined protein aggregation lubrication (PAL) mechanism in relation to metal-on-metal replacements, while several implications for implant tribology were highlighted and confronted with classical EHL mechanisms. For both, a reduction of contact pressure has a positive impact on film thickness. On the contrary, while the increase of sliding speed leads to an increase of lubricant film in the case of EHL, in the case of PAL, the effect is opposite; however, the composition of lubricant (i.e. protein concentration, protein ratio) must be taken into account.

In the further paper, Vrbka et al. [32] employed metal and ceramic femoral heads and the film thickness was investigated using the same experimental approach introduced above. Experiments were realized under various kinematic conditions (speeds, SRRs) under the constant load of 5 N. The contact was lubricated by 25% BS. Under pure rolling conditions, both materials exhibited increasing tendency of lubricant film, while metal head formed a thicker film, in general. Considering the slippage led to very complex character of film formation strongly dependent on positivity/negativity of SRR. Further, the authors pointed out that the different conformity, compared to real synovial joints, can significantly influence protein film formation.

Following this implication, the authors later changed the experimental configuration from non-conformal ball-on-disc to more conformal ball-on-lens [33]. The experiments were conducted under pure negative sliding; glass lens was kept stationary, and the ball rotated. The previous paper [32] showed that the film was extremely thin and could not be fully developed under negative sliding conditions. However, the change of experimental configuration caused a complete change of the film formation. Immediately after starting the experiment, the film reached almost 100 nm independently of sliding speed. After a short time, it started to gradually decrease within a few tens of seconds. Then, the film became stabilized with not substantial change until the end of the test, see Fig. 2.7.

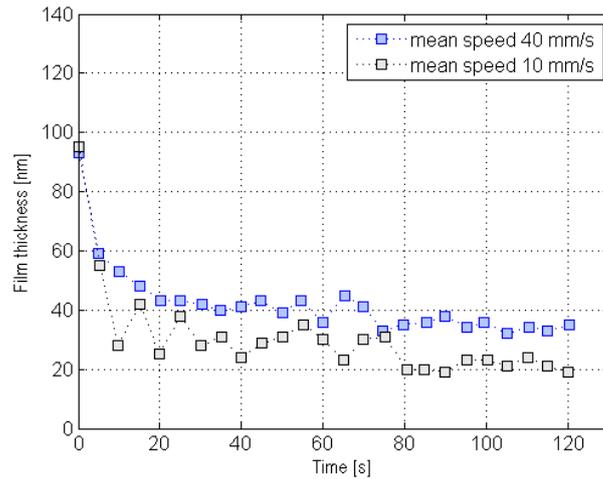


Fig. 2.7 Development of film thickness as a function of time for various sliding speeds considering ball-on-lens experimental setup [33].

Several findings were already introduced in relation to kinematic conditions. Nevertheless, it should be emphasized that the authors previously employing ball-on-disc tribometers usually applied simple unidirectional character of motion, which does not correspond to the kinematics of real joints. Both, natural and artificial joints operate under complex multidirectional motion and transient load, dependently on gait, jump, stair climbing, etc. Therefore, Myant and Cann [34] extended the knowledge considering three different types of motions. An experimental approach was still the same consisting of ball-on-disc tribometer and optical interferometry method for film thickness evaluation. The first test was conducted under constant speed and constant sliding direction. It was followed by the experiment performed under sinusoidal speed and constant sliding direction. The last investigation was realized under sinusoidal speed with reversing sliding direction over each cycle. The results are displayed in Fig. 2.8. It can be seen that the reversing character of motion led to a drop of the lubricant film by approximately 70%.

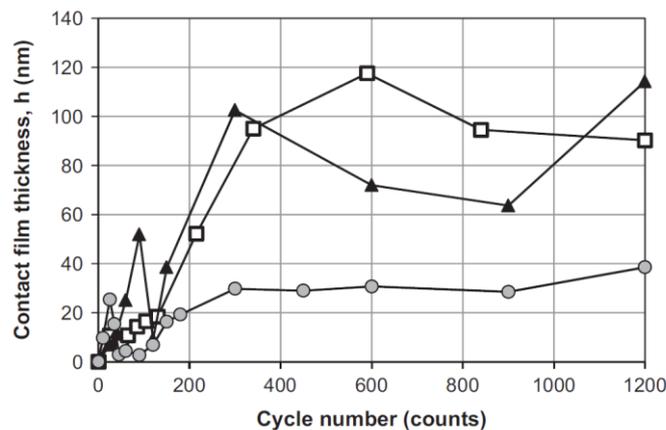


Fig. 2.8 Development of film thickness as a function of cycle number for various motion character; constant speed and direction (white squares), sinusoidal speed and constant direction (black triangles), sinusoidal speed and reversing direction (grey circles) [34].

3 SUMMARY AND CONCLUSION OF STATE OF THE ART

From the literature review, it is apparent that the biotribology of hip joint replacements is of a great importance due to limited service life of implants. Previously, the main attention was paid to the clarification of wear processes; however, there is still lack of information about the lubrication mechanisms in replacements. As the numerical simulations are extremely complicated due to SF nature and protein adsorption and agglomerations, the main attention is paid to the experimental investigations, while the choice of suitable experimental approach is particularly important.

As little is known about the role of protein constituents on lubricating film, an optical method based on fluorescent microscopy seems to be a suitable solution [10],[11]. The usability of the method is evident, since it enables to investigate even compliant non-reflective materials, to measure in a wide range of film thicknesses or to distinguish the individual constituents contained in the lubricant.

The method was initially used for the measurement of oil films on rotating steel cylinder [15]. Subsequently, the principles such as LIF [16], DELIF [19], ERLIF [20], or FRAP [23] were introduced, allowing to measure film thickness inside the contact of two bodies, to study surface topography, or to determine the lubricant flow through EHL contact. Recently, it was shown that the method enables accurate measurement of film thickness with very satisfactory readability [24]-[26].

For the investigation of lubricant film formation within hip joint replacements, an optical interferometry method in combination with ball-on-disc tribometers was employed several times. Based on the references, it is evident that the protein film formation is very complex phenomena depending on many factors such as mean speed [8],[27],[30],[32]; protein adsorption [9], model fluid composition [9],[28],[29]; load [29],[33]; time, rolling/sliding distance [29],[32],[34]; implant material [32],[33]; surface wettability and conformity [33]; or motion character [34].

It was also pointed out that the regime of lubricant supply can affect the results due to protein agglomerations observed in front of the contact zone when the contact is fully flooded [28],[30]. Nevertheless, the substance, so called inlet phase, was not observed when the lubricant was supplied continuously by a syringe pump [32],[33], indicating that the experimental conditions substantially affect the development of the protein film.

Although the importance of all the above parameters is indisputable, it should be pointed out that the absolutely fundamental factor is the composition of model fluid in terms of protein concentration and protein ratio. Some effort was conducted to clarify the single protein behaviour; however, the authors were able to investigate just simple protein solutions containing only one type of protein [28],[29] as the optical interferometry was employed for film thickness measurement.

According to author's knowledge, so far there is not such a study explaining the role of individual proteins in relation to lubricant film formation within hip replacements, considering complex model SF containing more than one constituent.

4 AIM OF THESIS

The aim of the dissertation is to establish an experimental approach enabling in situ observation of lubricant film formation in hip joint replacements, focusing on the role of particular proteins contained in SF. For this purpose, fluorescent optical method will be employed since it allows to concentrate on individual parts of the model SF. After method debugging, an extensive experimental analysis of lubricant film formation will be conducted under various operating conditions. To fulfil the main goal of the thesis, solution of the following sub-goals is necessary.

