MAPPING OF LUBRICATING FILM THICKNESS IN HUMAN HIP JOINT REPLACEMENTS

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This paper describes experimental mapping of lubricating film thickness and mechanism of its forming in contact of CoCrMo femoral head with a diameter of 28 mm and a glass disc with presence of bovine serum as a substitute of synovial fluid occurred in a natural joint. The contact area was illuminated by a xenon lamp and recorded by a high-speed camera. The load applied to the contact area was 5 N corresponding with the contact pressure of 271 MPa. Obtained data was evaluated by a thin film colorimetric interferometry. A pure rolling and partial sliding measurements were examined. From observed interferograms is apparent the deposition of proteins to the glass disc and femoral head surfaces, denaturation and formation of protein aggregations affecting the residual lubricating film thickness. The basic mechanisms of protein film forming were brought out and it is apparent that forming of protein lubricating film is a complex mechanism containing more influences.

Keywords

Biotribology, Bovine serum, Film thickness, Artificial hip joint, Colorimetric interferometry

1. Introduction

Applications of artificial joints represent the further hope to painless movement for patients with a damaged joint due to osteoarthritis, rheumatic arthritis, tumour or trauma. Total hip replacement is even assumed as the most successful surgical operation of 20th century. It is estimated that 959 000 surgeries are performed each year [Kurtz 2007]. From the arthroplastic registers is also evident the growth in the number of operations every year [Garellick 2010], [NJR 2011].

The main problem of current joint replacements still remains their longevity. It is supposed that THA reduces pain of the injured joints and improves their functionality for 15 to 20 years after an operation. However, more than 10% of all operations are comprised by revisions caused by dislocations, bone fracture, infection or prosthetic loosening [Garellick 2010]. For younger patients the revision rates up to 28% in the first 10 years after the operation [Corbett 2010].

More than 50% reasons to revision are caused by aseptic loosening of an implant [Garellick 2010]. It is induced by reaction of wear particles with a surrounding tissue. Up to 500 billion of polyethylene particles from metal-on-plastic (MOP) hip replacement can be created every year [Schmalzried 1999]. These particles get to the bone tissue and cause the inflammation and reducing of bone mass around the replacement and this process is called osteolysis [Unsworth 2000]. Due to this problem the hard prosthesis, such as ceramic-on-ceramic (COC) or metal-on-metal (MOM), are recommended for younger and more active patients. This "hard" replacement produces much lower wear particles, nevertheless these particles are much smaller and more reactive. Metallic wear particles from MOM replacements increase the number of metallic ions in blood and are associated with allergic reactions, tissue necrosis and prosthesis loosening. MOM replacements even have the highest number of revisions [NJR 2011].

The main approaches to improve the longevity thus still remain reducing of wear. This can be reached by usage of low wear materials for friction surfaces or by improving the tribological properties of current implants. It is known that fluid lubricating film fully separating frictional surfaces can significantly reduce wear. While the COC and MOM replacements can under certain conditions operate in a fully fluid film lubricating regime [Jin 1997], [Udofia 2003], MOP replacements operate in a mixed or boundary regime [Jalali-Vahid 2001], which results in contacts of surface asperities and increasing of wear. The formation of lubricating film is influenced, among others, by femoral head radius, radial clearance between femoral head and acetabular cup or surface roughness [Jin 1997]. Moreover, the presence of protein in the lubricant can significantly affect the formation of lubricating film. Unsworth et al. [Unsworth 2000] mentioned that the incipient elastohydrodynamic lubricating film can be disturbed by a protein layer adsorbed on articulating surfaces. This theory was also noted by Scholes et al. [Scholes 2006]. He carried out the friction measurements in an artificial joint simulator with protein containing solutions and he observed the change in frictional properties in contrast with lubricant without proteins. This was associated with proteins adsorption on frictional surfaces, which penetrate fluid lubricating film and arise the contact of protein layers of each surface.

It is apparent that proteins included in synovial fluid can affect the lubricating film via their deposition on articulating surfaces. They can act as a boundary layer affecting the wear of joint surfaces. However, there have not been published the exact mechanisms of forming of lubricating film in artificial joints and influence of biological particles to wear. The aim of this study is to investigate behaviour of lubricating film with biological substitute of synovial fluid.

2. Experimental method

For the film thickness measurement was used an optical testing device using thin film colorimetric interferometry. The contact area is formed between a glass disc and a metal femoral head AESCULAP NK430K with a diameter of 28 mm made from CoCrMo alloy (ISO 5832–12).

