

LUBRICATION OF THE RAZOR CARTRIDGE/SKIN CONTACT

By

Suzanna Whitehouse

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Tribology Group
Department of Mechanical Engineering
Imperial College London

ABSTRACT

The razor cartridge/skin contact is complex due to cartridge materials and geometry, and the mechanical properties of skin. It is thought that the ideal shaving lubricant is able to flow through the guard without being wiped away (so that a sufficient amount of lubricant can reach the blades) and resist starvation under multiple, successive razor cartridge components. The objectives of the research were to: understand the friction properties of shaving fluids in a model cartridge/skin contact, measure lubricant flow through the razor cartridge contact, and assess the suitability of PEO as a shaving lubricant.

Friction tests for a hard/compliant contact were carried out in conditions representative of shaving. These included improvements to surface chemistry with artificial sebum. Pure sliding tests produced variable results with poor repeatability. For a sliding/rolling contact, trends between lubricants were identified. Load, sliding speed, lubricant chemistry and surface chemistry were found to affect friction.

A fluorescence technique was developed to measure razor cartridge film thickness and excellent image clarity was shown, with film thickness measurable for hard and compliant counterfaces. The lower measurable limit was $2 \pm 0.4 \mu\text{m}$ (hard counterface) and $2 \pm_{-2}^{3.1} \mu\text{m}$ (compliant counterface). It was found that the guard and Lubrastrip maintain relatively thick and consistent lubricant films across the speed range, with minimum films formed at the blade cutting edges. Presence of the guard improved cartridge lubrication by stabilising film thickness across the blade cutting edges. Razor cartridge lubrication was found to operate in partially starved conditions, and replenishment mechanisms are discussed as well as the impact of contact conditions on cartridge film thickness. Evidence for viscoelastic effects were shown, and viscous and elastic effects were separated.

Results have provided guidance on identifying a potential shaving lubricants, and recommendations have been made for further investigation and development of experimental methods.

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NOMENCLATURE

γ	Surface energy, mJ/m ²
$\Delta\gamma$	Specific energy of adhesion, J/m ²
η	Viscosity, Pa.s
θ	Equilibrium contact angle, degrees
λ	Lambda ratio
μ	Friction coefficient
σ	Stress, MPa
a	Contact area, mm ²
c	Adhesive contact area, mm ²
E	Young's modulus, Pa
E'	Reduced elastic modulus, /Pa
F	Force, N
G	Shear modulus, Pa
h	Film thickness, μm
k	Arbitrary scaling factor
L	Contact length, mm
$P_{(ij)}$	Pixel intensity, cd
P_{max}	Maximum contact pressure, Pa
r	Radius, mm
R	Reduced radius, /mm
RMS	Surface roughness Route Mean Square, nm
R_a	Surface roughness, nm
SRR	Slide/Roll Ratio, %
t	Time, s
u	Entrainment speed, mm/s
ν	Poisson's ratio
W	Load, N

1. SHAVING AND TRIBOLOGY

1.1. Introduction

The purpose of this study is to gain a fundamental understanding of shaving tribology within the razor cartridge/skin interface. Tribology is the study of friction, wear and lubrication; the science of interacting surfaces in relative motion. As such, shaving is a complex tribological system and is affected by the skin, beard hair, razor cartridge and shaving lubricant. Procter & Gamble, UK (P&G) have found through panel testing that the user's perception of shaving comfort is linked to friction experienced in the skin/cartridge interface, which is partly controlled by lubricant properties.

The razor cartridge consists of three main components: guard, blades and Lubrastrip (Figure 1.1), and these each contribute to the process of cutting beard hair (Figure 1.2). The purpose of the guard is to stretch and smooth skin in preparation for the blades (improving the closeness of shave and reducing skin irritation) as well as controlling film thickness of the lubricant entering the blade/skin interface. The blades follow to cut the hair, and the Lubrastrip deposits a lubricant layer onto the skin in preparation for the next stroke.

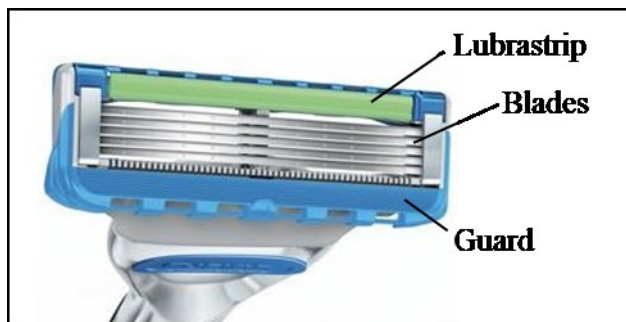


Figure 1.1: Razor cartridge components [1]

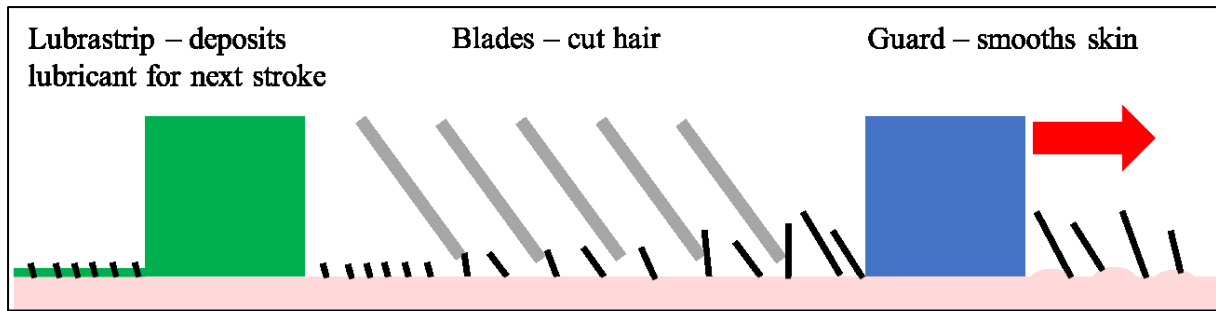


Figure 1.2: Interaction of razor components with skin and beard hair

The razor /skin contact is complex due to the different geometries and materials used in the cartridge, as well as the varying mechanical properties of skin. It is important to consider the effect of shaving lubrication on friction, as user comfort is strongly linked to the friction coefficient between the razor cartridge and skin:

- If friction is too low then the user experiences an undesirable “loss of control” feeling.
- If friction is too high then skin irritation and razor burn can occur.

The razor cartridge friction coefficient is complex and consists of contributions from the different cartridge components (guard, blades, Lubrastrip and clips), and these contributions may fluctuate depending on contact conditions (contact materials, lubricant, environment, geometry).

Skin friction is affected by many factors, and the mechanical properties can differ within one individual, depending on extrinsic and intrinsic conditions. The dominant factor in friction for this contact is likely to be adhesion and deformation of the skin. This will also affect film thickness distribution due to changes in contact geometry (increased contact area and deformation in and local to the contact interface), which, when compared to a hard counterface, may affect lubricant replenishment and loss mechanisms.

Figure 1.3 shows the ideal behaviour of a shaving lubricant, which is able to:

- Flowing through the guard contact without being completely wiped away, so that a sufficient amount of lubricant can reach the blades.

- Resisting starvation as it lubricates successive components in the razor cartridge (guard fins and blades). This is especially important for the blade contacts, as a separating film will increase protection between skin and sharp blades.

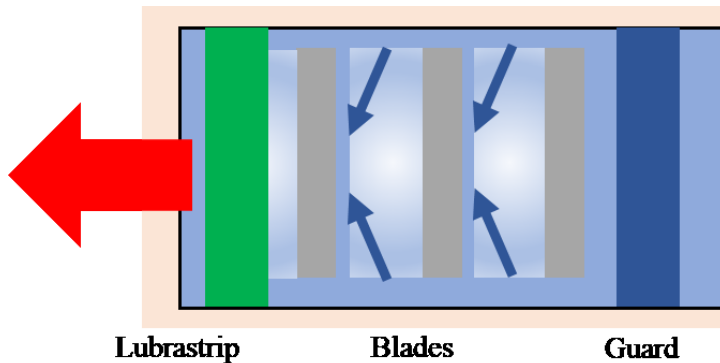


Figure 1.3: Ideal lubricant flow through the razor cartridge

The lubricant may be applied by the user, for example shaving foam, soap or oil, or as an “on-board” lubricant deposited from the cartridge Lubrastrip. The “on-board” lubricant is poly(ethylene oxide) (PEO): a polymer that forms a viscoelastic solution when hydrated and is deposited from the Lubrastrip at the back of the cartridge. There are several initial considerations for the properties and formation of a lubricant film between the razor cartridge and skin:

- What level of lubrication is provided by current shaving products?
 - What is the friction coefficient and film thickness?
- How does the lubricant travel through the cartridge and past each individual component?
 - Is it removed by the passage of the blades?
- Does the lubricant film recover between each contact interface?
- How does lubricant chemistry affect film thickness and friction?

New razor developments typically involve panel testing on over 10,000 men, who will shave with the new product for several weeks. Performance is evaluated through in-depth questionnaires and evaluation of skin irritation and closeness of shave. With increased understanding of the lubrication mechanism and improved model test methodologies, such extensive panel testing can be reduced for future razor and lubricant development.

An ideal shave is one that achieves the closest beard cut possible, but does not cause a “loss of control feeling” or skin irritation. Therefore, the dominating factor in panel tests for shaving comfort is friction. Friction experienced in the cartridge/skin contact is determined by the properties of the fluid (its chemistry and rheology) and the local film thickness in the contact. Friction response, fluid flow and film thickness for a range of lubricants in the razor cartridge/skin contact will be studied in this research project. The relationship between the model experiments is illustrated in Figure 1.4.

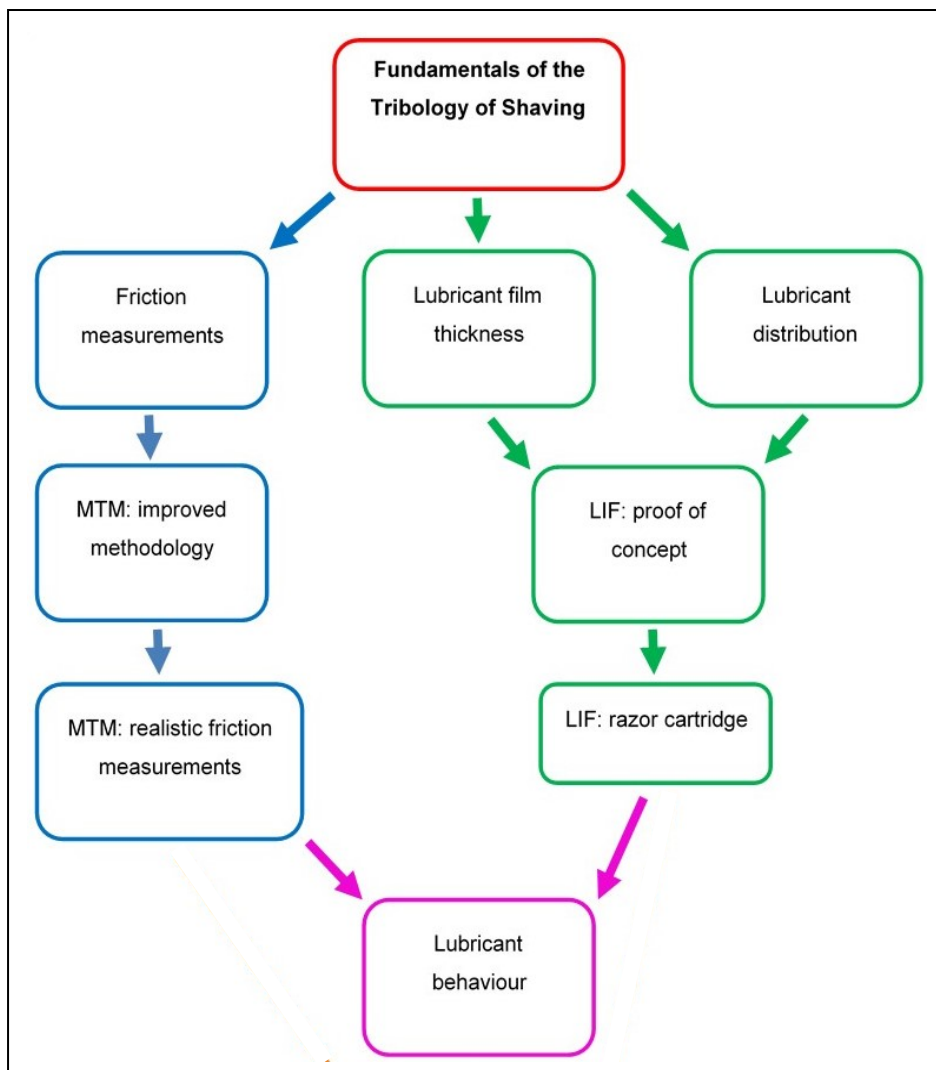


Figure 1.4: Research project outline

1.2. Objectives of research project

The objectives are to understand fundamental aspects of shaving tribology including:

1. Friction properties of shaving fluids in a model cartridge/skin contact

A standard test device – the Mini Traction Machine (MTM) – will be used to measure friction for a model blade/skin contact. The MTM is currently used by P&G as a screening test to assess friction of candidate fluids for cartridge lubrication.

- Modifications will be made to the P&G standard MTM test protocol to better simulate “real life” shaving.
- A series of lubricants with different chemical and rheological properties will be tested in the MTM to determine friction behaviour for simulated shaving test conditions.
 - The fluids include those with Newtonian, shear thinning and viscoelastic properties.

2. Lubricant flow through the razor cartridge during shaving

The requirement is to observe lubricant flow and measure film thickness in a cartridge/skin mimic contact. A new technique will be developed using laser induced fluorescence (LIF) to observe fluid flow and measure film thickness in and around razor cartridge components

3. Suitability of PEO as a shaving lubricant

Considering the friction, lubricant flow and film thickness results, the suitability and effectiveness of PEO as a shaving lubricant can be assessed. This may allow recommendations for new lubricants and justification of current lubricants.