- Implementation of the fluorescent method for film thickness analysis.
- Analysis of surface topography of the tested materials.
- Preparation of the model fluids containing fluorescently stained proteins.
- In-situ observation of lubricant film formation within hip implants considering various materials and operating conditions.
- Verification of the results by optical interferometry.
- Data analysis.
- Results publication and discussion.

4.1 SCIENTIFIC QUESTION

How is the influence of the individual proteins contained in model SF (albumin, γ -globulin) on the development of lubricant film thickness within hip replacements regarding to implant material and kinematic conditions?

4.2 HYPOTHESES

- *It is expected that the contribution of γ -globulin film to total film thickness will be much more substantial than the contribution of albumin film.*
- *In terms of material, metal heads should support protein adsorption due to higher hydrophobicity; therefore, the protein film will be thicker, in general.*
- *Considering the kinematic conditions, it is suggested that the main parameter influencing the protein film development will be the level of slippage between the contact components.*
- *Respecting the PAL mechanism, an increase of speed will cause a reduction of film thickness.*

4.3 THESIS LAYOUT

The dissertation is composed of the two papers published in peer-reviewed journals and three papers published in journals with impact factor. The performed studies present the development of the methodology for the determination of protein film formation in hip joint replacements in terms of particular proteins. As the approach is based on the combination of the two methods, the first study utilizes optical interferometry method for the measurement of BS film thickness considering real conformity of rubbing surfaces (1). To be able to distinguish individual

constituents of model SF, a fluorescent optical method had to be developed as one of the sub-goals of the present thesis. The usage of the method for the direct measurement of film thickness in both, rigid and compliant contacts, is presented in the follow-up study (2). Consequently, the fluorescent technique was employed in an effort to quantify the lubricant rupture ratio at EHL contact outlet overlapping the obtained knowledge to the area of starved lubrication conditions, demonstrating the measurement possibilities of the developed technique (3). The latest part of the thesis demonstrates the use of the introduced methods for the purpose of the assessment of lubricant film formation within hip replacements in relation to the role of albumin and γ -globulin considering metal (4) and ceramic (5) femoral components and various operating conditions.

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(Author's contribution 25%)
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(Author's contribution 40%)
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(Author's contribution 25%)
(Journal impact factor = 1.74)
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(Author's contribution 55%)
(Journal impact factor = 2.88)
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(Author's contribution 60%)
(Journal impact factor = 2.88)

5 MATERIALS AND METHODS

5.1 Experimental device

In the present thesis, three experimental devices have been employed. The novel methodology was developed using ball-on-disc tribometer. As the fluorescent measurement method was supplemented by the optical interferometry, the use of interferometry for film thickness measurement is demonstrated using pendulum hip joint simulator which enables to investigate lubrication processes considering real conformity of surfaces. The surface topography was analyzed using optical profiler.

5.1.1 Ball-on-disc tribometer

The experiments dealing with the development of a new methodology enabling to assess the role of proteins on lubricant film formation were realized on ball-on-disc tribometer [17], where the contact is formed between the femoral head and the glass transparent disc. Both components can be driven independently by their own servomotors; therefore, various kinematic conditions can be applied. The load is applied by putting the weight on the lever. The contact of the ball and the disc is observed through optical imaging system consisting of mercury lamp illuminator, microscope, scientific complementary metal-oxide-semiconductor (sCMOS) digital camera (Andor NEO), and PC. Scheme of the test device is shown in Fig. 5.1.

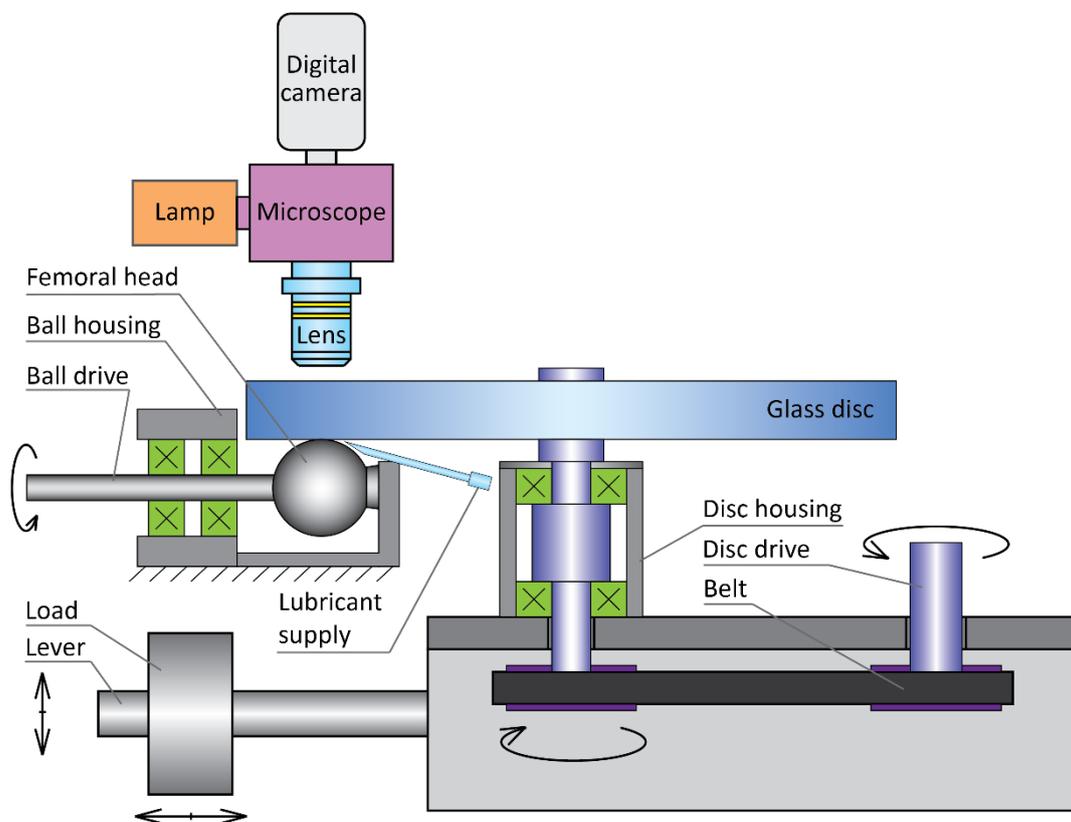


Fig. 5.1 Scheme of the ball-on-disc optical tribometer.

The simulator was also used in a modified inverted position of the test samples for the purpose of the quantification of lubricant division at the EHL contact outlet. In that case, the glass disc was substituted by the disc made from stainless steel, and the ball was placed on the top of the disc.

5.1.2 Pendulum hip joint simulator

As the optical interferometry method was also employed in the present thesis, one of the attached papers demonstrates the use of the method for lubricant film thickness evaluation under real geometry of the joint components. The experiments were realized on pendulum hip joint simulator, originally designed by Stanton [35]. The simulator consists of base frame with fixed acetabular cup and pendulum with femoral head. The optical chain is the same as in the case of optical tribometer; however, the complementary metal-oxide-semiconductor (CMOS) colour digital camera (Phantom V710) is used in this case.

The measurement principle is based on the initial deflection of the pendulum, its releasing and consequential free oscillation in the flexion-extension plane until the motion is naturally damped due to friction between the components, which can be evaluated using angular velocity sensor [36]. The scheme of the simulator, as well as the measurement principle, is displayed in Fig. 5.2. Although the presented simulator enables to consider real conformity, the importance of which was indicated in literature [33], most of the experiments were realized on ball-on-disc device since all of the previous studies focusing on lubrication within hip replacements employed the same configuration; therefore, the current data could be discussed in relation to previously published results.