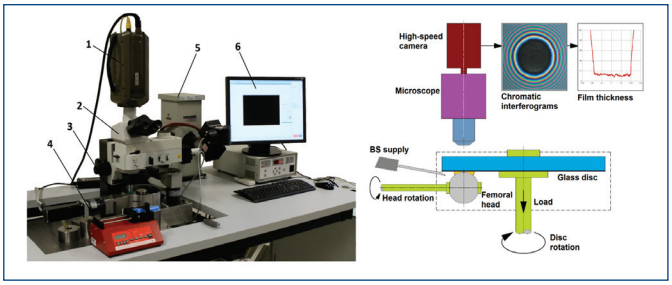

Figure 1. *Optical testing device (1 – high-speed camera, 2 – microscope, 3 – tribology simulator, 4 – syringe pump, 5 – light source, 6 – evaluating software) and schematic diagram of film thickness measurement method.*

The upper surface of the glass disc has an antireflective layer and a lower surface is coated with a semi-reflective chromium layer. The rotations of the disc and the ball are driven separately by servomotors, so the different slide-to-roll ratios can be realized. The contact area is observed by a microscope and recorded by a high-speed camera (Fig. 1).

Bovine serum (BS) Sigma-Aldrich B9433 with protein content 55.49 mg/ml was used as a substitution of synovial fluid in joint simulators. It was diluted to 25% w/w concentration for film thickness measurements and prepared in volumes of 12 ml. Samples were stored in a freezer at -20°C and unfrozen 2 hours before the experiment at room temperature 23°C. All parts of testing device were cleaned in 1% dodecyl sulphate, rinsed in distilled water and after drying up washed in isopropyl alcohol. This procedure was carried out before and after every measurement.

Lubricating film thickness was measured with the constant speed for 300 s. BS was supplied by a syringe pump with the constant flow rate 3.5 ml/min. The load applied to the contact area was 5 N corresponding with the contact pressure of 271 MPa. Obtained data was evaluated by thin film colorimetric interferometry [Hartl 2001, Hartl 1999]. All measurements were carried out at room temperature 23°C.

Film thickness was measured for pure rolling ($\Sigma=0$) and partial sliding with the glass disc faster than the ball ($\Sigma=1.5$) and the ball faster than the disc ($\Sigma=-1.5$). Slide-to-roll ratio is described by $\Sigma=2(u_D-u_B)/(u_D+u_B)$ [Krupka 2008]. Kinematic parameters of all lubricating film thickness measurements are summarized in Tab. 1.

Exp. num.	Slide-to-roll ratio	Disc speed	Ball speed	Mean speed
	Σ	u_D [mm/s]	u_B [mm/s]	u_M [mm/s]
1	0	5.72	5.72	5.72
2	0	10	10	10
3	0	20	20	20
4	0	40	40	40
5	1.5	10	1.43	5.72
6	1.5	40	5.72	22.86
7	1.5	70	10	40
8	–1.5	1.43	10	5,72

Table 1. *Kinematic parameters of lubricating film thickness measurements.*

3. Results and discussion

The results from measurements with pure rolling ($\Sigma=0$) are plotted in Fig. 2, which represent the mean film thickness as a function of time for all speeds. The uniform growth of film thickness with time is evident. Maximal values of thickness are 23 nm, 37, 95 nm and 300 nm in the end of the experiment for speeds 5.71 mm/s, 10 mm/s, 20 mm/s and 40 mm/s, respectively.

There is evident the uniform distribution of lubricating film over the whole contact without noticeable scatter (Fig. 3). In the end of measurements there was a visible layer of deposited proteins on the disc (Fig. 4). The width of the layer was approximately the same as a diameter of the contact area. It is possible that this layer of proteins forms the lubricating film and its thickness is predominantly affected by speed of rotation of the disc, i.e. by the frequency of deposition protein particles after passing the contact area.

At the measurements with partial sliding ($\Sigma=1.5$) there is apparent a rapid increase in film thickness immediately after the beginning of the experiment (Fig. 5.). Maximal film thicknesses are 120 nm and 300 nm in time 60 s for mean speeds 5.71 mm/s and 40 mm/s, respectively and 280 nm in time 75 s for mean speed 22.85 mm/s. After that arose the film thickness dropped and in the end of the