1.3. Project structure

The structure of the thesis is as follows:

- Chapter 2 describes the mechanical and tribological properties of skin and beard hair with respect to shaving.

- Chapter 3 discusses lubrication in a compliant contact.
- Chapter 4 describes common methods and materials used for experiments throughout this project.
- Chapter 5 contains the MTM friction test profile development and discusses the suitability of PEO and reference lubricants (described in Chapter 4) for shaving application.
- Chapter 6 describes the development of a fluorescence imaging method to visualise lubricant flow and measure film thickness in compliant contacts, as well as a suitable skin mimic for this experimental method. A compliant/hard and a compliant/compliant contact is analysed for all experimental fluids.
- Chapter 7 applies the fluorescence imaging method to a razor cartridge/skin mimic contact, and lubricant film thickness and distribution for reference fluids is measured.
- Chapter 8 applies the fluorescence imaging method to a razor cartridge/skin mimic contact, and lubricant film thickness and distribution for PEO solutions is measured.
- Chapter 9 considers the results from Chapters 5-8. Lubricant starvation and flow into the razor cartridge contact is discussed, as well as the suitability of PEO as a shaving lubricant. The relationship between friction measurements and film thickness is also discussed.
- Chapter 10 contains conclusions from this project, and recommendations for further work.

1.4. Summary

Friction experienced in the razor cartridge/skin interface is the distinguishing factor when a user evaluates the perceived quality of a shave, and friction will depend on the lubricant properties and film thickness in the razor cartridge/skin interface. This research project is designed to develop a fundamental understanding of the lubrication under simulated conditions. Experimental methods were developed to measure friction (MTM tests) for a simplified skin-cartridge contact. Fluid flow and film thickness have been investigated using a novel soft contact imaging method using laser induced fluorescence.

1.5. References

- [1] Shaving is cool. *Why cartridge razors are known as the best razor?* Available from:
<https://shavingiscool.co.uk/cartridge-razor-known-best-razor/>. [Accessed June 2013]

2. REVIEW OF SKIN, HAIR AND SHAVING

Summary

In this Chapter an engineering analysis of the shaving and the razor cartridge/skin interface is presented. The mechanical and chemical properties of skin and beard hair are reviewed with considerations to shaving and are found to be highly variable depending on many factors such as anatomical location, hydration, age and application of products. Friction is a significant marker in a user's assessment of shaving comfort, and as such it is important to understand skin friction. To achieve this model experiments will be conducted using skin mimics, which are available as either natural or artificial materials.

2.1. Introduction: skin properties

Shaving is dominated by tribology in the razor cartridge/skin interface, and as such an understanding of skin properties is required. The aim of this literature review is to understand the mechanical and chemical properties of skin, and the effect that this may have on shaving lubrication. Additionally, a suitable skin mimic will need to be identified for use in the model experiments, and this mimic should behave in a similar way to human skin to obtain “realistic” results.

Skin is a highly complex material with varying mechanical properties, surface properties and behavioural response to load, which makes it challenging to remove stiff, individual hairs without damaging the surrounding skin. Beard hair is particularly difficult to cut [1] as it has high density and stiffness, is relatively thick, has an irregular shape and a low emerging angle. However, the mechanical requirements for a close, clean hair cut will cause irritation and damage to the skin [1], so a compromise between the two objectives must be reached for the optimal shave.

2.2. Mechanical properties of skin

The basic structure of skin combines three distinct layers (Figure 2.1): subcutis, dermis and epidermis. The deepest layer is the subcutis which consists of adipose tissue, or fat cells. Above this is the dermis:

supporting the upper layer both structurally and nutritionally and where the main tension carrying elements (collagen and elastin fibres) are found, which provide the dermis with its strength and elasticity [2]. Under large deformations in particular, the mechanical properties of skin are mostly controlled by the dermis [3].

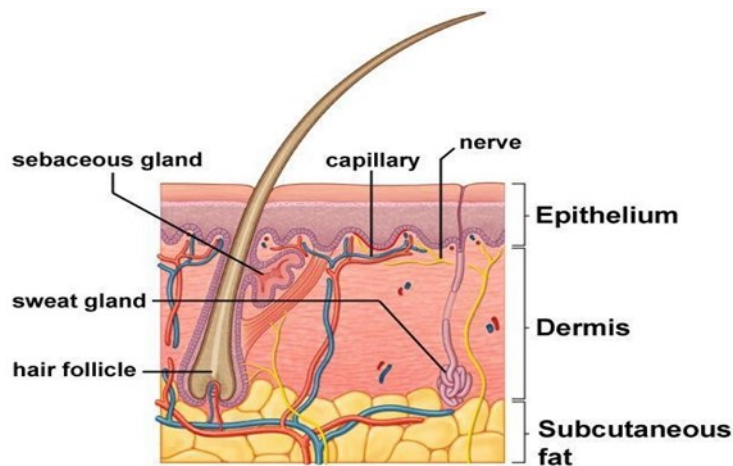


Figure 2.1: Skin structure [2]

The epidermis is the outer layer of skin: it acts as a protective barrier and is the layer of skin most affected by topically-applied creams. Its fundamental function is to generate the stratum corneum, which is a dead barrier that separates the body from the external environment [4]. A complete renewal of the stratum corneum can be accomplished in approximately 15 days, and involves a constant renewal process from the division of basal cells and the keratinisation of the uppermost layers. The epidermis has a range of other fundamental functions, which include [4]:

- Hormone secretion.
- Cytokine production, which rules angiogenesis and vasomotoricity in the dermis.
- Maturation of cells responsible for the immune barrier.
- Protection against ultraviolet light.
- Participation in the skin neurosensory function.
- Participation in the skin mechanical protective function due to its cellular abundant keratin filaments.
- The ability to self-repair.

The multifunctional nature of the epidermis means that skin mechanical properties are difficult to quantify. In particular, values measured for Young's modulus can vary by a factor of 3000, depending on the model proposed and the stress applied [5] and the fact that skin displays non-linear load-deformation behaviour. In the initial lax phase, large deformations result in low forces within the skin. As the deformation is increased, these forces rise until a stiffer, almost linear range is reached. If deformation is held at a constant level, however, the force experienced will fall (due to stress relaxation). Stiffness will also increase as displacement increases [3]. The variability in skin mechanical properties makes it a problematic surface interface to work with. Examples of the mechanical properties of skin are given in Table 2.1.

Table 2.1: Mechanical properties of skin

Model	Test and experimental conditions	Mechanical parameters
Linear elasticity [4]	Indentation - Skin	$G = 1 - 2 \text{ kPa}$
Linear elasticity [6]	Extensometry - Skin	$E = 3 \text{ MPa}$
Linear elasticity [6]	Suction - <i>stratum corneum</i>	$E = 57.8 \text{ MPa}$
Linear elasticity [6]	Ultrasound propagation - <i>stratum corneum</i>	$E = 13 \text{ MPa}$
Equation model [7]	Suction - Skin	$E = 129 \pm 88 \text{ kPa}$ $\sigma = 13.5 \pm 5 \text{ kPa}$
Linear elasticity [8]	Torsion - Skin	$E = 112 \text{ kPa}$
Linear elasticity [9]	Suction - Skin	<i>Man (20 years):</i> $E = 16 \text{ MPa}$ <i>Woman (20 years):</i> $E = 20 \text{ MPa}$
Viscoelastic model [10]	Extensometry - Skin	$E_1 = 522 \pm 134 \text{ kPa}$ $E_2 = 805 \pm 241 \text{ kPa}$ $\eta = 753 \pm 224 \text{ kPa.s}$
Orthotropic elastic model [10]	Extensometry - Skin	$E_1 = 657 \pm 219 \text{ kPa}$ $E_2 = 130 \pm 62 \text{ kPa}$ $G_{12} = 132 \pm 77 \text{ kPa}$

2.3. Skin surface chemistry

The skin surface supports a variety of resident bacteria and mycotic flora, which exist within an ecosystem that is a complex balance of lipids (sebaceous and epidermal origin), desmosomal and intercellular enzymatic protein degradation, transepidermal water, and sweat [4]. Physicochemical phenomena (surface tension and electrochemistry) also play a considerable role in this environment, which is able to constantly regenerate and remain stable despite daily shedding of one *stratum disjunctum* layer (as opposed to a 15-day complete renewal of the *stratum corneum*), which is approximately one third of the ecosystem thickness.

The presence of resident bacteria and mycotic flora is essential for ensuring healthy skin [11]. Typical skin flora are regulated by nutrients found in the area (especially lipids), humidity and pH. It is likely that they are also affected by other factors such as temperature, partial oxygen and carbon dioxide pressure and exposure to ultraviolet rays [4]. In contrast, the bacterial spectrum is reliant on local factors. For example, the micro-organism population density is almost constant; it reproduces itself quickly after scratching, washing or disinfecting [12]; bathing once a day or not at all for three weeks makes no difference [13]. There are three habitats distinguishable for resident bacteria and flora [4]:

1. Fatty habitat (scalp, face, shoulders, thorax). Marked by high levels of sebum secretion, with certain populations dependent on the secretion rate.
2. Humid habitat (body creases). Transcutaneous water loss cannot be evacuated and there is a higher supply of protein due to this environment easing corneocyte degradation.
3. Dry habitat (other hairless sites). Dryness is responsible for low bacterial density.

2.3.1. Surface acidity

Skin surface acidity (pH 4.2-6.1) controls the resident flora to a large extent and prevents colonisation of the skin by pathogenic species [14]. There are local pH differences on the body that contribute to the existence of particular flora although the overall value remains acidic. Skin acidity itself depends on the content of free fatty acids in the surface ecosystem – cleaning the skin (even with a soap with a higher acidity than the skin) increases the pH [14, 15], and stripping the stratum corneum is associated with a sharp rise in pH [16].

In new-born babies, skin pH is 6-7 and the skin surface free fatty acid content is lower than in adults [15, 17, 18]. On the first day, pH was found to be higher than in adults for all body sites (soles, back, abdomen, palms, forearm and forehead), with a mean for new-borns: 7.1 ± 0.17 , adults: 5.7 ± 0.16 . On the second day, the pH had decreased, but still remained statistically different from the adult values [19]. Only on the fourth day did the skin pH of babies match that of adults. One suggestion is that sweat (pH 4-6.8) may have an influence on skin surface acidity, but this cannot be correct as sites with a higher pH are those of continuous sweating [4].

2.3.2. Sebum

Sebum is an oily substance present on the skin and hair. It is produced by sebaceous glands, which are bag-shaped structures within the cutis and attached to hair follicles. Sebum is composed of squalene (12%), wax esters (26%), glycerides and free fatty acids (57.5%) and sterols (free and esters) (4.5%) [4, 20, 21]. On reaching the skin surface it is contaminated by lipids.

Sebum is secreted onto the skin surface, where it seeps into the main skin furrows and intercellular spaces of the stratum disjunctum – like a sponge. The quantity of sebum on a specific skin area tends to be constant for each individual [22], and regenerates completely after removal. Sebum has the following functions [4]:

- Amphiphilic wettability, and is a natural detergent.
- The size of the sebaceous glands is proportional to that of the adjacent hair follicles, which suggests that they contribute to the functional qualities of the hair.
- At concentrations above 0.5 %, sebum is fungistatic for *Microsporon audouini*, and fungicidal above 1% concentration. This is due to C7, C9 and C11 free fatty acids. It is 5-10 times less effective in children than adults, which is likely due to its lower free fatty acid content in children.
- The free fatty acids increase the acidity of the skin surface, which aids control of resident bacteria.
- It is a nutrient for some skin surface resident bacteria, particularly *Propionibacterium acnes*; its immune-stimulating properties are known under the name *Corynebacterium parvum*.
- If absorbed by the skin (which is probable), sebum components can provide the epidermis with compounds necessary for the synthesis of provitamin D as well as the synthesis of some compounds of the stratum corneum.
- It can protect the stratum corneum against extreme dehydration, as the glycerol (a by-product of triglyceride hydrolysis) is hydroscopic.

2.3.3. Surface topography

Skin surface topography (Figure 2.2) consists of furrows (which vary with age and gender), follicular orifices and sweat pores, and slightly protruding corneocytes [4]. For the majority of the body, the main furrows (primary lines) are 70-200 μm deep and are aligned in at least two directions [4, 23, 24]. The follicular orifices are located at the junctions between furrows, whilst the sweat pores are typically found in the plateaus or in more superficial furrows (secondary lines) of 20-70 μm deep [4, 24]. A third type of furrow separates groups of corneocytes [25].

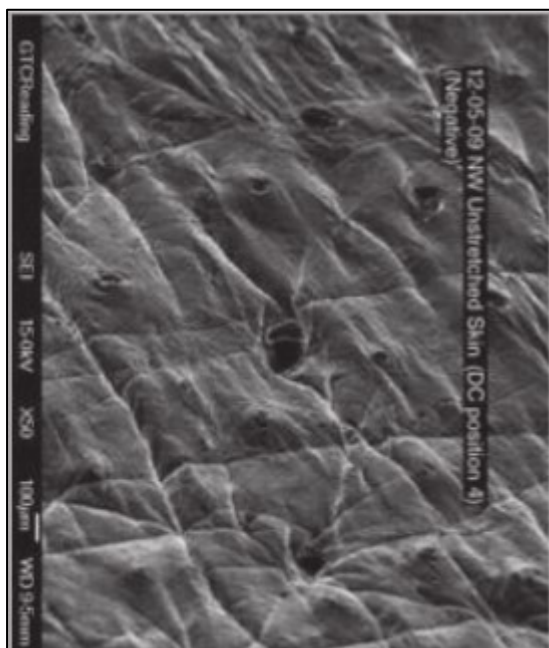


Figure 2.2: Skin surface topography [26]

The primary function of the furrows is understood to be mechanical [25]. By (partially) smoothing out, they allow the skin surface and epidermis to extend, and their anatomical distribution at each site reflects the direction of mechanical constraints sustained by the skin [4]. The deeper the furrows, the greater their physiological range of extension. Consequently, the stratum corneum *in vivo* (with deep furrows) experiences insignificant elongation stress and simply unfolds [28]. The furrows also act as channels for sebum and sweat flow and retention, depending on conditions [4]. They are able to trap and retain substances on the skin and may be preferential sites for percutaneous absorption.