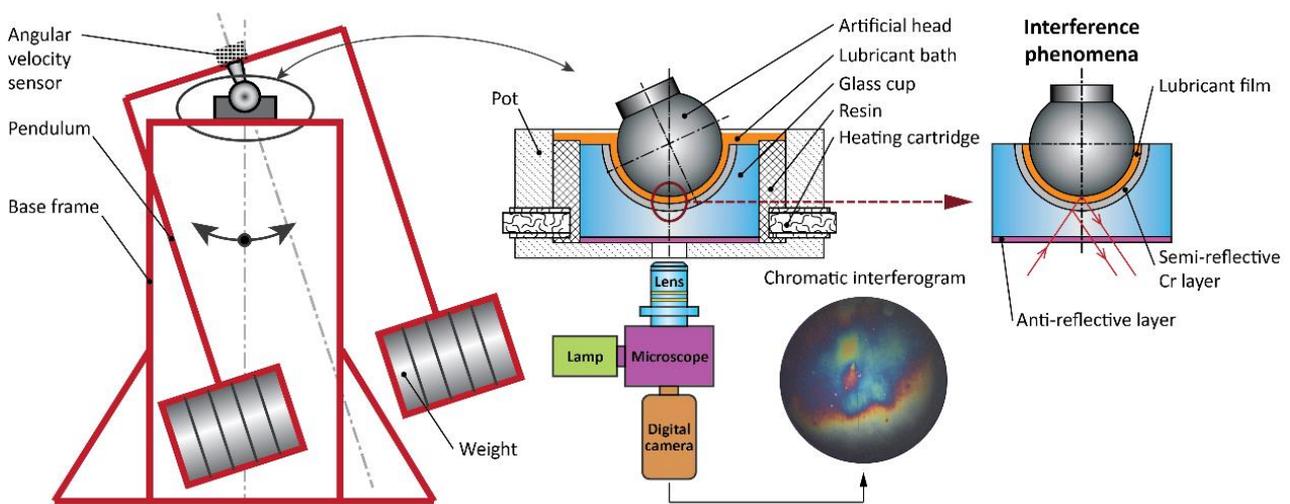


Fig. 5.2 Principle of the measurement using hip joint simulator.

5.1.3 3D optical profiler

In the case of all tested samples, initial surface topography was analysed in a greater detail. For this purpose, a 3D optical profiler (Bruker Contour GT-X8) was employed. The measurement is based on phase shifting interferometry technique.

The range of the vertical axis is down to 0.1 nm which is completely sufficient for the purposes of the present thesis, since the surface roughness of the tested balls is in the range of units of nm or higher.

5.2 Measurement methods

The main method, employed in the present thesis, is fluorescent microscopy. However, due to some limitations discussed in the following part, the experiments are supplemented by the measurements of quantitative film thickness by optical interferometry.

5.2.1 Fluorescent microscopy

Fluorescent optical method is based on the fluorescence phenomena (Fig. 5.3) previously described by Haugland et al. [37] as a consequence of the three following steps:

- **Excitation:** A photon is supplied by an external light source (lamp, laser) and is absorbed by the fluorophore, creating an excited electronic single state.
- **Excited-state lifetime:** It usually lasts 1 – 10 ns. During this time, the molecule undergoes relaxation (energy dissipation) and is left in a state from which it can emit fluorescence.
- **Fluorescence emission:** A photon of energy is emitted, while the fluorophore returns to its ground state. Due to energy dissipation during the previous phase, the photon has a lower energy and; therefore, a longer wavelength than the excited photon. The difference in wavelengths or in energy is known as Stokes shift, which is an absolutely fundamental, since it allows to separate the measured emission from excitation.

As was shown in chapter 2, the method was previously employed for the direct measurement of film thickness. However, in the case of hip replacement lubrication, quantitative film thickness was not possible due to several phenomena associated with the investigated materials.

a) Interference of light. In the case of both tested materials (metal, ceramic), interference fringes, arising at the interface of the bottom surface of the disc and lubricant, and at the interface of the lubricant and the ball, could be observed. This phenomenon was also discussed in literature [18]. The authors solved this problem by a substitution of the test sample (steel ball) by a glass lens for calibration. However, it was later pointed out by Myant et al. [24] that the different optical properties of the calibration and test samples can lead to some inaccuracies in results.

b) Quenching effect. The presence of chromium in CoCr alloy femoral heads causes the quenching of fluorescent intensity. The phenomena was introduced in literature [38]. It should be highlighted that the level of intensity loss is influenced by the chromium content, as well as the type of the applied fluorophore. Therefore, it is very complicated to determine the exact effect on

the thickness of the lubricant film in the specific cases. Nevertheless, the methodological approach is based on matching of the curves of film thickness given by optical interferometry with the curves describing the qualitative development of protein film obtained by fluorescence. Although the results of fluorescent intensity might be affected by the quenching due to chromium presence, the measurement uncertainty is constant in the course of entire measurements; therefore, the general information about film thickness development is relevant.

c) **Natural fluorescence of ceramics.** Contrary to metal head, a natural fluorescence was observed in the case of both tested ceramic materials. Even if there was no fluorophore in the excited area, the materials emitted a low level of fluorescence. Moreover, so far there is not a study describing the interaction of a level of natural fluorescence and specific fluorophores. However, as in the case of quenching, the self-emitting fluorescence effect does not significantly influence the results, since the particular values of fluorescent intensity are not decisive, as the evaluation is based on qualitative increase/decrease character of intensity compared to the initial state.

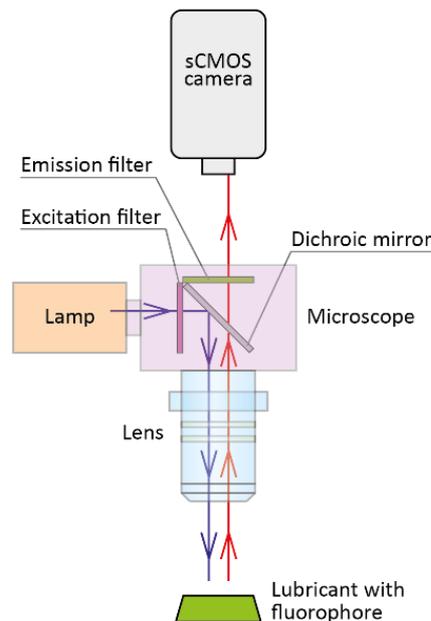


Fig. 5.3 Principle of the fluorescent method.

5.2.2 Optical interferometry

Optical interferometry is well established experimental method for very accurate measurement of film thickness. If the contact of two bodies; while one of the bodies is transparent and the other one is reflective, is illuminated, then Newton rings, also known as Fizeau rings can be observed. The interference phenomenon is based on the composition of reflected light beams. The incident beam passes through the optical chain, being split on the contact surface of the transparent counterpart and lubricant. One part of the beam is reflected back to the lens, while the second one passes through the lubricant and reflects at the interface of the lubricant and the ball.

Since the travelled distance of the two beams is different, the phase is changed. Hartl et al. [14] proved that the method enables to measure the separation of the surfaces down to 1 nm with the resolution of units of nm.

5.3 Test samples and experimental conditions

Test samples, as well as experimental conditions, differed according to the test type, applied simulator, or measurement method. Particular details related to the particular tests are summarized in Table 5.1. In the case of ball-on-disc tribometer, when the film thickness and protein film formation was investigated, the configuration consisted of the transparent glass disc and the ball. For the purpose of optical interferometry measurement, the disc was, moreover, coated with a thin chromium layer enhancing the contrast of interference. As one of the application of fluorescent method deals with the quantification of lubricant division at the EHL contact outlet, the configuration was modified, substituting the glass disc by the disc made from stainless steel. In the case of pendulum simulator, the contact consisted of femoral head and glass acetabular cup, which contact convex surface was, again, coated with the chromium layer ensuring sufficient contrast of light interference.