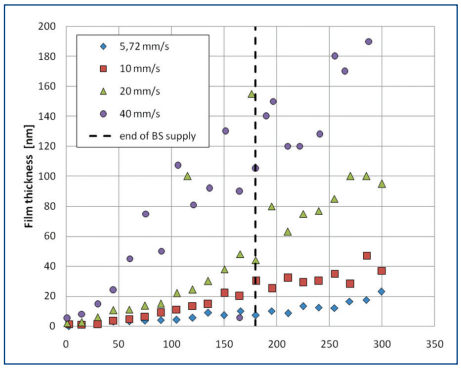

Figure 2. *Film thickness as a function of time for different mean speeds under pure rolling conditions ($\Sigma=0$).*

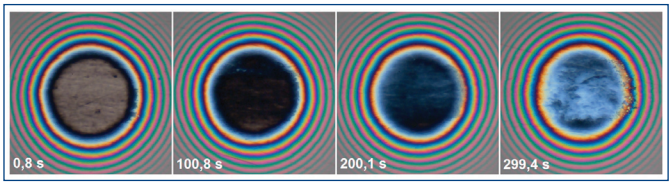

Figure 3. *Selected chromatic interferograms of different instants of time for speed 20 mm/s ($\Sigma=0$).*

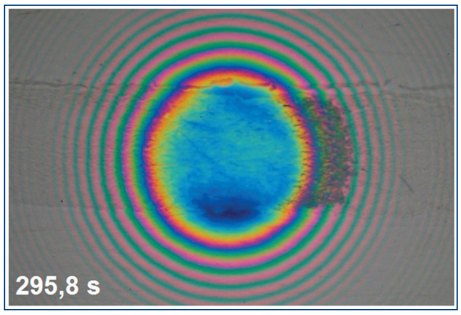

Figure 4. *Detail of layer of deposited proteins on disc ($\Sigma=0$, uM = 40 mm/s).*

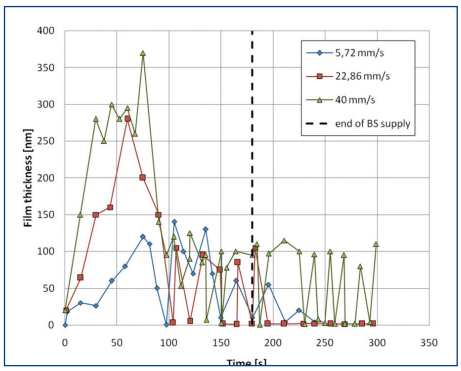

Figure 5. *Film thickness as a function of time for different mean speeds under partial sliding conditions ($\Sigma=1.5$).*

measurement the thickness was 2 nm, 1.5 nm and 110 nm for mean speeds 5.71 mm/s, 22.85 mm/s and 40 mm/s, respectively. After the measurement, there was also noticeable the layer of the deposited proteins on the glass disc as was visible in a pure rolling measurement (Fig. 6). The width of this layer was wider then diameter of the contact area. This can be due to splash of lubricant after passing the contact area. The hypothesis of deposition of proteins on the glass disc also supports the abrupt increase of film thickness at the beginning of the measurement with whole revolutions of the disc (Fig. 8). Constant film thickness over one revolution of the disc was visible, and then followed abrupt increase of thickness and a constant film was visible

again. Moreover, this effect was visible only with connection of whole revolutions of the disc and never with connection with the femoral head.

The last experiments were carried out with slide-to-roll ration Σ=–1.5. Absolutely different results were obtained at this measurement. The mean film thickness over the whole experiment varied in range of tenth of nanometres. There was noticeable only occasional presence of protein aggregations with thickness around 10 nm (Fig. 9), but there was no evidence of tendency of increase of film thickness with time.