2.3.4. Surface energy

Overall, the skin surface is hydrophobic. This property is characterised by a low surface wetting critical tension, which is 27.5 ± 2.4 mN/m on the volar forearm [29]. Hydrophobic properties add to the skins low permeability, allowing sweat enough time to evaporate (and therefore contribute to thermoregulation). Even during profuse sweating, the excess sweat will drip down the skin surface and does not emulsify with sebum [4].

Surface free energy on the forearm is 38.7 ± 6.4 mJ/m² [30]. This is broken down into three components: apolar (35.6 ± 5.8 mJ/m²), basic polar (4.2 ± 3.0 mJ/m²) and acidic polar (0.8 ± 0.7 mJ/m²). From an electrochemical standpoint, the skin surface is therefore mainly monopolar basic as the acidic polar component is below 1 mJ/m² and is therefore considered negligible [31].

On seborrheic areas where there is an excessive secretion of sebum, such as the forehead, the skin surface becomes more hydrophilic, with its surface wetting critical tension greater than 50 mN/m [29] and the surface free energy (42.5 ± 3.9 mJ/m²). This is higher than on the forearm because of the larger basic polar component (28.3 mJ/m²) [30], which is related to the large amount of fatty acids in sebum.

During shaving the skin surface will be more hydrophobic, as pre-cleaning the skin removes sebum. This may reduce the lubricant flow through the cartridge, increasing friction.

2.4. Skin friction

As the medium through which users evaluate shave feel (via mechanoreceptors), it is useful to describe skin in terms of its surface characteristics, such as friction. There are various factors that affect the friction properties of skin. These include: adhesion and hysteresis [32, 33]; hydration, anatomic region, age, and lubricants, emollients and moisturisers [34]. Friction coefficients most applicable to shaving would be those where friction is measured for a skin counterface contact lubricated by a water based fluid. The second contact material should be elastomer (guard), stainless steel (blades) or a hydrated Lubrastrip. Table 2.2 outlines realistic conditions for measuring skin friction in a razor cartridge contact.

Table 2.2: Testing for friction properties of skin in a razor cartridge contact

Counterface material	Contact material	Geometry	Lubricant	Average speed, mm/s	Force, N
Human skin	Elastomer (guard)	Multiple line contact	Water-based fluid / gel / foam	150	2.5
	Stainless steel (blades)	Multiple line contact			
	Stainless steel (clips)	Line contact			
	Lubrastrip	Line contact			

Skin friction coefficient is highly variable depending on skin location and conditions. In order to create a steady feel from the razor cartridge/skin interface, this inconsistency needs to be reduced. The simplest way to this is to use a lubricant which:

- Can provide consistent lubrication across the cartridge.
- Does not facilitate stick-slip behaviour.
- Is unaffected by load and speed changes.
- Is unaffected by changes in skin mechanical and chemical properties.

2.4.1. Adhesion and hysteresis

For viscoelastic materials, the two main mechanisms affecting friction are adhesion and hysteresis [32,34], and this will vary with normal force and surface dimensions [34]. When adhesion occurs, local bonds form at asperities and the frictional force is the force required to shear these bonds. Hysteresis is the delayed response of a material to the forces acting on it, and when present a larger force is required to shear adhesive bonds between two surfaces to compensate for the energy dissipation [33]. Hysteresis increases with skin hydration [36-40] because water inside the tissue can redistribute when a force is applied, as well as the associated skin swelling (increasing contact area and adhesion) [41]. As skin is viscoelastic and therefore does not follow Amonton's law [42], the frictional force is not proportional to the normal force and is dependent on contact area. Friction increases with adhesion and hysteresis

[33, 43] and a nonlinear deformation with reduced normal loads (compared to hard contacts) occurs [2, 44].

2.4.2. Hydration

Hydration is influenced by intrinsic and extrinsic factors and studies have connected variation in skin hydration with changes in the friction coefficient. These studies show that friction decreases with drier skin and increases with hydrated skin [34, 35, 42, 45-49]. This is because hydration causes softening and swelling of skin [50], a reduction in skin surface roughness [51, 52] (and therefore an increase in contact area), and an increase in adhesion and hysteresis [33]. However, if the skin is very wet – rather than simply hydrated – then the friction coefficient will decrease due to the lubricant layer separating the surfaces [53].

2.4.3. Anatomic region, age, gender and race

Age related studies have been ambiguous and may be influenced by the anatomical site used for comparisons, as friction coefficient does vary with position on the body. Cua et al. [45] found that friction coefficients varied from 0.12 on the abdomen to 0.34 on the forehead. This was attributed to differing hydration levels, non-apparent sweating and sebum secretions in skin of different areas of the body. Zhang and Mak [36] found friction coefficients to range from 0.4 on the leg to 0.62 on the palm, and suggested that hydration levels may explain the differences between anatomical sites. Skin roughness also varies significantly at various anatomical sites, which may be due to differences in environmental influences (e.g. sun exposure) and hydration [54].

There have been no significant differences found between either gender [45, 46], or race [45, 54]. Gender and ethnicity related friction studies have shown no significant changes in the friction coefficient [45, 46]. It has been found that there are no differences in roughness and scaliness between black and white skin [54] and no differences in the friction coefficient amongst subjects of Caucasian, African-American, Asian or Hispanic/Latino descent, or in their response to treatments [45].

2.4.4. Lubricants, emollients and moisturisers

A significant amount of research has been carried out to determine how the application of certain ingredients can influence the perceived feel and touch of skin, as well as grip. These products influence skin feel by controlling the hydration levels, and therefore friction coefficient. The effects of powder, oils and skin creams on friction have been studied [53]. Important qualitative characteristics in skin topical agents include smoothness, greasiness and moisturisation [48], as these characteristics affect friction and therefore the perceived hydration of skin.

2.5. Skin mimics for tribology research

Skin is a compliant material, so a mechanically similar skin mimic is required to replicate “real life” shaving in the model experiments of this research project. There are many drawbacks to using human skin, mainly due to the variability between people leading to poor reproducibility of results. There may also be experimental systems that simply do not suit human skin (e.g. destructive testing), so a “best match” material suitable for the application must be identified. Choosing a skin mimic with properties comparable to real skin allows the simplification of the shaving system to study the effect of skin properties, cartridge components and lubricants on shaving friction and lubrication.

Skin mimics may vary depending on the application, but ideally they must match the mechanical properties, surface properties (chemistry, texture, energy) and react to hydration in the same way as skin. Skin mimics can be divided into two categories: natural and artificial.

2.5.1. Natural materials as skin mimics

The best *in vitro* model is human skin, but limited availability and high costs make animal samples a necessary substitute [55]. For *in vivo* interactions with the skin to be realistically reproduced *in vitro*, fully functioning and vascularised skin is required [56]. An isolated perfused porcine skin flap allows studies to be conducted on a viable skin preparation that has normal anatomical structure and a functioning microcirculation [56]. This type of skin model is typically used in toxicology and

pharmacology and has proved to be a useful tool in the study of percutaneous absorption into the skin [57-59].

Porcine skin is histologically and biochemically similar to human skin, and is therefore the preferred *in vitro* model for human skin [55, 60]. The tissue has similarities and dissimilarities of structure to human skin [61, 62], but maintains a similar penetration of topically applied substances [61-63], particularly for hydrophilic compounds [64]. This model acts as a stepping stone between *in vitro* and *in vivo* studies, and in cases where *in vivo* human studies are impossible it can be used to provide realistic results [56]. The effects of temperature, humidity, flow rate, perfusate composition and dosage [55] can be studied in a way that is impossible with artificial mimics. However, innate differences in skin samples between animals (e.g. biophysical and biochemical variation) can affect the repeatability of results. Knowledge on differences in absorption and metabolism between animal species is also limited, so caution must be taken when extrapolating results from one study to another animal species [55]. Biological material is also very susceptible to changes in structure after the organism has died, so preservation and preparation must be optimised to prevent changes in the tissue structure influencing tribological results [65].

2.5.2. Synthetic skin mimics

Skin structure is that of a fibre-reinforced lower layer (dermis), a thinner middle layer (epidermis) and a stiff top layer of stratum corneum. This combination of layers is anisotropic, have a non-linear force-displacement relationship and are viscoelastic. In terms of artificial materials as a mimic, soft rubbers also show viscoelastic material and are therefore a suitable material for skin mimics [66].

There is a range of skin mimics commercially available, each having been designed with a specific application (and therefore with specific properties) in mind [67]. Most commercial mimics have been developed for either testing cosmetic skin products or for the treatment of skin trauma, but tribological properties have often not been considered [68]. Silicone elastomers and polyurethanes are the most frequently used skin mimic materials [67] as they are easy to work with, although may require surface treatment to reduce hydrophobicity if hydration is present. Mimics with mechanical properties varying

through the depth have been developed to better replicate skin structure, and there have been some attempts to develop a multi-layer skin mimic for experimental analysis.

Schwartz [69] constructed a laminar skin simulant to study the incidence of friction blisters. The skin structure was mimicked with a thin polyurethane top layer, and a textured gum foam rubber lower layer, which were mounted on an acrylic backing plate. Friction blisters were produced on the skin mimic, and the effect of normal load on the total number of cycles to produce a blister was investigated. The results showed that there is a threshold value of inter-facial shear stress required for the formation of blisters, and the layered skin mimic was a promising tool for investigating dermal injury without the need to subject human subjects to discomfort. The layered structure is particularly significant for loading in shear, as the effect will be greater at the layer interface. However the loading cycles that create blisters are not expected to occur during shaving, and it is likely that the effect of hydration on surface roughness and therefore friction will be more significant.

Jansen [66] developed a skin mimic to study shaving applications; it was constructed with different layers to represent skin structure: a lower layer of soft and sticky silicone rubber and an upper layer of stronger, less sticky silicone rubber. Different profiles were applied to the top layer to simulate skin surface roughness. The thickness of the lower layer was consistent, but the top layer varied across the sample, which affected the measurements of mechanical properties. In terms of the mechanical properties of this skin mimic, it was found that:

- Although the rotational and translational friction measurements do not match those of skin, they are of the same order. It is thought that this property is dependent on layer thickness.
- The experimental techniques used made it difficult to determine the effect of surface roughness on mechanical properties. Although it was established that stiffness of the silicone rubber is influential.
- Rubber combinations are up to three times stiffer than skin.
- When the dynamic modulus of skin is compared to that of the mimic, the mimic is found to be up to ten times higher.

Franklin et al. [67] attempted to develop artificial skin which is mechanically similar to skin tissue in that the coefficient of friction changes with hydration and dryness as it would for biological skin. The model produced consists of two layers: a very soft under layer (artificial dermis and hypodermis) and a stiffer, hydrophilic top layer (artificial epidermis). The top layer is textured similarly to that of human forearm skin and the under layer consists of a very soft polyurethane gel and provides approximately the same force displacement characteristic as a forearm.

The top layer is formed from a hydrophilic silicone that absorbs water [67]. Many skin mimics are hydrophobic, and a material that does not absorb water in a moist environment can create a surface film that reduces friction [70]. This is unlike skin, which absorbs moisture and its friction increases with moisture content until saturated [50, 71]. Therefore, a soft material that is able to absorb water with increasing friction should provide friction, film thickness and deformation results similar to that of skin. Mechanical properties of the artificial skin model developed by Franklin et al. is compared to skin in Table 2.3.

Table 2.3: Mechanical properties of human skin and artificial skin model [67]

Material	Hydration, AU		Coefficient of Friction		Reduced elastic modulus, kPa	
	Dry	Moist	Dry	Moist	Dry	Moist
Volar forearm skin	28 – 33	60 – 73	0.73	1.26	8.9	7.4
Artificial skin model	0	21 – 30	0.67	1.24	35.0	30.0

One of the main limitations of this artificial skin model is the time required to reach hydration, as the top layer of silicone rubber is hydrophilic, although this can be improved by reducing the thickness of the top layer [67]. Further investigation into the behaviour of the model is also required, as variables here were limited to one normal load and two hydration conditions. However, as the model's structure is simpler than skin, it should be more resistant to wear [67]. The friction results for the artificial model

from dry and moist conditions show similar behaviour to skin. The deformation behaviour of the model (shown in the elastic modulus) was also within the range expected for the skin dermis [67].

Several materials for use as mechanical skin models were investigated by Derler et al. [72] (Table 2.4), which used the friction response as a measure of how well the mimic behaved compared to skin.

Table 2.4: Shows how each artificial material compares to human skin. Friction was measured when each material was rubbed against a reference fabric in dry conditions [72]

Material	Description	Thickness (mm)	Surface roughness, Ra (μm)	Hardness, shore (A)
Lorica® Soft	Skin-like surface. Polyamide fleece with PUR coating. Surface structure similar to skin.	0.9	14.93 ± 1.73	42.5 ± 1.8
PUR	Sheet material, smooth.	1	0.211 ± 0.022	70.2 ± 0.4
Silicone	Sheet material, smooth.	1.5	1.060 ± 0.120	51.2 ± 1.0
Vinylpolysiloxane	Smooth	-	0.006 ± 0.001	48.4 ± 0.7
Vinylpolysiloxane	Matt	-	1.166 ± 0.052	48.4 ± 0.7
Vinylpolysiloxane	Rough	-	11.94 ± 1.38	48.4 ± 0.7
Vinylpolysiloxane	Smooth	-	Not measured	48.4 ± 0.7

From the skin models, Lorica demonstrated the best correspondence with the friction behaviour of human skin under dry conditions. Results [72] (Figure 2.3) for vinylpolysiloxane show the significant effect of surface roughness on friction: smooth surfaces produced higher friction coefficients, due to an increased effective contact area and adhesion.