	(1)	(2)	(3)	(4)	(5)
Load (N)	532	12	12; 26; 41	300	5
Contact pressure (MPa)	28.7	401.7	66.5; 83.8; 100	800	270 280
SRR (%)	-200	0	-150 – 150	-150; 0; 150	
Mean speed (mm/s)	5.9 – 0	10 - 500	60; 220; 450	5.7; 22	
Ball diameter (mm)	28	25.4	25.4	28	
Diametric clearance (μm)	92	-	-	-	
Ball material	CoCrMo alloy	Si3N4	Phenol	Stainless steel	CoCrMo alloy
Test lubricant	25% BS	Mineral oil	Mineral oils	Protein solution	
Lubricant viscosity (Pa·s)	-	0.644	0.19; 0.45; 0.64; 1.4	-	
Protein content (mg/ml)	22.4	-	-	10.5	
Temperature ($^{\circ}\text{C}$)	37	Ambient			

Tab. 5.1 Summary of the experimental conditions employed in the performed studies.

6 RESULTS AND DISCUSSION

Thin film colorimetric interferometry technique for film thickness measurement has a long tradition at the Institute of Machine and Industrial Design (IMID). The method was developed by prof. Hartl and prof. Křupka who established tribology research group at IMID more than twenty years ago. The usage of interferometry method is not the main contribution of the author of the present dissertation; however, it is used for the supportive measurements of film thickness, so the use of the technique is illustrated in one of the attached the papers (1).

Film thickness was measured in the real geometrical configuration (ball-on-cup), since it was indicated in literature that the conformity can substantially affect the formation of protein film. 28 mm CoCrMo alloy femoral head was loaded against the glass acetabular cup and the film thickness was measured as a function of time and pendulum deflection, respectively. The obtained results are shown in Fig. 6.1. Immediately after the beginning of the experiment, the film thickness reached almost 240 nm. Then, it started to continuously decrease and was stabilized after approximately 10 seconds between 80 and 100 nm with no significant change until the end of the test. The character of film formation was in a good agreement with that of ball-on-lens configuration presented by Vrbka et al. [33], who were the first who changed the non-conformal ball-on-disc configuration to a configuration with the higher degree of conformity (ball-on-lens). From the particular interferograms of the contact zone, it was apparent that, at the beginning, a strong aggregation of proteins in the central contact zone occurred, while the increasing time led to thinning of the layer, which was uniform over the contact area. The experiment was repeated once more under the same operating conditions, finding that results were almost the same, proving the precision and reproducibility of the employed technique. Moreover, the test was performed with PAO oil of a viscosity $\eta = 0.0255 \text{ Pa}\cdot\text{s}$ as a representative of simple Newtonian fluid. Completely different character of film formation could be observed in that case. If the rubbing surfaces were not protected by the proteins contained in BS, breakdown of the lubricating film could be observed in less than 5 seconds leading to a rapid wear of chromium layer on the contact surface of the cup. On the other hand, although a thinner film was detected, in general; the natural swinging of the pendulum lasted longer compared to the test performed with BS (75 s vs. 50 s). This indicates that the shear forces between the proteins cause an increase of friction, as was previously discussed in literature [39].

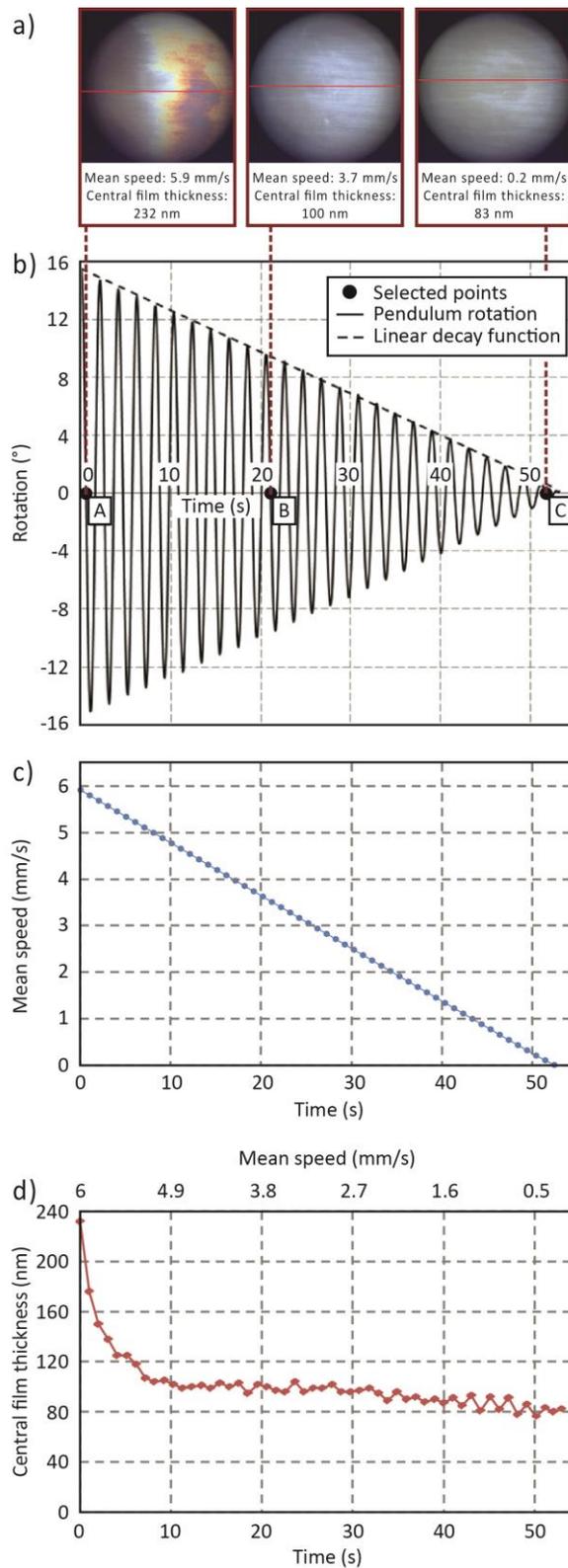


Fig. 6.1 From the top: Chromatic interferograms (inlet is on the left) depicting the behaviour of lubricant film thickness in selected points A ($t_A = 0.6$ s, $u_{mA} = 5.9$ mm/s), B ($t_B = 21.1$ s, $u_{mB} = 3.7$ mm/s) and C ($t_C = 51.8$ s, $u_{mC} = 0.2$ mm/s), which correspond to the equilibrium state position of the pendulum ($\varphi = 0^\circ$, $F_{\max} = 532$ N) and are highlighted in the graph b) showing the damping of pendulum oscillation. c) Dependence of mean speed of pendulum equilibrium points on time. d) Development of central film thickness as a function of time and mean speed.

As the optical interference does not allow to separate the individual constituents of the model fluid, fluorescence optical method had to be developed as one of the main goals of the current dissertation. Following study (2) presents the ability of the technique for the film thickness measurement in both, EHL and i-EHL contacts. Initially, the method was verified comparing the results of film thickness in rigid EHL contact (ceramic vs. glass) with the theoretical prediction. The experiments were realized under pure rolling conditions, considering the range of speeds from 10 to 500 mm/s. Constant load of 12 N was applied for all the rolling speeds. Film thickness continuously increased over a speed range, it varied from 100 nm at 10 mm/s to 1.5 μm at 500 mm/s. The film thickness profiles well corresponded with the EHL theory, while typical horseshoe-shaped constriction could be observed on the contact images with increasing speed. With the exception of the lowest rolling speeds, the measured central thicknesses were in an excellent agreement with the prediction, proving the validity of the method (see Fig. 6.2).

