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In contact observation of model synovial fluid lubricating mechanisms

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ABSTRACT

This paper examines the fundamental mechanisms of synovial fluid lubrication in artificial joints. Film thickness measurements were made for bovine serum solutions in a model test device. In contact imaging was also carried out to aid interpretation of these results. The results indicated that two types of film are formed; a boundary layer of adsorbed protein molecules, which are augmented by a high-viscosity fluid film generated by hydrodynamic effects. The high-viscosity film is due to inlet aggregation of protein molecules forming a gel which is entrained into the contact preferentially at low speeds. As the speed increases this gel appears to shear thin, giving much lower lubricant film thickness. Results suggest that protein-containing fluids do not obey classical Newtonian EHL models.

1. Introduction

Artificial hips experience complex kinematic and loading patterns during use, which coupled with the varied physical and chemical properties of lubricating synovial fluid (SF) represents a very difficult tribological problem. Failure of both Metal-on-Metal (MoM) and Metal-on-Polymer (MoP) joints has been linked to excessive wear of components due to poor tribology. Damage of the rubbing surfaces is due to physical (abrasion or adherence) or chemical (corrosion) wear mechanisms resulting in the formation of micron (polymer) or nanometre (metal) sized debris. Wear is essentially determined by the properties of the implant surfaces and the nature (chemical and physical) of the lubricating film. In recent years there has been considerable research into material wear in both model and hip simulator studies [1–4], however there are relatively few studies of SF lubrication mechanisms and film properties in the literature.

Two distinct mechanisms, Elastohydrodynamic (EHL) and Boundary Lubrication (BL), are usually described in the literature. The EHL theory suggests that film formation in articular joints is dominated by entrainment and squeeze effects [5,6]. These models have been used to predict film thickness over the gait cycle using a very simple isoviscous, continuum fluid model. The results suggest that for MoM hips the contact operates in the mixed regime (lambda ratio, $\lambda < 3$) for at least part of the gait cycle [6]. In the EHL models, film thickness is essentially determined by the bulk viscosity and mean speed of the articulating surfaces. The EHL theory also predicts that film thickness is relatively insensitive to pressure [7]. BL theories of SF lubrication propose that the articulating surfaces are protected by a thin adherent adsorbed or reacted film. Different components of SF have been identified as boundary additives, including proteins, glycoproteins and phospholipids [8,9].

Recent research carried out by the authors has examined the fundamental mechanisms of model SF. Initial results [10] showed that for simple protein containing solutions in model sliding contacts, friction and film thickness were dependent on protein content and lubricant chemistry. Fan et al. [11] suggested that film formation was determined by an aggregation mechanism which controlled protein behaviour in the inlet of the contact. In a new paper [12] the authors concluded that protein-containing solutions demonstrate complex time-dependent film thickness behaviour that is not characteristic of a simple Newtonian fluid. An aggregation mechanism, due to flow effects in the inlet, created a new gel-like protein phase. This protein gel formed an inlet reservoir, feeding the contact with high viscosity lubricant generating larger than predicted film thickness. Proteins which passed through the contact formed thick deposited films on the metallic surface. This observation is supported by other studies [13–15] which reported thick protein deposits on joint surfaces after *in vitro* and *in vivo* (explant) use. It is usually suggested that these films act as protective surface layers reducing adhesion and wear [15]. The proposed lubrication mechanism is very different from those of classical EHL models; larger than predicted films were observed. This was tentatively linked to a change in the rheological properties of the lubricating fluid local to the contact and the formation of thick boundary layers.

Abbreviations: BCS, bovine calf serum; BL, boundary lubrication; EHL, elastohydrodynamic lubrication; λ, lambda ratio=minimum film thickness/surface roughness (Ra); MoM, metal-on-metal; MoP, metal-on-polyethylene; SF, synovial fluid; SRR, slide-roll ratio

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Currently, computational analysis of articular joints assumes that the lubricating SF behaves as a Newtonian fluid throughout the gait cycle, allowing the lubricant to be based on an isoviscous, incompressible physical model [6]. Such models assume that articular joints predominantly operate within the EHL regime. It should be noted that within this lubrication regime, film thickness is determined by the viscosity of the material in the contact inlet [16]. However, the lubricant rheological properties employed in numerical predictive models are based on the bulk solution and not the fluid present in the inlet. The film thickness findings discussed above [12] showed that for protein suspensions a complex multi-mode regime exists during sliding, which leads to chaotic film distribution dependent upon the properties of the fluid local to the contact. This has large implications on numerical predictive models which at present are used as a basis for developing new hip implant designs which is dangerously simplistic. These models may lead to incorrect component design due to poor understanding of the tribological mechanisms and oversimplified lubricant behaviour.