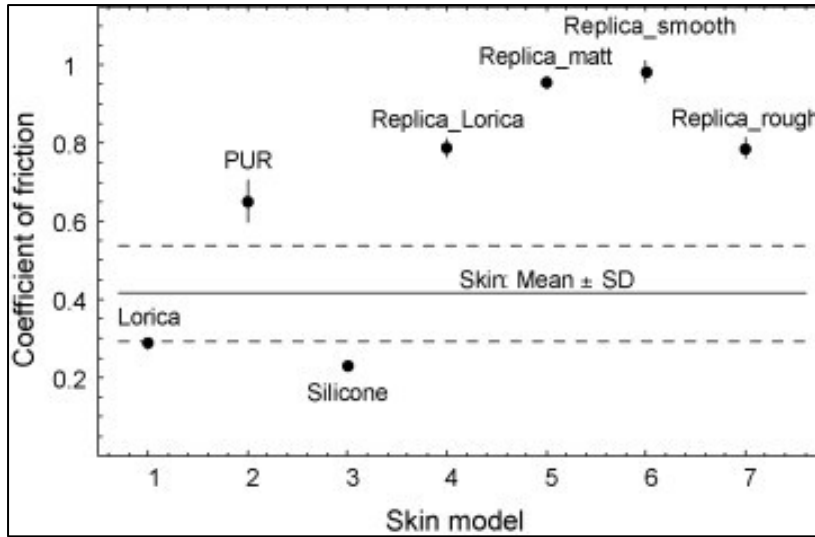


Figure 2.3: Friction coefficients (mean value $\pm$ S.D.) of the reference fabric against seven different skin models [72]

Skin friction increases with hydration, but can be low if there is an excess of water [54]. Lornica shows qualitative agreement with skin when moistened with water (Figure 2.4), but as further investigations with human subjects were needed to understand the effect of skin hydration on friction it could not be compared quantitatively [72].

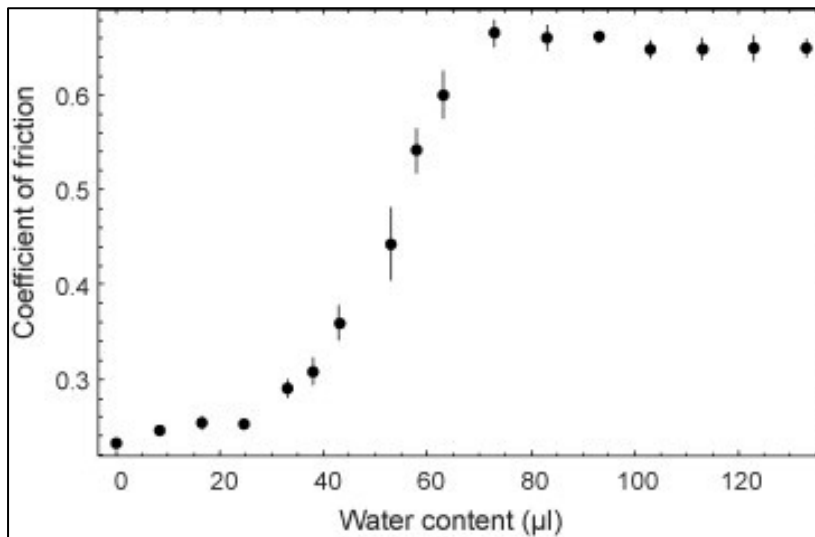


Figure 2.4: Influence of moisture on the friction of the reference fabric against the skin model Lorica [72]

Franklin et al. [67] compared the reduced elastic modulus of synthetic skin materials with human skin for different loads. The results from Derler et al. [72] and Franklin et al. [67] (Table 2.5) show the importance of selecting a skin mimic with appropriate mechanical properties for the application, as the

results for synthetic mimics are so varied. From the results shown in Table 2.5, polyurethane gel is the most appropriate skin mimic when compared to human skin due to its reduced elastic modulus being the most similar to human skin for all loading conditions.

Table 2.5: Reduced elastic modulus of human skin and synthetic skin [67]

Maximum load, mN	Material	Reduced elastic modulus, kPa	Standard deviation, kPa
30	Human skin	8.9	1.1
	Polyurethane gel	14	0.1
	Technogel®	24	2
	SynDaver skin	47	8
	Silicone rubber	139	21
20	Human skin	9.5	1.0
	Polyurethane gel	13.5	0.3
	Technogel®	28	1.4
	SynDaver skin	55	19
	Silicone rubber	154	11
10	Human skin	9.7	1.4
	Polyurethane gel	12.8	0.1
	Technogel®	28	3
	SynDaver skin	44	3
	Silicone rubber	168	9

2.6. Hair properties

2.6.1. Mechanical, density, shape

In order to manufacture high quality consumer products for use on hair, a good understanding of its structure and behaviour under load is required. The microstructure (shown in Figure 2.5) consists of three main components: cortex, medulla and cuticle [74]. The cortex makes up the bulk of the hair and is the part that contributes mainly to tensile strength [75]. Hair is a non-homogenous complex material, consisting of 95% keratin and can be likened to a polymer [76].

Much work has been carried out in an attempt to understand the behaviour of scalp hair under tension, as well as under torsion, bending and friction. Changes in hydration in particular strongly influence the mechanical behaviour: the Young's modulus of scalp hair in the Hookean region reduces by a factor of 3 from a dry to a wet state, whilst torsional stiffness can vary by a factor of 10 from a dry to wet state [75, 77].

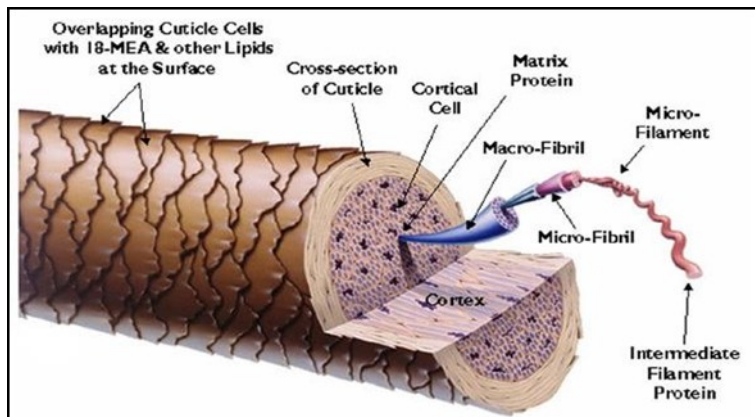


Figure 2.5: Hair structure [73]

The mechanical properties of hair vary with factors such as subject, location, age, ethnic origin and colour. For example, relaxation time is related to a person's age and is influenced by the cortex, whilst stiffness is related to their ethnic origin. [76]. Beard hairs are particularly difficult to cut close to the skin for the following reasons [78]:

- Density (kg/m^2)
- Thickness
- Stiffness/elasticity
- Shape
- Fast growth rate
- Low emerging angle
- High heterogeneity of all of the above

The density of beard hair follicles is between 20-80 follicles/ cm^2 [79, 80], and changes with facial area and ethnicity. High densities of hair follicles can increase the need for multiple-stroke shaving [78].

Beard hair thickness significantly affects the shaving process [78]: the greater the cross-sectional area of the hair, the greater the force required to cut it. Beard hair differs from scalp hair in that there are more cuticle layers [81], which doubles their diameter and increases the force required to cut them [81, 82].

The tensile stress-strain behaviour of beard hair is similar to that of scalp hair, with three distinct regions [74]: elastic, yield and post yield region. Tensile tests also indicate a strong effect of hydration on Young's modulus and yield stress, with both decreasing by a factor of 3 when wet. Aged samples undergoing tensile tests showed a substantial drop in Young's modulus (wet and dry conditions), but a drop in yield stress was only significant in the dry state [74]. When dry, beard hair stiffness is very high and therefore resistant to deformation (such as cutting force from a blade) [78]. Beard hair is more than 1000 times stiffer than perifollicular hair [26] and is comparable to copper wire of a similar diameter with respect to the force required to cut it [83]. This high stiffness of beard hair and corresponding high forces required to cut it may contribute to the total forces applied during shaving [78]. However, this stiffness can be reduced from 30-65 % by hydration [82, 84]. The cutting force is reduced by approximately 20 % within the first minute of hydration, and by 40 % after four minutes [83].

Beard hair is more variable in shape than scalp hair and can have elliptical, asymmetric, oblong and trilobal profiles [81]. During shaving, the blade turns the hair (which can rotate in its follicle) to present to the blade with its largest diameter. This increases blade contact area and cutting force required [26].

2.6.2. Growth rate

Hair growth occurs in cyclic phases of active growth (anagen) and resting (telogen), with a transient intermediate phase (catagen) [78]. At any given time, 85-90 % of hairs are in the anagen phase [85]. During the anagen phase, hair follicle cells show high mitotic activity in the hair bulb and dermal papilla, which results in hair shaft development [86]. Beard hair grows at a rate of 0.3-0.5 mm per day. This is similar to the growth rate of scalp hairs, but twice that of eyebrow hairs [87]. Growth rate is also

affected by environmental and endogenous factors, such as hair pigmentation. E.g. white beard hair grows more than twice as quickly (1.12 mm per day) as pigmented hair (0.47 mm per day) [88].

Beard hairs have lower emerging angles than scalp hairs, particularly on the neck (which is one reason why there is a high rate of shaving-induced skin irritation in this area) [78]. Low emerging angles contribute to ingrown hairs and *pseudofolliculitis barbae* (razor bumps), as well as being difficult for a blade to cut compared to hairs with $> 45^\circ$ emerging angles [78].

2.7. Tribology analysis of shaving

The challenge in shaving is removing stiff individual hairs without negatively affecting the soft skin from which they grow. Many requirements for improved hair removal will increase damage to the surrounding skin [1], so a compromise between the requirements of each biomaterial must be reached. As well as the mechanical contrast between skin and hair, there is extreme variability between people: hair growth direction, coverage, density, growth rate and cross-sectional shape, as well as facial curvature [1, 74]. Due to the extreme variation seen in facial hair, shaving often results in skin irritation, and is the most frequently mentioned male cosmetic complaint in Europe and the U.S.A. [89]. Only 12 % of men have never experienced shaving irritation [1]. The neck is a particularly difficult area to avoid irritation due to multiple hair growth directions, lower elevation angle hairs, increased skin surface roughness and looser skin [26].

The experience of shaving is heavily influenced by friction. The force required to cut the hair with a blade arises from plastic deformation of the hair as the blade advances, then friction occurs between the blade and the cut surface of the hair and between the blade and the skin [90]. Both normal (dry) and very wet (lubricated) skin have a relatively low friction coefficient, but moist and hydrated skin produces higher friction values. The elastic modulus of skin is lowered by hydration, which results in a greater contact area with an opposing surface and higher friction forces, often accompanied by stick-slip characteristics [90]. There are three main components to the force exerted by the cartridge during shaving [1]:

- Perpendicular to the skin
- Parallel to the skin
- Hair cutting force

2.7.1. Force perpendicular to the skin

The razor cartridge rests on the skin and is loaded by a force from the user (total force approximately 2.5 N), who also controls the sliding speed (average 150mm/s). The shaving interface exists between the cartridge components and skin surface, with the Lubrastrip providing a lubricant.

The applied load is a direct result of the user pressing the razor cartridge against the face. Both individual preference and cartridge choice have a significant effect on the applied load [1]. Figure 2.6 shows the razor cartridge component loading (P&G) and supposed lubricant distribution from visual analysis of the razor cartridge construction.

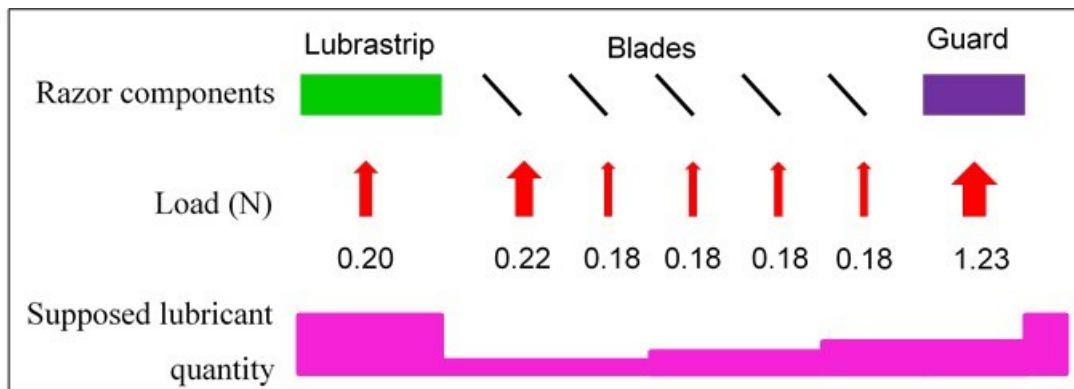


Figure 2.6: Razor cartridge component loading and supposed lubricant distribution

From computational modelling and experimental work, it has been shown that a significant amount of the load is transmitted through the blades, whilst the rest is transferred through the cartridge [1].

The load on each blade is affected by both the quantity and spacing of blades [91]:

- Adding blades without decreasing the distance between each blade increases total cartridge size and therefore drag due to increased contact area.
- Adding blades and narrowing the distance between each blade decreases the load on each blade and reduces skin bulge between blades.

2.7.2. Force parallel to the skin

As the razor cartridge travels across the skin surface, the stratum corneum is subjected to stretching [1]. As skin is anisotropic and non-linear, stiffness increases to resist further elongation [91]. The initial skin response is governed by elastin fibres, but as the force increases the collagen fibres are straightened and this causes the stiffening of the skin [1]. Skin strains of up to 20 % occur during shaving [92], so the initial elastin response to stretching is the most relevant.