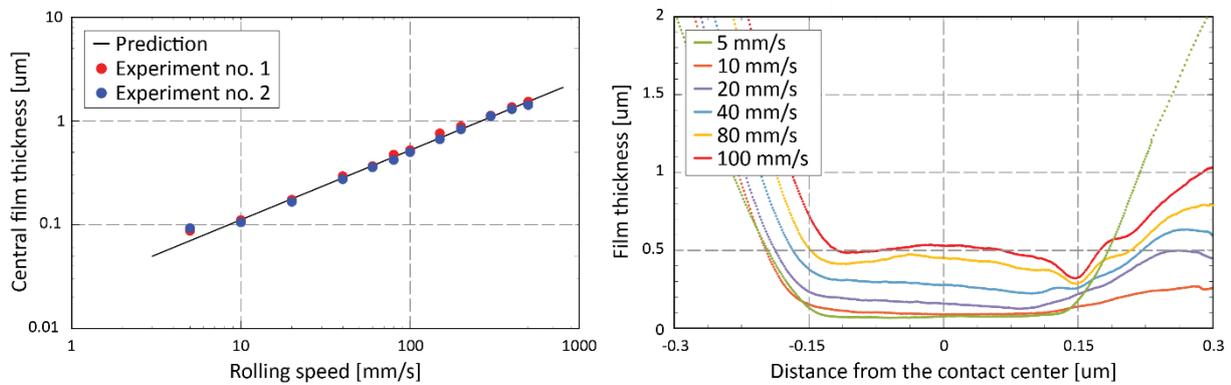


Fig. 6.2 Left: The dependence between film thickness and rolling speed. Right: Film profiles for selected rolling speeds (inlet is on the left).

Subsequently, the experimental configuration was changed, substituting the ceramic ball by the ball made from phenol. Modulus of elasticity of phenolic ball was 4 GPa representing compliant contact body. The speed range was the same as in the case of EHL contact; however, three different load levels were investigated. In general, there was no significant effect of load on the lubricant film thickness, as can be seen in Fig. 6.3. What was in discrepancy with i-EHL theory was that the film slightly increased with increasing load, while opposite behaviour was expected. Nevertheless, the same phenomena was observed even by Fowell et al. [40]. For all the tested loads, the film linearly increased with increasing speed, while the measured data were a little bit lower compared to prediction when the load was 12 N, and 26 N, respectively. In the case of the highest load (41 N), a satisfactory agreement of prediction and experimental data could be observed. When focusing on the profiles of lubricant film, it might be concluded that the slope of the central zone increased with increasing speed. However, the slope was not as significant as previously observed [24],[25]. The difference probably comes from the differences in elastic moduli. In the mentioned references, the authors investigated the samples,

whose elasticity was just in the range of units of MPa. As the modulus of phenol is 4 GPa, it is estimated that the central region of the contact zone becomes flattened with increasing stiffness of the contact body. This statement is supported by classical EHL theory derived for rigid bodies, where the central plateau region can be observed.

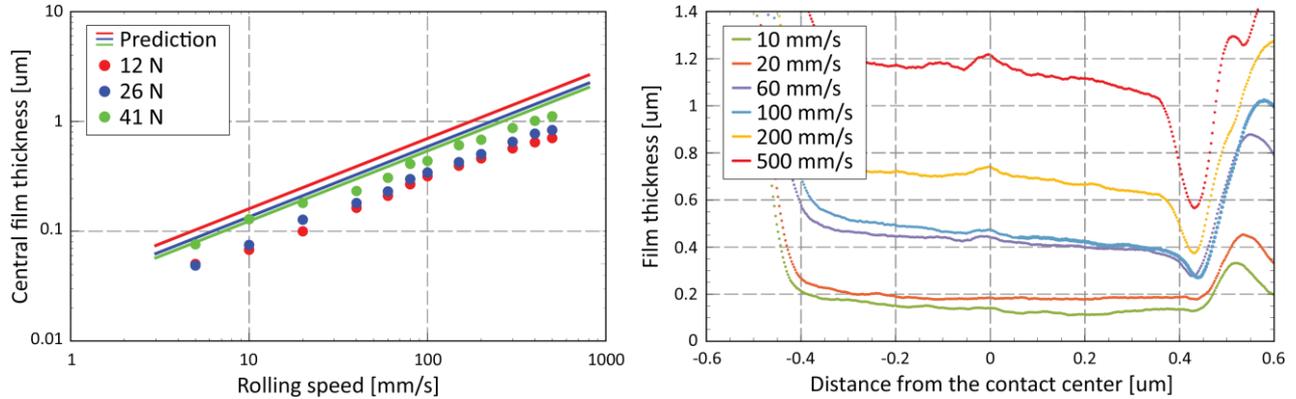


Fig. 6.3 Left: The dependence between film thickness and rolling speed for different loading conditions. Right: Film profiles for selected rolling speeds for load equal to 41 N (inlet is on the left).

In the literature review, it was presented that the fluorescent method can be applied for several applications. Therefore, we employed the developed technique for the investigation of the lubricant rupture ratio at EHL contact outlet (3). The experimental configuration consisted of the steel ball and the steel disc in an inverted position compared to the previous study. To check the effect of contact ellipticity, the ball was consequently substituted by the rollers of a various radius of curvature resulting to the ellipticities from 1 to 4. Experiments were realized under various mean speeds and SRRs, while the evaluation was based on the qualitative comparison of the intensities of the central parts of the contact drags on the both components. The effect of lubricant viscosity was also studied. So far, there was no an experimental study investigating the phenomena of lubricant division after passing the contact. Therefore, the data were confronted with those based on numerical simulation [41]. The results showed that the film tend to attach to the faster rotating component while the ratio increased with increasing SRR, as can be seen in Fig. 6.4. Similar behaviour was observed for all the tested speeds and ellipticities. The effect of lubricant viscosity seemed to be not a substantial parameter. Although the trend well correlated with the mentioned numerical analysis, the slope of the curve was not as steep. The difference was attributed to several aspects which could not be considered in the theoretical analysis; such as thermal processes, or shear thinning behaviour of fluid. In addition, the configuration was highly non-conformal, while it might be better to investigate these phenomenon using a pair of identical rolling elements to avoid the effect of different surface geometry.

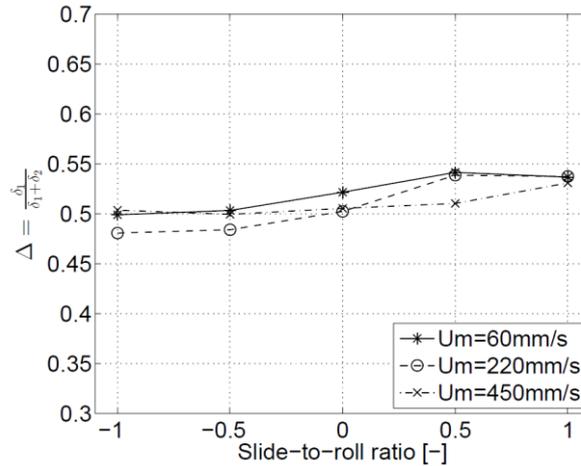


Fig. 6.4 Outlet film thickness rupture ratio Δ as a function of SRR for 3 different mean speeds.