If the accuracies of artificial joint computational models are to be improved, and therefore the longevity and performance of the artificial joint; it is important to understand the mechanisms, local to the contact, which control the rheological properties of the lubricating film. The work thus far has been confined to film thickness measurements to support the concept of an inlet aggregation mechanism and the formation of a gelphase [12]. In the current paper further film thickness data is presented but the main focus is in-contact imaging which is used to explain the proposed film formation mechanisms in more detail.

2. Experimental

2.1. Film thickness measurement and in-contact imaging

Lubricant film thickness was measured using a commercial optical interferometric tribometer (Ultra-Thin Film Measurement System PCS Instruments, UK). The standard steel ball specimen was replaced with an "as cast" commercial grade CoCrMo resurfacing femoral head (38 mm diameter). This was held in the test device and loaded against the underside of the rotating glass disc. The head was held in a supporting mount (Fig. 1) and could be rotated so that a different position was used for each test. The femoral head was held stationary, allowing tests to operate in pure sliding conditions. A copious supply of lubricating fluid was pumped onto the femoral head and entrained into the contact by rotation of the glass disc. A thick liquid layer on the glass disc was maintained throughout the test period to avoid effecting contact through film evaporation. The underside of the glass disc was coated with a thin chromium layer (~10 nm) overlaid by silica (~500 nm); this provides the necessary reflection condition to measure the film thickness in the glass/metal interface. Single-position film thickness measurements from the centre of the contact were obtained using a spectrometer. Further details of this method may be found in [12]. For some tests the spectrometer system was replaced by a CCD camera and the contact zone observed directly so development of the interfacial film could be followed.

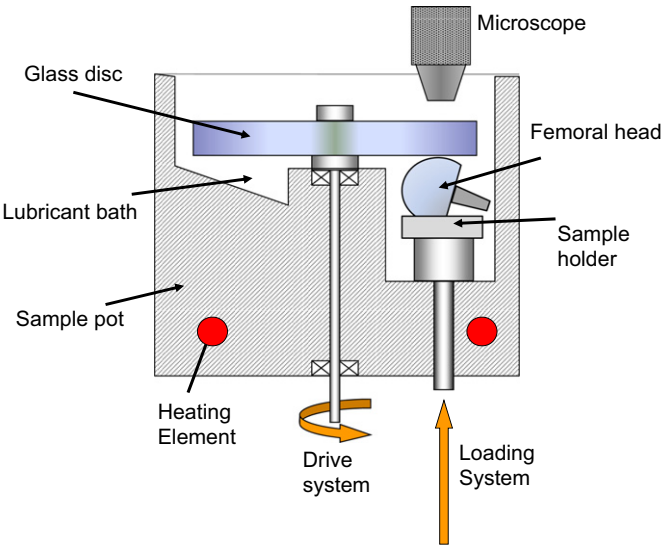

Fig. 1. Schematic of the experimental setup.

The test specimens were cleaned ultrasonically in 1% sodium dodecyl sulphonate solution in deionised water. The specimens were then rinsed three times in deionised water and finally washed in Analar isopropanol. The test specimens were air-dried and then mounted in the optical device, which was held at 37 °C for 1 h prior to testing. The test solution was fed directly into the contact zone using a syringe to prevent contamination. Lubricant supply was maintained throughout the test period to insure a substantial fluid meniscus around the contact zone. The test conditions (sliding seed, contact pressure) were chosen to be representative of those occurring during the gait cycle in MoM hip joints [12].

2.2. Test programme

The work has concentrated on film formation by protein-containing solutions. The test programme was as follows.

1. Film formation under cyclic loading at constant speed (0, 10 mm/s): the contact was loaded (5 N) for approximately 15 s while film thickness measurements were taken and then un-loaded for approximately 45 s; this was repeated every minute for test period (12 min). Fresh fluid was continuously supplied to the contact. Film formation at zero and a mean speed of 10 mm/s was measured.
2. Film formation as a function of sliding speed: at the end of the constant speed test a speed-sweep test was carried out over the range 5–50 mm/s. Film thickness readings were taken periodically over the entire speed range.
3. In some experiments colour interferograms were captured using a 3CCD RGB camera (CV M9CL, JAI). A magnification of 5X (objective) was used to observe both the Hertzian contact region and inlet/outlet areas.

2.3. Test lubricants

Bovine Calf Serum (BCS, Sigma-Aldrich 12133C protein concentration 72 mg/ml) was used as the model SF, in all tests it was diluted to 25% w/w with distilled water (Sigma-Aldrich, S-37531-356). BCS contains primarily a mixture of albumin and γ-globulin proteins. No additional buffers or anti-bacterial agents were used. All fluids were stored at 5 °C and used within a few days of preparation.

3. Results

Initially film thickness was studied as a function of time under cyclic loading ($U=0$) and constant load pure sliding ($U=10$ mm/s) conditions. Fig. 2 presents typical spectrometric film thickness measurements for BCS plotted against time/load cycle number. For the cyclic load investigation 1 min represents a loading and