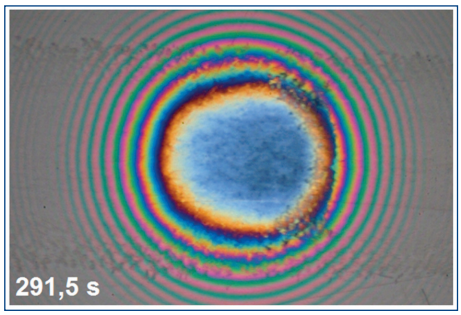

Figure 6. *Detail of layer of deposited proteins on disc (Σ=1,5, uM = 40 mm/s).*

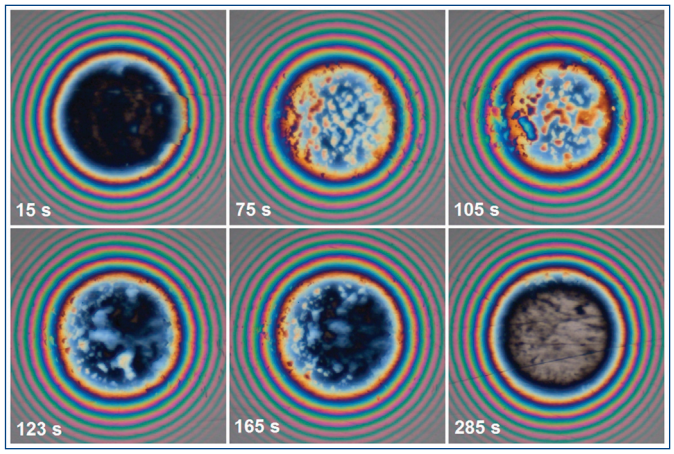

Figure 7. *Selected chromatic interferograms of different instants of time for mean speed 5.72 mm/s (Σ=1.5).*

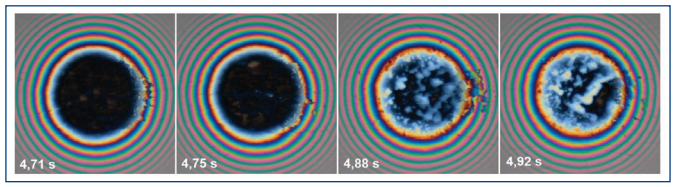

Figure 8. *Abrupt increase of film thickness after first revolution of disc (Σ=1.5, uM = 40 mm/s).*

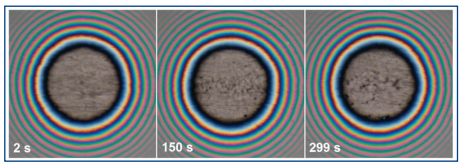

Figure 9. *Selected chromatic interferograms of different instants of time for mean speed 5.72 mm/s (Σ=–1,5).*

From the results of measurements is apparent that forming of protein lubricating film demonstrate the increase of thickness with time and the rate of increase is influenced by speed of articulating surfaces. Kinematic conditions also have the substantial impact on forming of lubricating film. Time dependent behaviour published also Fan et al. [Fan 2011]. They supposed that combination of hydrodynamic theory and protein aggregation and deposition influences lubricating film forming. Protein adsorption on CoCrMo femoral head published also Myant et al. [Myant 2012] and the reason mentioned the tendency of proteins adsorb on hydrophobic surfaces. On the other side, bovine serum proteins belong to proteins with low internal stability, sometimes called soft. These proteins tend to adsorb to all surfaces irrespective to their hydrophobicity or hydrophilicity [Nakanishi 2001]. This could mean that the process of a protein adsorption on a femoral head surface published by Myant et al. [Myant 2012] could be supported by adsorption or deposition of disturbed proteins on a glass disc surface. There remains a question of the influence of a chromium layer on the glass disc and its effect on protein degradation. This will be the object of a further research.

Proteins could also desorb from surfaces and repeated adsorption and desorption back to bulk can lead to formation of protein aggregations and denaturation [Randolph 2002]. Denatured proteins can act like nucleus for further protein aggregation and insoluble precipitation [Arakawa 2006], which can deposit on articulating surfaces. Shear strain or high pressure also has an influence on the formation of protein aggregations [Arakawa 2006]. Moreover, repeated adsorption and desorption can lead to high percentage of loss of native proteins [Randolph 2002]. This could cause the sudden decrease of film thickness in partial sliding experiments (Σ=1.5).

Another possible way of formation of lubricating film is formation of gel phase. Aoki et al. [Aoki 1968] published that protein solution containing aggregations can change to gel by applying of high pressure. Myant et al. [Myant 2012] also informed about presence of gel phase in the inlet zone to contact during film thickness measurement with bal-on-plane configuration. It is possible because it is known that macromolecular solutions can in certain circumstances pass to gel.

It is apparent that forming of protein lubricating film is a complex mechanism containing more influences. This can be adsorption on frictional surfaces, formation of protein aggregations or gel phase and protein denaturation. These particles can subsequently deposit on articulating surfaces and affect the forming of lubrication film.

4. Conclusion

In this report were made experiments of lubrication film thickness mapping. A pure rolling and partial sliding measurements were examined. It is obvious that film thickness increases with time independently of speed and various kinematic conditions have important influence on film formation. It has been shown that there exist several mechanisms of protein degradation which can significantly affect the forming of lubrication film by depositing on articulating surfaces. Because this current work examined only the effect of kinematic conditions to film thickness and forming, in the future studies authors want to better simulate real conditions occurred in a synovial joint. It is related to e.g. influence of temperature, synovial fluid components, material or variable load.

5. Acknowledgements

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