In this study, we also checked the reproducibility of the fluorescent method in a greater detail. The contact was lubricated by mineral oil and 20 images of the contact drag were captured with 1 second delay. As the speed was constant, it was expected that the thickness of the layer is also constant. It was found that the maximal deviations against the mean value were from -2.6 % to 2.9 %.

The main part of the dissertation is focused on the assessment of the lubricant film formation in hip joint replacements in terms of individual proteins. As the film thickness could not be measured by the fluorescent microscopy, all the experiments were initially realized with the use of optical interferometry determining the lubricant film thickness development as a function of time. Three commonly used materials of artificial heads were investigated; CoCr alloy (4), BIOLOX®*forte* (Al_2O_3) and BIOLOX®*delta* (75% Al_2O_3 , 24% ZrO_2 , Cr_2O_3) (5), respectively. As all of the previous studies dealing with the lubrication of hip replacements, with the exception of our paper (1), were performed utilizing ball-on-disc tribometers, our experiments were conducted in the same setup to be able to confront the results with previously published data. The tests were realized under two mean speeds, three SRRs and constant load. Following the experiment design, all the tests were repeated three times under the same operating conditions with various lubricants. The content and ratio of albumin and γ -globulin was still the same; however, firstly the both proteins were non-stained (film thickness); secondly, albumin was stained (albumin protein film development); and finally, γ -globulin was stained (γ -globulin protein film development). The curves describing the thickness as well as particular protein film evolution were later compared allowing to define the role of individual constituents in relation to complex film behaviour.

The first paper (4) dealt with the development of the methodology, while the main attention was paid to metal femoral head. The results showed that the fundamental parameter influencing the protein film formation is the level of slip between the components. Under pure rolling conditions, the lubricant film gradually increased with time for both the tested speeds (Fig. 6.5), while the total film

thickness was approximately two times higher at higher speed. When focusing on the role of proteins, the change of fluorescent intensity of γ -globulin was almost negligible; however, the intensity of albumin film well corresponded with the development of film thickness. Therefore, it was concluded that film is formed predominantly due to presence of albumin. Considering the negative sliding (the ball is faster than the disc) led to a completely different character of film formation. At lower speed, the film was very thin just in the range of units of nm over the whole time of the experiment. The protein film intensities were very low as well, indicating that the film could not be fully developed. This fact was attributed to the disruption of the film as a consequence of the fast rotation of the ball. Increasing the sliding speed caused an increase of film thickness during the second half of the test while the film was attributed to γ -globulin. On the images of excited area, it could be observed that γ -globulin layer thickness increased on the bottom of the disc due to gradual protein adsorption onto the surface. When the disc was faster than the ball (positive sliding), the film increased rapidly up to 120 nm at lower and 40 nm at higher speed. After reaching the maximum, the film started to decrease. The increasing/decreasing tendency could be observed for both speeds while the difference was the time/sliding distance before reaching the maximum. In terms of proteins, albumin intensity was in a good agreement with the global tendency; therefore, it was concluded that the film was formed mainly due to presence of albumin as in the case of pure rolling. However, even the contribution of γ -globulin was remarkable especially at lower sliding speed.

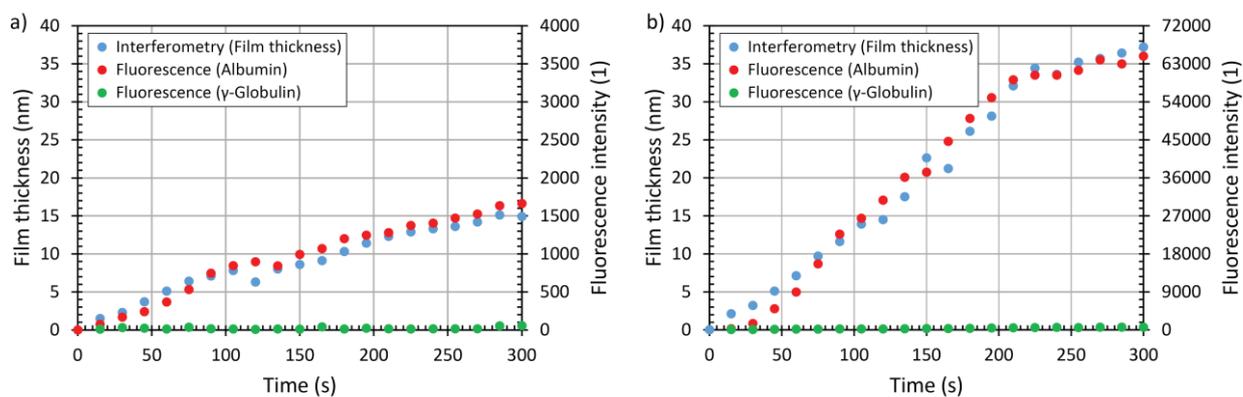


Fig. 6.5 Development of film thickness and fluorescence intensity of labelled proteins as a function of time under pure rolling conditions for different mean speeds; a) 5.7 mm/s; b) 22 mm/s.

Finally, the developed methodology was applied for the determination of protein film formation considering ceramic femoral heads (5). The same experimental conditions were investigated in an effort to compare the results with those of metal head. Under pure rolling, the development of film thickness was very similar to metal component – continuous increase was detected independently of sliding speed and the type of ceramic. Again, the effect of albumin was dominant; nevertheless, the thickness of γ -globulin slightly increased with time. The results

under negative sliding were not as clear and were strongly affected by both, material and sliding speed. Forte ceramic exhibited combined increasing/decreasing tendency. At lower speed the film was formed by the combination of both proteins, while in the case of higher speed, the contribution of γ -globulin was negligible. Similar behaviour was observed for delta ceramic at low speed regime. At higher speed, the film increased just after the start of the test, as a consequence of an immediate increase of γ -globulin film. Within the first minute, γ -globulin dropped to a very low level, while the further development of protein film was relatively stable between 12 and 20 nm and was attributed to albumin film. In the case of positive sliding, similar character of film formation compared to metal head was obtained for forte ceramic. The role of albumin was crucial; however, the contribution of γ -globulin increased with sliding distance at higher speed. Delta ceramic exhibited a rapid initial increase followed by a slight continuous decrease with the same behaviour of proteins as in the case of forte. The measured film thicknesses for the both femoral heads are depicted in Fig. 6.6.

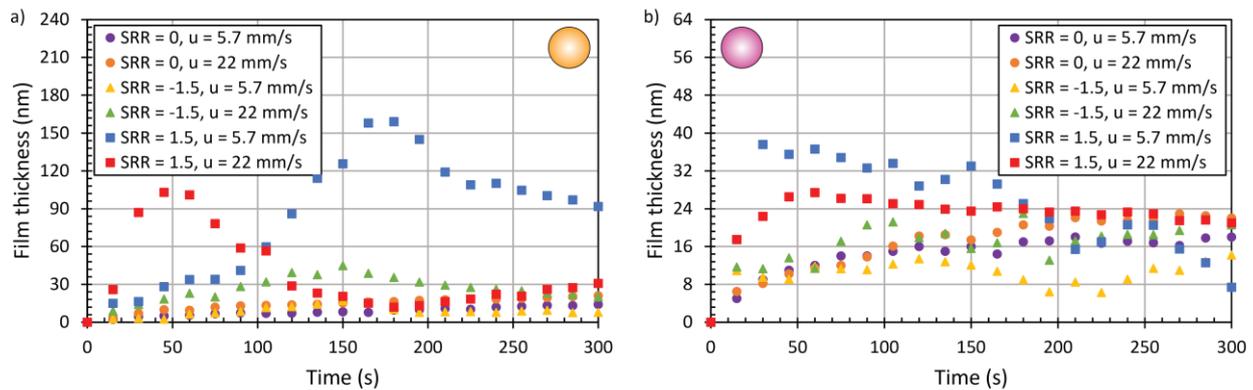


Fig. 6.6 Comparison of film thicknesses under various operating conditions. a) BIOLOX[®] forte; b) BIOLOX[®] delta.