The drag force is a result of applied load and friction at the razor cartridge/skin interface, and comes from both skin and hair interaction [1]. Shaving lubricants, such as those found in the on-board lubricating system (Lubrastrip), reduce friction and therefore drag [83]. However, the drag force cannot be overly reduced without negatively affecting the shaving process: a minimal amount of drag is desired by the user to preserve a feeling of control of the razor [1]. Drag is also reduced with the guard at the front of the cartridge: the elastomer fins stretch the skin, reducing surface roughness and skin bulge between blades, which in turn reduces drag [26].

2.7.3. Hair cutting force

Each blade within a razor cartridge cuts several hairs simultaneously [1]. For a double-edged blade, beard hair has a peak cutting force of 0.05 N [82]. This can vary significantly due to blade edge and hair properties, but remains a small proportion of the force required to completely remove a hair from its follicle [94].

In order to maximise comfort during shaving, the cutting force should be minimal. Hair follicles are encased within a network of nerve fibres, so sensitivity to forces on the hair shaft is very high [95]. Additionally, the surrounding skin is densely interspersed with free nerve endings, making it sensitive to stresses linked to hair deflection and lateral displacement. These nerve sensations from cutting hair are felt as a “tug and pull” and/or discomfort and scraping of the skin [1].

2.7.4. Cutting behaviour of beard hair

There are many variables that can influence the cutting behaviour of beard hair, and high speed cutting tests [84] can provide an insight into their significance. These variables include moisture, blade approach angle and proximity of the initial contact point from the base of the hair on the cutting force for the beard hair. Moisture is the main variable that affects peak cutting stresses: when the beard hair is hydrated, peak cutting stress is reduced by 20-40 % [83, 84]. Blade angle has no significant impact on the cutting stress, and moisture reduced the force in the cutting direction more than the hair-tip-bending direction.

Video recordings of SEM cutting tests (Figures 2.7-2.10) and high speed cutting tests showed four mechanisms of failure in hair cutting [84]:

- Mechanism M1 (Figure 2.7) is characterised by longitudinal splitting of the hair filament, produced by a partial penetration of the blade into the hair. It occurs in dry cuts when the contact point between the hair and the blade is less than 2 hair diameters from the base.

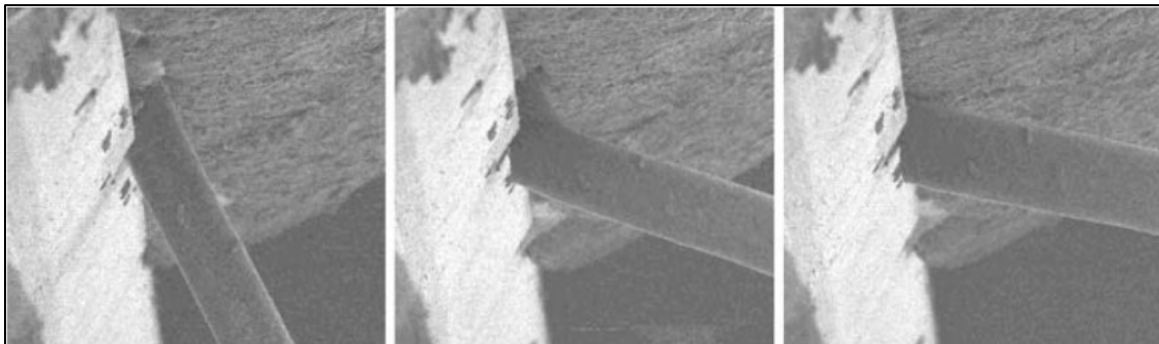


Figure 2.7: Series of video images from an SEM cutting test exhibiting failure mechanism M1 [84]

- Mechanism M2 (Figure 2.8) is characterised by a partial stable penetration of the blade into the beard hair, followed by a quick, unstable cut. As with M1, M2 also occurs when the contact point is close to the base of the hair, but is more likely to occur in wet cuts.

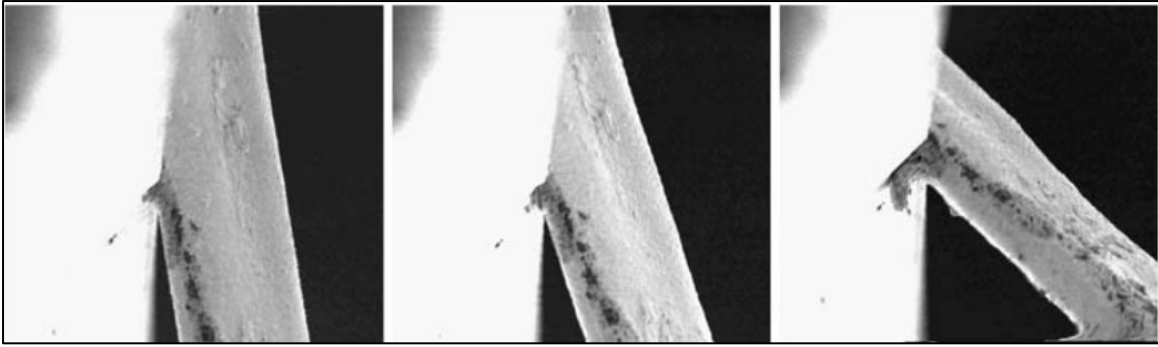


Figure 2.8: Series of video images from an SEM cutting test exhibiting failure mechanism M2 [84]

- Mechanism M3 (Figure 2.9) commonly occurs when the contact point between the blade and the beard hair is approximately 4-6 hair diameters away from the base and is characterised by minor sliding of the blade over the beard hair surface, followed by a skiving cut prompted by the bending of the hair.

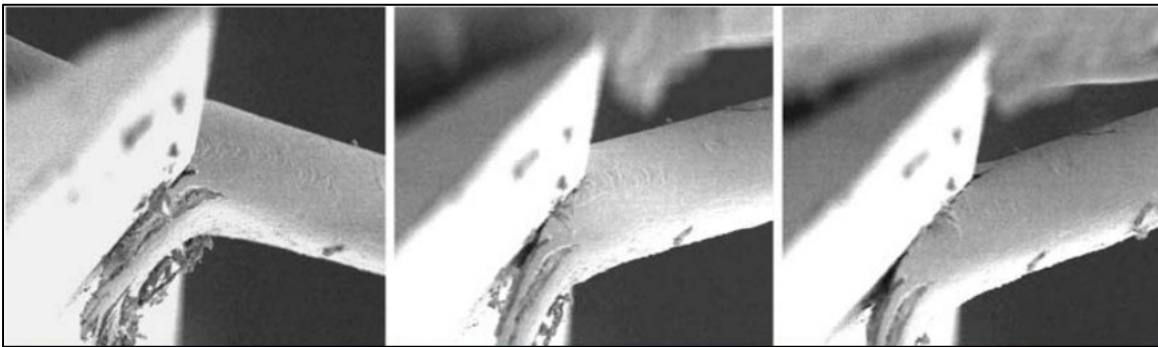


Figure 2.9: Series of video images from an SEM cutting test exhibiting failure mechanism M3 [84]

- Mechanism M4 (Figure 2.10) is an extreme version of M3, and occurs when the distance from the base to the contact point is more than 6 hair diameters. It is characterised by extreme sliding of the blade over the beard hair surface, followed by a partial skiving cut that travelled the length of the hair axis, cutting the hair shaft in two.

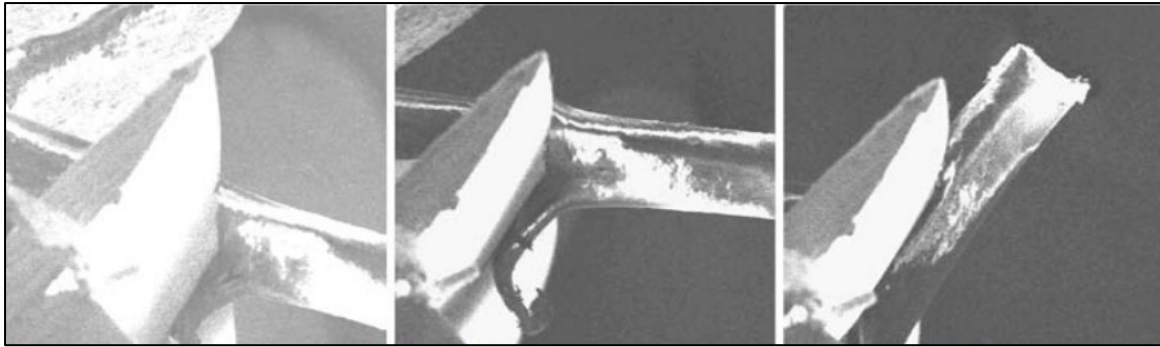


Figure 2.10: Series of videa images from an SEM cutting test exhibiting failure mechanism M4 [84]

2.8. Conclusions

Skin is a highly complex material with varying mechanical properties, surface properties and behavioural response to load, which makes it challenging to remove stiff, individual hairs without damaging the surrounding skin. The Young's modulus of skin is one example of skin's variability as it can differ by a factor of 3000 depending on conditions. Friction is a strong factor in a user's consideration of shaving comfort, and from previous studies skin friction coefficients of 0.3-1.92 may be expected. Although no studies used conditions similar to that of shaving. There are natural and artificial skin mimics available for model experiments, and although less mechanically and chemically similar to human skin than natural skin mimics, artificial mimics provide consistent properties between samples and are easily obtainable. Whilst it is useful to understand the mechanics of beard hair in the context of shaving, this research project does not encompass the cutting of beard hair; the focus is on the razor cartridge/skin interface only.

2.9. References

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3. COMPLIANT CONTACTS AND SHAVING LUBRICATION

Summary

This Chapter summarises compliant contact lubricant regimes and factors affecting friction. Shaving comfort is strongly linked to friction in the razor cartridge contact, and it is currently thought that an ideal shaving lubricant is one which provides low friction and glide at higher speeds, but a high friction feel at low speeds (for greater control over difficult areas) (P&G). It was assumed that shaving lubrication operates predominantly in the I-EHL regime, where the contact pressures are very low [8]. This is typical of compliant contacts, and produces a large film thickness [8, 11]. Changes in material properties, contact parameters, lubricant properties and surface properties will all affect the friction coefficient in some way, and should be considered with a “real life” shaving contact in mind when designing model experiments. Shaving products typically consist of active ingredients, moisturisers, foaming agents, lubricants and preservatives [52-53]. The on-board lubrication system on the razor cartridge (Lubrastrip) deposits an aqueous PEO lubricant onto the skin surface. This viscoelastic polymer is thought to rebound and recover as it lubricates the razor cartridge interface (P&G), although little evidence for this exists. Further investigation into this theory is included in the research project.

3.1. Compliant contact lubrication

Compliant contacts are common within the human body, and include human skin contacts, synovial fluid articular cartilage lubrication, eye/contact lens/eyelid contact and food oral processing [1-3]). Tactile perception through skin contact is one of the most important factors in the decision-making process of cartridge users [4-7] and is the result of stimuli experienced by compliant contacts (e.g. fingertips) with the environment. This sensory evaluation provides constant feedback about the

environment and has a significant bearing on the shaving process, as the overall comfort experienced by the user impacts their final opinion.

Skin is a deformable viscoelastic substrate, which creates a situation during shaving where either one or both of the contact materials are compliant. When this occurs the lubrication mode will be a mixture of boundary, mixed and isoviscous-elastohydrodynamic lubrication (I-EHL). Figure 3.1 shows a typical Stribeck curve. Although this has been developed for high pressure hard contacts and is therefore not necessarily applicable to a compliant contact system, it illustrates the changes in friction coefficient for each lubrication regime.

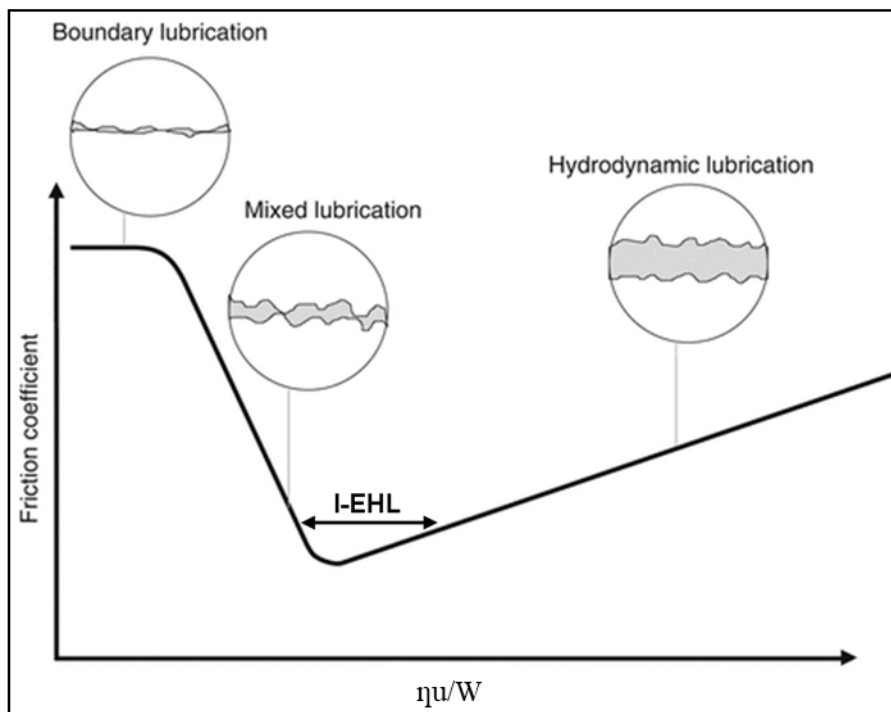


Figure 3.1: Stribeck curve [8]

In boundary lubrication, the surfaces are not separated by the lubricant – the fluid film effects are negligible and there is substantial asperity contact [9, 10]. It typically occurs in the start up and shut down of machine elements [10], and high friction occurs, causing significant energy loss [8]. The lubrication mechanism is dictated by physical and chemical properties of thin surface films of a molecular magnitude [9]. Therefore, aside from determining whether a fluid film forms at all, properties of the bulk lubricant are of minor importance and the friction value is independent of fluid

viscosity; friction is determined by the properties of the contact materials and the lubricant film, which can vary in thickness from 1-10 nm [9].