The performed studies present the development of the methodology for the determination of protein film formation in hip joint replacements in terms of particular proteins. As the approach is based on the combination of the two methods, the first study utilizes optical interferometry method for the measurement of BS film thickness considering real conformity of rubbing surfaces (1). To be able to distinguish individual constituents of model SF, a fluorescent optical method had to be developed as one of the sub-goals of the present thesis. The usage of the method for the direct measurement of film thickness in both, rigid and compliant contacts, is presented in the follow-up study (2). Consequently, the fluorescent technique was employed in an effort to quantify the lubricant rupture ratio at EHL contact outlet overlapping the obtained knowledge to the area of starved lubrication conditions (3). The latest part of the thesis demonstrates the use of the introduced methods for the purpose of the assessment of lubricant film formation within hip replacements in relation to the role of albumin and γ -globulin considering metal (4) and ceramic (5) femoral components.

7 CONCLUSIONS

The present dissertation deals with the lubrication mechanisms within hip replacements. Although total hip arthroplasty became one of the most successful and most applied surgery; the service life of implants is still limited. As the main attention of the researchers was paid to the quantification of wear rate previously, so far, little is known about the lubrication mechanisms inside the contact. However, such a knowledge can help to better understand the mechanisms leading to implant failure. Recently, the protein film development was studied in a model ball-on-disc configuration, while several effects were extensively investigated. One of the most important factor seems to be the composition of model SF. Nevertheless, none of the performed studies could explain the role of particular proteins contained in SF in relation to the protein film formation. When focusing on individual constituents, only simple protein solutions were used; which does not correspond to the behaviour of complex fluids. To be able to distinguish the constituents in lubricant, optical method based on fluorescent microscopy was developed as a part of the PhD thesis.

The first part of the thesis discusses potential experimental approaches for in situ analysis of film thickness inside the contact. A fluorescent method is described in a greater detail, presenting the possibilities of the method published in the last 40 years. Consequently, the studies focusing on the protein film formation in hip replacements are introduced, giving the general overview of the parameters apparently influencing the protein film. The defined aim of the thesis comes from the critical analysis of the current state of the art in the field. The latter part deals with the employed experimental devices and applied measurement methods.

The main goal of the thesis was to perform an experimental analysis of protein film formation focusing on the role of the particular proteins. For this purpose, fluorescent method was developed and verified by the measurement of film thickness in EHL and i-EHL contact. The ability of the method is later demonstrated as a tool for the quantification of the lubricant division at EHL contact outlet. As the method was supported by optical interferometry, the use of the method for the measurement of film thickness considering real conformity of rubbing surfaces is also presented. Finally, the methodological approach for the assessment of the role of proteins while the simultaneous presence of another protein on lubrication mechanisms within hip replacements is widely presented.

The current thesis contains original results extending the knowledge in the area of hip joint replacements lubrication. The results are confronted with the previous studies. The further step is to employ a developed methodology approaching the real conditions in joints such as conformity, multidirectional motion, transient loading conditions and higher complexity of model SF.

The main contribution of the thesis can be summarized into the following points:

- For the first time, protein film formation under real conformity of rubbing surfaces was analysed in situ.

- An optical method based on fluorescent microscopy was developed, enabling direct measurement of film thickness in both, rigid and compliant contacts.
- The ability of the fluorescent method was demonstrated investigating lubricant division at EHL contact outlet.
- Analysis of protein film formation within hip joint replacements with respect to implant material and various operating conditions was conducted, focusing on the role of particular SF proteins, considering complex model fluids.

Regarding to scientific question, the obtained knowledge can be summarized to the following concluding remarks:

- Contrary to previously published results, it was found that under most conditions, albumin protein is responsible for film thickness development. This proves that it is necessary to study complex model fluids, not just the simple protein solutions, since the interaction of the constituents can substantially affect the formation of the protein film (**HYPOTHESIS WAS FALSIFIED**).
- Under pure rolling conditions, film formation was similar for metal and ceramic heads, while the total film thickness was higher in the case of metal (especially at higher rolling speed), confirming the effect of surface wettability. However, when rolling/sliding conditions were taken into account, the character of film formation was completely different, dependent on implant material, sliding speed, and positivity/negativity of the slippage, while the thickness was higher in the case of ceramic heads, in general (**HYPOTHESIS WAS FALSIFIED**).
- From the investigated factors, the main parameter influencing the protein formation is indisputably the level of slippage between the surfaces (**HYPOTHESIS WAS CONFIRMED**).
- With the exception of partial positive sliding, film thickness was always higher at higher rolling/sliding speed (**HYPOTHESIS WAS FALSIFIED**).

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1. VRBKA, M.; NEČAS, D.; HARTL, M.; KŘUPKA, I.; URBAN, F.; GALLO, J. Visualization of lubricating films between artificial head and cup with respect to real geometry. *Biotribology*, 2015, 1-2, 61-65.
2. NEČAS, D.; ŠPERKA, P.; VRBKA, M.; KŘUPKA, I.; HARTL, M. Film thickness mapping in lubricated contacts using fluorescence. *MM Science Journal*, 2015, 2015(4), 821-824.
3. KOŠTÁL, D.; NEČAS, D.; ŠPERKA, P.; SVOBODA, P.; KŘUPKA, I.; HARTL, M. Lubricant rupture ratio at elastohydrodynamically lubricated contact outlet. *Tribology Letters*, 2015, 59(3), 1-9. **(Journal impact factor = 1.74)**
4. NEČAS, D.; VRBKA, M.; URBAN, F.; KŘUPKA, I.; HARTL, M. The effect of lubricant constituents on lubrication mechanisms in hip joint replacements. *Journal of the Mechanical Behavior of Biomedical Materials*, 2016, 55, 295-307. **(Journal impact factor = 2.88)**
5. NEČAS, D.; VRBKA, M.; KŘUPKA, I.; HARTL, M.; GALANDÁKOVÁ, A. Lubrication within hip replacements – Implication for ceramic-on-hard bearing couples. *Journal of the Mechanical Behavior of Biomedical Materials*, 2016, 61, 371-383. **(Journal impact factor = 2.88)**
6. VRBKA, M.; NEČAS, D.; BARTOŠÍK, J.; HARTL, M.; KŘUPKA, I.; GALANDÁKOVÁ, A.; GALLO, J. Determination of a friction coefficient for THA bearing couples. *Acta chirurgiae orthopaedicae et traumatologiae Cechoslovaca*, 2015, 82(5), 341-347. **(Journal impact factor = 0.39)**
7. TKACHENKO, S.; NEČAS, D.; DATSKEVICH, O.; ČUPERA, J.; SPOTZ, Z.; VRBKA, M.; KULAK, L.; FORET, R. Tribological performance of Ti–Si based in situ composites. *Tribology Transactions*. 2016, 59(2), 340-351. **(Journal impact factor = 1.35)**

CONFERENCE PROCEEDINGS

1. NEČAS, D., VRBKA, M.; ŠPERKA, P.; DRUCKMÜLLER, M.; SKLÁDAL, P.; ŠTARHA, P.; KŘUPKA, I.; HARTL, M. Qualitative analysis of film thickness in rolling EHD contact by fluorescence technique. *Lecture Notes in Mechanical Engineering*, 2014, 615-622.
2. TKACHENKO, S.; NEČAS, D.; DATSKEVICH, O.; ČUPERA, J.; SPOTZ, Z.; VRBKA, M.; KULAK, L.; FORET, R. Tribological behavior of Ti– Si based in situ composites under sliding. *Metal 2014*, 2014, 2704-2709.

3. NEČAS, D., VRBKA, M.; YARIMITSU, S.; NAKASHIMA, K.; SAWAE, Y.; ŠPERKA, P.; KŘUPKA, I.; HARTL, M. Frictional properties of PVA hydrogel. *The Latest Methods of Construction Design*, 2016, 159-164.

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1. VRBKA, M.; NEČAS, D.; URBAN, F.; KŘUPKA, I.; HARTL, M.; GALLO, J. A novel approach for in situ observation of lubricant film at the interface between artificial head and cup of THA. *EORS 22nd Annual Meeting*, 2014, Nantes, France.
2. SAWAE, Y.; VRBKA, M.; URBAN, F.; NEČAS, D.; YARIMITSU, S.; NAKASHIMA, K.; MURAKAMI, T.; HARTL, M. Friction characterization of ceramic-on-hydrogel hip joint in pendulum test. *2nd International Conference on Biotribology*, 2014, Toronto, Canada.
3. NEČAS, D.; SAWAE, Y.; YARIMITSU, S.; NAKASHIMA, K.; VRBKA, M.; HARTL, M.; MURAKAMI, T. Protein adsorbed film formation and frictional characteristics of CoCrMo-on-UHMWPE sliding pair in reciprocating sliding test. *2nd International Conference on Biotribology*, 2014, Toronto, Canada.
4. NEČAS, D.; VRBKA, M.; URBAN, F.; KŘUPKA, I.; HARTL, M.; GALLO, J. Observation of lubricant film between artificial head and cup. *Tribology Frontiers Conference*, 2014, Chicago, USA.
5. KOŠTÁL, D.; NEČAS, D.; ŠPERKA, P.; SVOBODA, P.; KŘUPKA, I.; HARTL, M. Lubricant division in EHL contact outlet. *Tribology Frontiers Conference*, 2014, Chicago, USA.
6. URBAN, F.; NEČAS, D.; VRBKA, M.; KŘUPKA, I.; HARTL, M.; GALLO, J. In Situ Observation of Lubricant Film within Artificial Hip Joints. *International Tribology Conference*, 2015, Tokyo, Japan.
7. NEČAS, D.; VRBKA, M.; URBAN, F.; KŘUPKA, I.; HARTL, M.; GALLO, J. An experimental investigation of lubricant film formation in artificial hip joints. *The 8th International Biotribology Forum, The 36th Biotribology Symposium*, 2015, Yokohama, Japan.
8. NEČAS, D.; ŠVACHOVÁ, M.; VRBKA, M.; KŘUPKA, I.; HARTL, M. The effect of albumin and γ -globulin on lubricant film formation in artificial hip joints. *The 17th Nordic Symposium on Tribology - NORDTRIB 2016*, 2016, Hämeenlinna, Finland.

CURRICULUM VITAE

Ing. David Nečas

Date and place of birth: 02/11/1987, Nové Město na Moravě

Education

- 2012 – 2016 Doctoral study at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology. Topic of the dissertation thesis: The effect of synovial fluid constituents on lubrication of hip joint replacements.
- 2010 – 2012 Master study at Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology. Topic of the diploma thesis: Stress strain analysis of the femur based on the CT data collection. Passed with distinction.
- 2007 – 2010 Bachelor study at Faculty of Mechanical Engineering, Brno University of Technology. Topic of the bachelor thesis: Summary of unconventional aircraft concepts.
- 2003 – 2007 Higher Professional and Secondary Technical School, Žďár nad Sázavou. Branch: Engineering. Passed with distinction.

Awards

2012 – Dean's award for the excellent diploma thesis

2006 – Talent of Vysočina region

2006 – Award of Vysočina region governor

Teaching and scientific activities

Lectures

- Finite element method – ANSYS Classic (ZSY-A)

Seminars

- CAD (3CD)
- Finite element method – ANSYS Classic (ZSY-A)
- Finite element method – ANSYS Workbench (ZAW)
- Machine design – Machine Elements (5KS)
- Machine design – Mechanisms (6KM)
- Machine design – Mechanical Drives (6KT)
- Team project (ZKP)
- Tribology (ZTR)

Participations in scientific projects

- 2015 Innovation of tribology lessons for the method based on fluorescent microscopy (FV 15-14).

- 2013 – 2015 The influence of joint fluid composition on formation of lubricating film in THA (NT14267).
- 2014 – 2016 Study of friction, wear, and lubrication of hip replacements (FSI-S-14-2336).
- 2013 Study of tribological aspects of wheel-rail contact regarding to insufficient lubricant distribution (FSI-J-13-2096).

Internships

- 07/2010 ESEM Summer School 2010, Trinity College, Dublin, Ireland
- 06/2013 – 08/2013 Kyushu University, Fukuoka, Japan
- 07/2015 – 09/2015 Kyushu University, Fukuoka, Japan

Language skills

Czech, English (B2/C1)

Scientific activities

- Lubrication and friction of hip joint replacements
- The use of optical methods in biotribology of hip joint replacements
- Isoviscous-elastohydrodynamic lubrication

ABSTRACT

The dissertation thesis deals with the lubrication mechanisms within hip joint replacements. A systematic study of protein film formation considering various materials and operating conditions was conducted, focusing on the role of particular synovial fluid proteins while the simultaneous presence of other proteins. Since the previously applied experimental approaches did not allow to separate the individual constituents of the model fluid, an optical measurement method based on fluorescent microscopy was developed. The verification of the method is presented performing two different studies focusing on the film thickness determination and lubricant rupture ratio at lubricated contact outlet, respectively. Due to several limitations of the fluorescent microscopy, the research was supported by the use of optical interferometry method, whose usage is demonstrated in the study dealing with the protein film formation in hip joint replacements considering real conformity of rubbing surfaces. The latest part of the thesis introduces a novel methodological approach enabling to assess the role of proteins in relation to protein film thickness based on in situ observation of the contact zone. The thesis presents original results extending the knowledge in hip replacement biotribology area towards the further development of implants preventing its failure due to limited service life.

ABSTRAKT

Dizertační práce se zabývá mechanismy mazání v náhradách kyčelního kloubu. Byla provedena systematická studie formování proteinového filmu při zahrnutí různých materiálů a provozních podmínek. Hlavní pozornost je přitom věnována roli jednotlivých proteinů obsažených v synoviální kapalině při současné přítomnosti dalších proteinů. Jelikož metody aplikované v předchozích studiích neumožňovaly separovat jednotlivé složky maziva, byla vyvinuta optická měřicí metoda na principu fluorescenční mikroskopie. Z důvodu verifikace metody byly provedeny dvě nezávislé studie zaměřené na měření tloušťky mazacího filmu a dělení maziva na výstupu mazaného kontaktu. Z důvodu určitých limitací fluorescenční mikroskopie byla dále využita i metoda optické interferometrie, jejíž využití je ilustrováno ve studii zabývající se formováním mazacího filmu v náhradách kyčelního kloubu při uvažování reálné konformity třecích povrchů. Závěrečná část práce představuje nový metodologický přístup založený na in situ pozorování kontaktní oblasti umožňující popsat roli jednotlivých proteinů ve vztahu k vývoji tloušťky mazacího filmu. Práce obsahuje originální výsledky, které přinášejí nové poznání v oblasti biotribologie náhrad kyčelního kloubu vedoucí k dalšímu vývoji implantátů při snaze zabránit jejich selhání v důsledku omezené životnosti.