Mixed lubrication occurs at the intermediate regime between boundary and hydrodynamic lubrication. It arises if the contact pressure is too high, or entrainment speed is too low, and the lubricant film can be the same order of magnitude as the surface roughness [8], resulting in some contact occurring between the asperities [8, 9]. This lubrication regime is governed by a combination of boundary and fluid film effects [8, 9], as interaction takes place between one or more molecular layers of boundary lubricating films [9]. A partial fluid film will form in the bulk of the space between the contact materials and average film thickness is in the range $1 > 0.01 \mu\text{m}$ [9].

I-EHL occurs in compliant contacts, and differs from hard contact EHL by displaying large distortions in the contact interface, even for light loads [9, 11]. There is a local elastic deformation of the contacting materials that provides coherent fluid films, generally preventing asperity contact, which implies that the frictional resistance to motion is due to the lubricant shearing [9]. The maximum pressure for I-EHL is typically 1 MPa, which is considerably less than GPa level associated with hard contact EHL [9], and too low to cause a substantial increase in lubricant viscosity [11]. The minimum film thickness for I-EHL is typically $1 \mu\text{m}$ [9].

Hydrodynamic lubrication is usually seen in bearings and thrust bearings [12], where the two contact surfaces are completely separated by a lubricant film [8, 13]. The film thickness at which this occurs depends on the surface roughness of the contact surfaces [13], and increases in friction are due to shearing of this progressively thick lubricant film [14].

3.2. Friction in compliant contacts

Shaving comfort is strongly linked to friction in the razor cartridge contact, and it is currently thought that an ideal shaving lubricant is one which provides low friction and glide at higher speeds, but a high friction feel at low speeds (for greater control over difficult areas) (P&G). These two characteristics are defined by dynamic (where the friction exists as two surfaces move relative to each other) and static (where the friction builds up immediately before movement) friction respectively.

According to Amontons' laws of friction, the dynamic friction coefficient remains unchanged regardless of applied normal load or apparent area of contact between surfaces. However, due to the viscoelastic nature of skin and many compliant materials, a nonlinear deformation with reduced normal loads occurs [2, 23]. Additionally, with the presence of liquids (as is the case with shaving), the friction coefficient can also change with velocity [6]. The following sections provide an overview of the contributions to friction in compliant contacts. These include material properties, contact parameters, lubricant properties and surface properties.

3.2.1. Material properties: Adhesion

A common assumption made in contact mechanics is that the two contacting surfaces are frictionless and that shear stress cannot be sustained at the interface [15]. Whilst this “frictionless” assumption is often applicable for stiff materials when adhesive forces are relatively unimportant, the same cannot be said for softer, compliant materials where adhesive forces play an integral role in the friction [15], (providing that boundary lubrication does not dominate). Adhesive interactions allow tensile forces to be supported whilst contact stresses within a surface interface are purely compressive [15]. As a result of this support, actual values of load and displacement of a contact area are lower than might otherwise be supposed.

Increasingly compliant materials will be more susceptible to adhesion effects [16]. An inelastic deformation of contact materials causes ‘adhesion hysteresis’ [16], the result of which is to increase the work required to separate the surfaces. Viscoelastic deformation of the contact interfaces can cause the effective work of adhesion to increase with speed of separation [16]. Adhesion between rough surfaces which are nominally flat is strongly influenced by the dispersion in the asperity heights [16]. When the combined root mean square of asperity heights is greater than twice the elastic extension of an average asperity at pull-off, adhesion between the surfaces is destroyed [16, 17].

It is possible for surface roughness to remove adhesion completely [18-22]. This is due to the dispersion of asperity summit heights that causes some asperities to become compressed and others stretched. As a result of this, the elastic energy stored at the surface interface can be used to break

adhesive bonds. Although it has also been shown [21] that despite the diminishing adherence force, the area of real contact is always affected by the adhesion, even for high surface roughness. Adhesion therefore affects friction even when no adherence force is necessary to separate the contacting surfaces, as friction is related to how large the actual contact area is [23].

As a result the contribution of adhesion hysteresis to friction cannot be neglected. Different theories have been suggested to explain this adhesion hysteresis. Some studies [24-27] noted that the molecular rearrangement of the outermost polymer molecular groups at the sliding interface has a significant influence on the adhesion hysteresis and, consequently, friction. In a compliant material, polymer chains are able to interpenetrate during loading, and separate during unloading, but as the time required for separation is shorter than the relaxation time of the molecules, the loading-unloading cycle becomes an irreversible process and energy dissipation occurs: the energy required to separate the surfaces is only partially recovered when they are brought back into contact. Another theory [28] is that of local mechanical instabilities producing adhesion hysteresis. The attractive force between interacting surfaces, which decreases as distance increases, produces rapid jumps of molecules accompanied by energy dissipation.

3.2.2. Contact parameters: Load, speed, temperature

Sliding friction is strongly dependent on applied load across all lubrication regimes [7]. The friction coefficient increases with normal load due to an increase in contact area, which results in higher energy dissipation per unit sliding area and greater adhesion friction [4, 7, 29-31].

Increased fluid entrainment occurs with increasing speed and leads to a decrease in friction coefficient [6]. Friction can have different values for the same relative speed, depending on whether the velocity is increasing or decreasing; the coefficient will be larger during acceleration than deceleration. When accelerating, the instantaneous friction is greater than steady state friction corresponding to the same velocity. The opposite occurs during deceleration. This multi-valued friction coefficient is mainly attributed to temporal delay between changes in sliding speed and friction [30].

Increasing sliding velocity can lead to an increase in friction for a number of reasons, but is mostly attributed to varying interfacial shear strength, adhesion and thermal effects [31]. Thermal effects increase adhesion at high speeds: local heating of a compliant material as a result of friction leads to softening and an increase in contact area, adhesion and friction [29, 32]. However, if lipids are present on the elastomer (such as those contained in sebum), these can act as an insulating layer that restricts heat conduction and local heating [31].

3.2.3. Lubricant properties: Viscosity, chemistry

Viscosity of a lubricant can be associated with its resistance to flow [9]. High viscosity fluids do not flow easily and although they can create a large film thickness, the friction is also high due to shear forces within the lubricant [14]. However, too low a viscosity and the lubricant will not be able to support the two contact surfaces, creating boundary lubrication [9]. Lubricating properties of a compliant contact is largely determined by the lubricant's viscosity [4-6, 33].

Pressures in compliant contacts are low compared to those of hard contacts, and pressure-induced changes to lubricant viscosity are therefore negligible [4, 11]. A shaving lubricant will be subjected to significant shear forces due to the multiple contacts, which may cause the fluid to progressively thin, affecting film thickness and friction.

This research project studies the effects of Newtonian, shear thinning and viscoelastic fluids on lubrication properties. Newtonian fluids are characterised as having a constant viscosity, and during lubrication increased viscosity promotes entrainment and film thickness, reducing friction [5, 6].

Polymer shear thinning solutions (xanthan gum and guar gum), where viscosity decreases with increasing shear rate, produce a reduced friction response with increasing speed and increasing polymer concentration [6, 34]. It is important to consider the relationship between viscosity and shear rate, as it will affect flow at low rates of shear/low speeds and the fundamental understanding of lubricant behaviour [35].

The viscoelastic fluids in this project are low concentration poly(ethylene oxide) (PEO) solutions (more detail on these fluids is provided later in this Chapter), which are reported to have a near-constant viscosity

at low shear rates [36, 37]. However at higher shear rates it is difficult to predict the friction or film formation of these fluids, as their viscosity varies with shear rate and they behave as viscoelastic materials [33]. Previous work has found friction coefficient to fall with increasing polymer content [33], and these elastic fluids experience lower torque, and therefore drag coefficient, than Newtonian fluids [38, 39]. Two main reasons for this have been proposed [39]: polymer extension, which suppresses the formation of eddies; and boundary layer alterations associated with the addition of a polymer.

Aqueous lubricant properties – such as friction, wear, anti-bacterial and anti-foaming [40] – can be modified with additives, for example by use of surface/interfacial active molecules [41]. Tomala et al. [40] conducted an experiment on the effects of amines and glycols in aqueous solution on friction, and the results are shown in Figure 3.2. Ethylene glycol, which is listed as one of the additives tested in Figure 3.2, is chemically similar to PEO (present in the Lubrastrip), but with a lower molecular weight of < 100,000 g/mol. The results demonstrate that not only is it important to identify the correct additive for the intended application, but also the correct concentration. Therefore, after identifying a potential additive for shaving lubrication, it may be useful to screen different concentrations for an “ideal” friction response. It has also been noted from this study [40] that additives can enhance one property whilst negatively affecting another.

Work by Røn et al. [42] also found that poly(ethylene glycol) (PEG) reduced the friction coefficient of water in a polydimethylsiloxane (PDMS) contact. However poly(acrylic acid) was found to have a negligible effect on friction, and polymer additives should therefore be assessed individually.

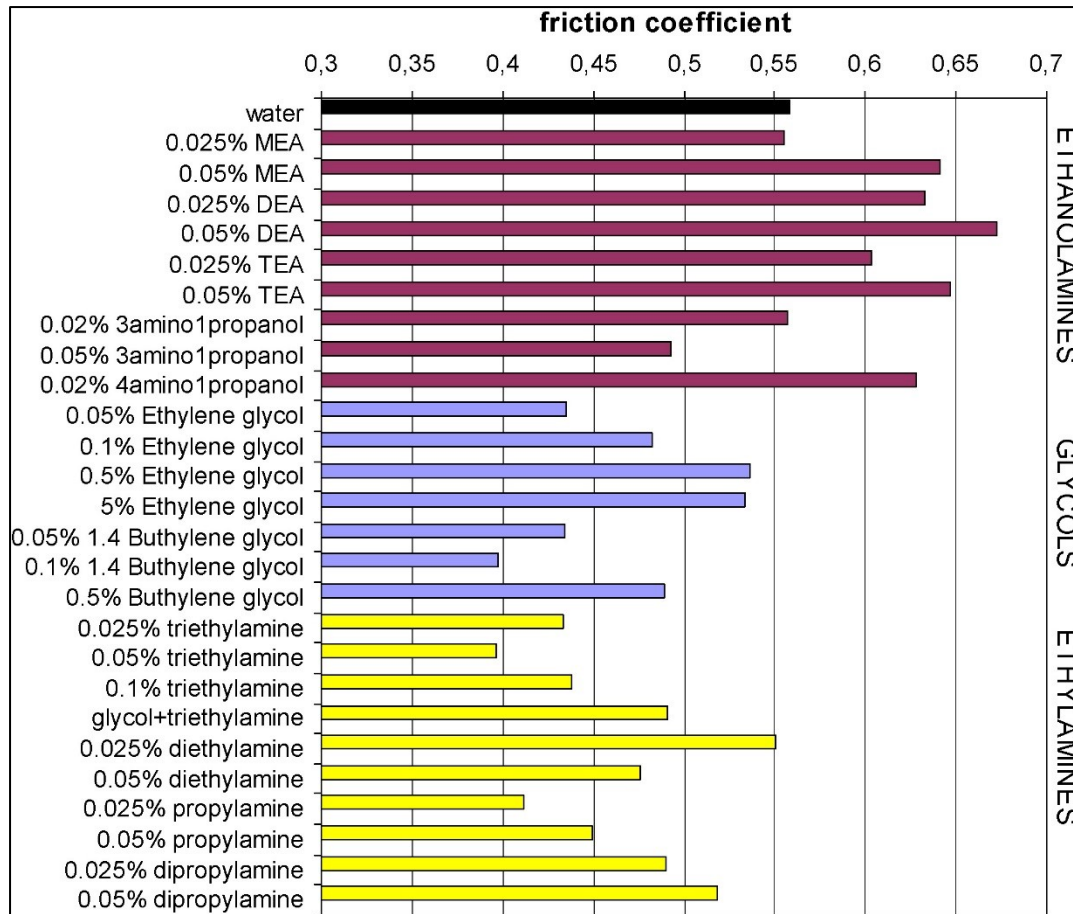


Figure 3.2: Effect of additives on aqueous lubrication [35]

3.2.4. Surface properties: Texture, surface wetting, hair

Surface roughness has a significant effect on the friction and adhesive properties of soft contacts [17], and biosurfaces in particular vary greatly in their topography. For example: hair cuticles have a roughness scale in the order of 100 nm [43], while the tongue can have a roughness in the order of 20-300 μm [43, 44]. In particular, biomimetics research has shown that hierarchical surface structure can allow the surface to achieve specific tribological properties. Geckos and many insects are able to climb vertical surfaces and ceilings, which is attributed to the co-working characteristics of roughness hierarchy, fluid secretion and van der Waals interaction [45-47].

In compliant/compliant contacts surface interactions between the materials often dominate, which can hinder formation of a stable lubricating film [48]. For I-EHL of elastomers lubricated by water, the failure of the lubricating film is usually due to an increase in adhesion as most elastomers are hydrophobic [49, 50]. The hydrophobic nature of non-metallic test samples used in this project may

therefore affect the ability of a stable film to form in the razor cartridge contact, resulting in high friction at low speeds [4].

The surface properties of a material can be changed from hydrophobic to hydrophilic by plasma polymerisation [51]. This process has been used throughout this research project to reduce hydrophobic effects on lubrication. It removes impurities and contaminants from a surface, using a dielectric barrier discharge (DBD) plasma created from gaseous species such as argon and oxygen. For example, plasma polymerisation of PDMS changes the surface chemistry and produces silanol terminations (SiOH) on its surface, rendering PDMS hydrophilic for approximately thirty minutes [52]. The degree to which a surface is hydrophobic or hydrophilic can be measured by the contact angle; surfaces with a lower contact angle are more hydrophilic. Friction has been shown to decrease with decreasing contact angle and increased entrainment into the contact [4].

It is currently assumed that the razor cartridge is lubricated in the I-EHL regime, and for I-EHL, the influence of hydrophobicity on friction for compliant contacts is negligible [4, 33]. However should this assumption prove incorrect it is important to minimise starvation due to hydrophobic interactions in order to observe cartridge lubrication.

The contact angle of the human skin counterface in “real life” shaving changes due to sebum secretions and hydration variability [4]. Consumer products containing surface active ingredients (oils, polymers etc.) will also influence surface wetting. Once a stable, separating film is formed, contact angle and surface roughness has no effect on the I-EHL lubrication regime. So for relatively thick films the response of the lubricant is dominated by its rheological properties [4]. This also applies to the hydrodynamic regime, where contact surface are completely separated by the lubricating film [8, 13].

3.3. Shaving products

The aim is to design easily gliding shaving products with low friction and minimum skin deformation, which increases perceived skin comfort and reduces skin irritation. However, there is also occasion for optimum grip properties, which are related to static friction behaviour and different skin deformation characteristics [53]. Below is a brief review of lubricants commonly used for shaving.

3.3.1. Common ingredients

Table 3.1 below lists a few of the ingredients most commonly found in shaving preps. Shaving preps typically consist of active ingredients (to improve general skin health), moisturisers, foaming agents (it is reported that users prefer a shave prep that foams (P&G), lubricants and preservatives [54, 55]. This project will focus on the lubricant ingredient only, although it is useful to consider the other components to understand the context in which a complete shaving prep is formed.

Table 3.1: Common shaving prep ingredients

Active ingredients	Aloe vera [54]	Strengthen skin's natural defences. Increases blood circulation to skin cells.
	Grapeseed oil [55]	Vegetable oil from pressed Vitis vinifera grape seeds. A by-product of wine making. Believed to aid regeneration of skin cells through maintaining the normal structure of epithelium cells and nerve cells.
	Menthol [55]	Organic compound derived from peppermint or other mint oils. Chemically triggers cold-sensitive receptors in the skin, producing a cooling sensation. Used in a wide range of products and can be either natural or synthetic.
	Lavender oil [55]	A natural antiseptic and pain reliever. The aromatic scent is also known to have a calming effect and can help to relieve pain from tension headaches, coughs and respiratory infections.
	Sesame seed oil [55]	Source of vitamin E, which is a strong antioxidant. Also contains magnesium, copper, calcium, iron, zinc and vitamin B6.
	Clove bud oil [55]	A natural antiseptic with anesthetic properties. Can be used to treat acne.
Moisturiser	Glycerine [54]	Derived from coconut and/or palm kernel oil. Hydrates by adding and binding moisture.
	Glycerol cocoate [54]	Coconut oil extract. Water soluble, oil restoring agent.
Foaming agent	Cocamidopropyl betaine [54]	Coconut oil extract. Foaming agent. May reduce irritant effect of other tensides.
	Sodium laureth sulphate [54]	Coconut and palm kernel oil extract. Most widely used tenside as it has low skin irritation and good foaming agent properties.

	Disodium laureth sulfosuccinate [54]	Foaming agent. May reduce irritant effect of other tensides.
Lubrication	Poly(ethylene glycol)	Reduces friction. Molecular weight less than 100,000 g/mol.
	Poly(ethylene oxide)	Reduces friction. Molecular weight = 100,000-8 million g/mol.
Preservative	Soya bean oil [55]	Commonly used vegetable carrier oil. Extends the duration of the action of essential oils.
	Sodium benzoate / natrium benzoate [54]	Preservative commonly used in food products.
	Potassium sorbate / kalium sorbate [54]	Preservative commonly used in food products
	Sodium sulphite [54]	Prevents product oxidation.
	Citric acid / ascorbic acid / ascorbate [54]	Natural vitamin C acts as a pH regulator

3.3.2. Poly(ethylene oxide)

Currently, poly(ethylene oxide) (PEO) in aqueous solution is used in the on-board lubrication system (Lubrastrip) incorporated into the cartridge design. Although its razor cartridge lubrication properties are not yet fully understood, it has been identified through user panel tests as a preferred lubricant (P&G). PEO has good water solubility at room temperature and is an elastic liquid with a near constant viscosity, defining it as a Boger fluid [36]. Boger fluids are highly elastic, dilute solutions of a high molecular weight polymer.

A key property of a Boger fluid is its almost constant viscosity at low shear rates [36, 37]. In a polymer solution, the polymer chains are loosely coiled, entangled and randomly orientated. These chains can be stretched out and straightened by shearing, aligning them in the direction of shear to minimise resistance to shearing [36]. This stretching and alignment increases with shear rate, which causes a polymer solution to be shear thinning. If, however, the solution is sufficiently dilute (such as the PEO solutions in the razor cartridge contact), then the viscosity contributed by the polymer is

only a small fraction of the total viscosity. The decrease in viscosity with shear rate is therefore so small that the fluid is assumed to have a constant viscosity [36].

Liquid elasticity is related to polymer chain extension and to Brownian motion of the solvent [36]. Brownian motion opposes stretching and alignment of the chains by acting to keep the chains in random configurations. In a fluid flow, the degree of extension relies on how much the viscous forces dominate the forces due to Brownian motion. When the applied stress is removed (i.e. when the flow stops), the chains relax to their equilibrium state, which is observable at macroscopic level as elastic recoil [36]. The rate of stress relaxation is determined by the fluids relaxation time. This relaxation time, which is zero for Newtonian fluids, is a measure of fluid elasticity.

The viscoelastic behaviour is thought to allow the PEO solution to rebound and recover after passing through the razor cartridge contact interface (illustrated in Figure 3.3), although little evidence for this exists and viscoelastic replenishment of the cartridge contact is one of the aspects investigated in this project. The repeat unit in these polyethers is $-\text{CH}_2-\text{CH}_2-\text{O}-$ and it is available in a wide range of molecular weights (100,000- 8 million g/mol). A molecular weight of 1 million g/mol is currently used in the Lubrastrip.

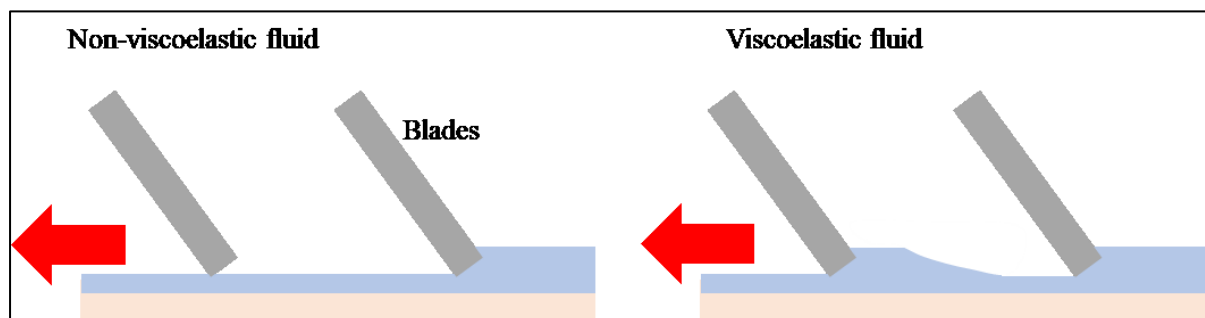


Figure 3.3: Supposed ability of viscoelastic PEO solution to rebound and recover between razor cartridge components

One of the reasons that PEOs are used in the Lubrastrip is that they are comparatively stable. Rate of degradation at room temperature is slow, although the rate of fall of viscosity and elasticity of aqueous PEO solutions increases with the molecular weight. Dontula et al. [56] found that the viscosity and elastic modulus of a 0.5 wt. % aqueous PEO solution of 7 million g/mol molecular weight fell by 5 % within 15 days, while that of a 4.1 wt. % solution of 400,000 g/mol fell

immeasurably even after 28 days. PEO solutions can be stabilised over longer periods of time using allyl, ethyl and isopropyl alcohol, as these are selectively oxidised and compete for peroxides and free radicals in solution more effectively than PEO [57].

However, PEO shows limited thermal stability. It oxidatively degrades in the presence of oxygen by forming hydroperoxides that decompose into free radicals in the presence of metallic ions. These free radicals then split other polymer molecules [58]. The process is accelerated by metallic ions like Fe^{3+} and Cr^{3+} , as well as exposure to ultraviolet light [56]. This thermal instability increased by UV light may cause premature degradation of PEO in the Lubrastrip, as razor cartridges are not necessarily stored in a cool, dark place.

As with many other polymers, high molecular weight PEO ($M_w > 1$ million g/mol) degrades mechanically when subjected to intense deformation for prolonged times. The viscosity of a 0.5 wt. % aqueous PEO solution of 7 million g/mol molecular weight fell by approximately 10 % after shearing for 120 s at 1000 s^{-1} in a Couette fixture [56]. Shear rates experienced during shaving are assumed to be much larger (based on preliminary information), which could affect the PEO's ability to rebound between successive blades.

3.4. Summary

For the purpose of tribological analysis, it is assumed that shaving during lubrication operates predominantly in the I-EHL regime, where the contact pressures are very low [9]. This is typical of compliant contacts, and produces a large film thickness [9, 11]. Shaving comfort is strongly linked to friction in the razor cartridge (P&G), and it is therefore important to understand the properties potentially governing cartridge lubrication in order to design appropriate model experiments.

Adhesion contributes significantly to compliant contact friction [15], even when a full film is present, as it affects the actual contact area [23]. It is unlikely that significant increases in load will occur during shaving, as the face is a sensitive area. It is also unlikely that the speeds applicable to shaving will be high enough to create significant thermal effects. However shaving does occur over a speed

range (low speeds over the “tricky bits” and a higher average speed for “easy” areas such as the cheek), so the impact of speed on shaving lubricant friction should be considered. The importance of surface roughness and surface wetting on the razor cartridge contact depends on the lubrication regime [4, 8, 13, 33] (as yet unknown, but to be established in this project), although it may hinder the initial formation of a film [48].

Viscosity has a strong bearing on the film thickness and friction in a lubricated contact [4-6, 33]. Fluids with a higher viscosity produce thicker films and a reduced friction can occur as the result of the formation of a separating film. But once a film exceeds a certain thickness friction will increase due to shear forces within the lubricant [14]. Lubricant chemistry and response to shear forces also affects friction. Additives can be used to improve lubricant properties for a specific application [40], but it is difficult to improve one property without negatively affecting another [40]. The quantity of additive (as well as the type of additive) can drastically affect friction [40, 42], so the consideration of both of these factors in a shaving lubricant is important.

Shaving products typically consist of active ingredients, moisturisers, foaming agents, lubricants and preservatives [54, 55]. The on-board lubrication system on the razor cartridge (Lubrastrip) deposits an aqueous PEO lubricant onto the skin surface. This viscoelastic polymer is thought to rebound and recover as it lubricates the razor cartridge interface (P&G), although little evidence for this exists and further investigation into this theory is included in the research project.

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4. COMMON TEST SPECIMENS, SPECIMEN PREPARATION AND THEORETICAL CALCULATIONS

Summary

This chapter details the common test specimens, specimen preparation for experimental methods and theoretical calculations used in this project. These include:

- *Razor cartridge components*
- *Test specimens*
- *Test fluids*
- *Mechanical properties*
- *Specimen cleaning methods*
- *Theoretical calculations*

4.1. Introduction

The research project is comprised of the following:

1. Analysis of tribology conditions in a shaving contact.
2. Measurement of shaving prep fluid friction using a MTM and rheology properties.
3. Development and application of a laser induced fluorescence method to visualise lubricant flow and film thickness in the contact.
4. Development of a skin mimic suitable for use in the laser induced fluorescence method.
5. Application of the fluorescence method to measure lubricant flow through the razor cartridge contact.

Common materials, processes and calculations for the research project are included in the subsequent sections of this Chapter.

4.2. Test components and fluids

4.2.1. Razor cartridge

A Gillette razor cartridge (Figure 4.1) is used throughout this study as the razor cartridge contact, and the three main components are (from front to back of the cartridge):

- Guard
 - Stretches and smooths the skin to reduce skin irritation from blades
 - Removes excess lubricant from the contact.
- Five blades
 - Each blade is spring loaded, and held in place by the clips.
 - Closely spaced, multiple blades improve close-cutting of beard hair and reduce skin bulge between blades (which reduces skin irritation).
- Lubrastrip
 - This distributes the on-board lubricant (PolyEthylene Oxide, PEO) onto the skin in preparation for the next stroke.
 - PEO is held within a polystyrene matrix, and released when hydrated.

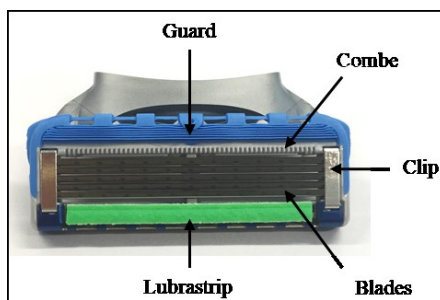


Figure 4.1: Razor cartridge as used in lubricant distribution and film thickness tests with labelled components.

Average load during facial shaving is 2.5 N (Proctor & Gamble, UK), and the breakdown of force distribution and material properties across cartridge components is listed in Table 4.1.

Table 4.1: Razor cartridge component typical loads and material properties

Component	Load (N)	Material	Young's modulus
Cartridge	2.50	N/A	N/A
Guard	1.23	PolyOne TPE elastomer	50 MPa
Blades 1-4	0.18	Coated stainless steel	205 GPa
Blade 5	0.22	Coated stainless steel	205 GPa
Lubrastrip	0.20	Polystyrene and 1×10^6 g/mol M_w PEO	Changes with hydration
Clips	0.13	Stainless steel	205 GPa

PolyOne TPE elastomer (which the guard is made from) is hyperelastic and so does not have a constant Young's modulus. The value in Table 4.1 has been calculated using stress-strain data from P&G. The guard consists of several flexible fins (Figure 4.2) and these are able to bend, stretch and compress during loading.



Figure 4.2: Cartridge guard fins

The load on the guard is comparatively high, at 49.2 % of total razor cartridge load. However, due to the compliancy of PolyOne TPE elastomer, the contact pressure here is not expected to be high.

After the guard, load increases towards the back of the razor cartridge, so a reduction in lubricant film thickness for blade 5 would be expected here, compared to the leading 4 blades. As the blades are made of stainless steel, which has a significantly higher Young's modulus than the guard material, contact pressures in the cartridge are expected to be highest here, with blade 5 exerting more pressure on the counterface than blades 1-4. Table 4.2 shows approximate values for razor cartridge contact pressure at the guard and blade interfaces. Due to the complex geometry and material properties in the contact, these values are illustrative only.

Table 4.2: Approximate cartridge component contact pressures

Component	Load (N)	Max. Pressure (MPa)
Guard	1.23	15
Blades 1-4	0.18	880
Blade 5	0.22	990

4.2.2. MTM specimens

Friction was measured for a lubricated stainless steel ball/skin mimic contact using the Mini Traction Machine (MTM, PCS Instruments, UK). The skin mimic mechanical and chemical properties are described in Sections 4.2.2.1 and 4.2.2.2.

4.2.2.1. PDMS skin mimic

A Poly(dimethylsiloxane) (PDMS) disc was chosen for use as a skin mimic in the MTM friction measurements. PDMS is a silicone elastomer with the empirical formula $(C_2H_6OSi)_n$ [1], and is available with mechanical properties that are comparable to skin. Silicone elastomers are advantageous over other materials such as gelatine, keratin and hydrogels because they are not susceptible to drying and have little sensitivity to ionic content or pH of aqueous solutions [2].

The siloxane bonds in PDMS allow the formation of a flexible, viscoelastic polymer chain via cross-linking. Once cross-linking has occurred between the monomer chains, PDMS becomes a hydrophobic elastomer, which prevents polar solvents (such as water) from spreading on the surface.

PDMS does not allow water, glycerol, methanol or ethanol infiltration and consecutive deformation. It is therefore ideal to use for experimentation with water-based lubricants, although it will deform and swell in the presence of di-isopropylamine, chloroform and ether, as well as (to a lesser extent) acetone, propanol and pyridine [1], so care must be taken not to allow contact with these chemicals.

PDMS LSR 4330 A/B is an elastomer particularly suited for use as a skin mimic as its mechanical properties are comparable with skin (Table 4.3), which are detailed in Chapter 2. It is manufactured by Bluestar Silicones (Bordon, UK), and supplied by PCS Instruments.

Table 4.3: PDMS LSR 4330 A/B mechanical properties

Durometer, ShA	30
Young's modulus, MPa	1.23
Tensile stress, MPa	9.7
Fracture strain, %	790
Tear strength, kN/m	34
Specific gravity	1.11
Appearance	Clear
Typical applications	Modified healthcare and medicinal parts

4.2.2.2. PDMS surface chemistry

A PDMS disc with similar mechanical properties to skin is a good starting point for modelling skin surface interactions, and its surface chemistry can also be modified to better match skin. This is important as skin surface chemistry plays a significant role in skin tribology [3-6]. Coating PDMS with artificial sebum may be a solution to mimicking the skin surface chemistry.

The surface of skin is usually covered by a layer of sebum. This is an oily substance secreted onto the skin surface, where it seeps into the main skin furrows and intercellular spaces. It is composed of squalene (12 %), wax esters (26 %), glycerides and free fatty acids (57.5 %) and sterols (free and esters) (4.5 %) [7-9]. Once sebum reaches the skin surface, it is contaminated by lipids: triglyceride composition does not vary significantly between individuals, but at the skin surface hydrolysis of triglycerides occurs to form fatty acids, glycerol and very small quantities of mono- and diglycerides [10].

It is spread on the skin surface as an unevenly distributed sheet [11]. Sebum film thickness can vary significantly: at the majority of skin locations (e.g. arm, back, leg), film thickness is $< 0.5 \mu\text{m}$, but some areas of the sebum-rich face have a film thickness of $> 4 \mu\text{m}$ [11]. The formation, assembly and orientation of sebum on the skin surface is currently unknown [12].

Whatever the thickness of sebum on the skin surface, it is the fundamental parameter of skin surface energy [13-15]. For example, the contact angle for distilled water on the forearm is 92°, but increases to 127° once sebum is removed [13]. This has also been reported in other studies [14, 15] which indicate sebum creates a more hydrophilic environment on the skin surface.

A simplified artificial sebum [8, 16, 17] was created in the lab and used for the MTM experiments. The composition is summarised in Table 4.4 and consists of the four main components found in naturally occurring sebum – these components are either like-for-like or a similar alternative (identical matches were difficult to obtain due to cost and availability), and the ratios of these components was similar to those found in sebum (listed earlier in this section). Lanolin is melted at 37 °C (melting point 36 °C) before mixing with the three other components. This forms a yellow/white, solid substance which can be stored at 4 °C for at least 28 days without loss of chemical integrity [10, 16].

Table 4.4: Artificial sebum composition

Component	Supplier, part number	Quantity (wt. %)
Squalene	Sigma-Aldrich, UK, #S3626	10
Lanolin	Sigma-Aldrich, UK, #L7387	25
Triolein	Sigma-Aldrich, UK, #Y000113	35
Palmitic acid	Sigma-Aldrich, UK, #P0500	30

Previous experimental studies have spray-coated artificial sebum onto mechanical skin models to evaluate friction, adhesion and wetting behaviour of liquids and emulsions on simulated skin-surface conditions [10]. However, manual spraying is labour intensive and substantial amounts of the solution can be lost. For this investigation the PDMS disc was heated to 37 °C (to facilitate softening of the artificial sebum), the artificial sebum was spread onto the disc surface with a spatula and then wiped with tissue. This created a “dirty surface” chemically similar to skin, with a film thickness of approximately 50 µm and increased hydrophobicity, where the contact angle is more than 90° [18] [13]. This film thickness is >12.5 times larger than observed in “real life”, but is intended as an initial investigation into the importance of surface chemistry changes on friction in a model shaving contact.

Coating the PDMS disc with artificial sebum increases the surface lipid content and therefore also hydrophobicity [12]. Additional hydrophobicity may also occur to the steel ball due to adherence of lipids to this surface [12].

4.2.3. LIF skin mimics

A skin mimic counterface was used for the laser induced fluorescence method to visualise lubricant flow through the contact and measure film thickness in Chapters 6-8. It was required to meet certain criteria in order for visualisation and film thickness measurements to be possible in this experimental setup:

- Optically transparent; for clear imaging.
- Non-absorbent; so that skin mimic material properties are not affected by lubricant absorbance.
- Abrasion resistant; skin mimic must not degrade during testing.
- Adhere to glass; allows easy adaptation to current imaging techniques.

Two materials were identified as possible skin mimics for the fluorescent imaging method (described in detail in Chapter 6). These were a gelatine gel and a silicone elastomer, and their mechanical properties compared favourably to those of skin and other skin mimics (listed in Chapter 2).

4.2.3.1. Gelatine

Leaf Gelatine (Dr. Oetker U.K. Ltd.) was chosen as a possible skin mimic as it is derived from the selective hydrolysis of collagen [19] and therefore similar to natural skin. The mechanical properties of a gelatine gel can be adjusted by altering the gelatine concentration [20], and once set it creates a clear, viscoelastic, thermoreversible gel. Leaf gelatine was dissolved by stirring in distilled water over a heat of 60 °C before pouring into a mould and leaving to set at room temperature overnight.

The concentration was chosen to match the approximate stiffness of skin (90 N/m) (Figure 4.3), and a range of gelatine samples were tested using the Biomomentum Mach-1™ (further details in section 4.3.1) to achieve this.

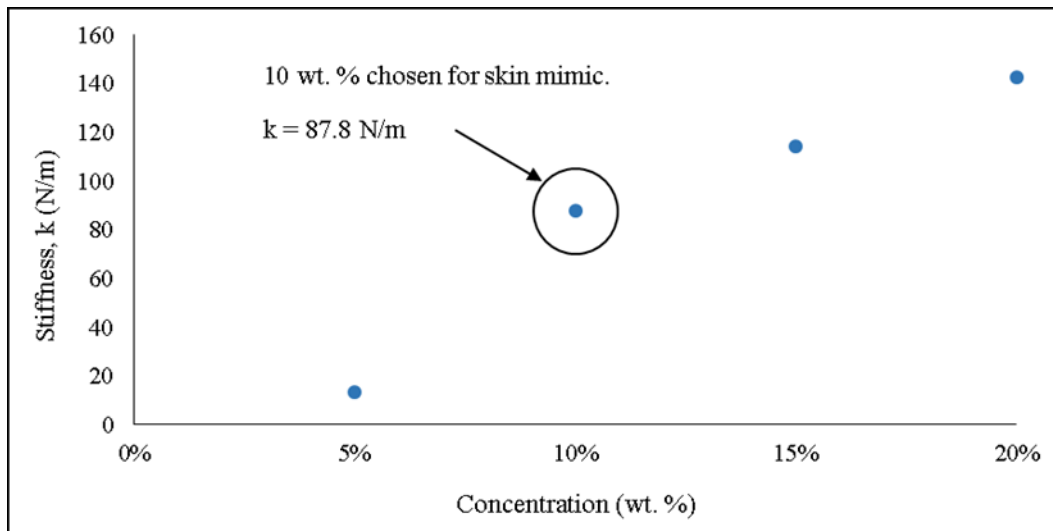


Figure 4.3: Gelatine gel stiffness verses wt. % concentration

4.2.3.2. Silicone elastomer

Silicone elastomers are advantageous over other materials such as keratin, gelatine and hydrogels because they are not susceptible to drying and have little sensitivity to ionic content or pH of aqueous solutions. They also show negligible ageing effects after a long period (8 months) of storage [2]. This material will therefore produce repeatable results and remain unaffected by environmental conditions. However, its surface chemical properties are very unlike skin:

- Hydrophobicity/contact angle
- Single layer structure
- Surface roughness
- Reaction to hydration
- “Clean” surface – no sebum/sweat/micro-organisms

The silicone elastomer used was MED-6021, supplied by Polymer Systems Technology Ltd., U.K. (Table 4.5) and is a pourable, optically clear two-part silicone for moulding, potting and coating applications [21].

Table 4.5: Mechanical properties of silicone elastomer

Tensile strength [21]	1.9 MPa
Young's modulus	200 kPa
Poisson's ratio	0.48
Stiffness	2 kN/m
Refractive index [21]	1.407

Parts A and B of the silicone elastomer are mixed in a 50:50 ratio before being poured into a water-tight mould with the glass disc at the base (this removed the necessity of gluing the cured elastomer to the disc, as it bonded to the glass surface during curing). The mould was then placed into a vacuum chamber to remove bubbles formed in the silicone elastomer during mixing. Once degassing was complete, the mould was placed into an oven at 150 °C for 30 minutes. Upon removal from the oven the silicone elastomer was left to cool before removing from the mould (Figure 4.4).

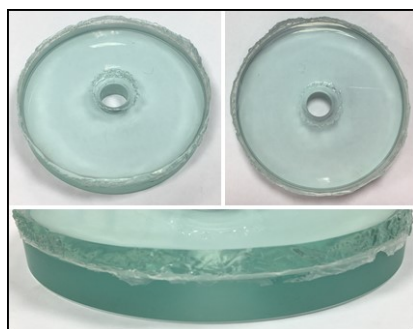


Figure 4.4: Silicone elastomer coated glass disc

Unlike gelatine, it is not possible to alter the mechanical properties of the silicone elastomer e.g. by changing the two-part ratio or curing temperature. Deviations from the standard process to create the silicone elastomer result in incomplete curing.

4.2.4. Shaving preparation test fluids

The Lubrastrip on the razor cartridge supplies a shaving prep of 1×10^6 g/mol M_w PEO (1 wt. % aqueous solution), which has been found to be the most pleasing lubricant to the user (information supplied by Proctor & Gamble, UK). Taking this into consideration, a range of PEO solutions with different

molecular weights were identified to study the lubrication mechanism through the razor cartridge and recognise lubricant characteristics that users may respond positively to. Four reference fluids were also chosen (three Newtonian and one shear thinning) to isolate any lubrication properties in PEO that may be due to viscoelastic mechanisms. Reference fluids and PEO solutions used in this thesis are listed in Table 4.6.

Table 4.6: Lubricant solutions

Aqueous solution	Fluid property	Concentration	Supplier, part number	Mixing method
Distilled water	Newtonian	100 wt. %	N/A	N/A
Decon 90*		2 wt. %	Decon Laboratories Ltd., UK, SDS-D90	In the lab, with a magnetic stirrer.
Glycerol		60 wt. %	Sigma-Aldrich, UK, #49781	Stored at room temperature.
Xanthan gum	Shear thinning	1 wt. %	P&G, UK	Supplied pre-mixed. Stored at room temperature.
200 x10 ³ g/mol M _w	Viscoelastic	1 wt. %	Sigma-Aldrich, UK, #181994	In the lab with an overhead stirrer, using a radial flow impeller. Mixed for 24 hours and stored at 4 °C for 30 days.
400 x10 ³ g/mol M _w		1 wt. %	Sigma-Aldrich, UK, #372773	
1 x10 ⁶ g/mol M _w		1 wt. %	P&G, UK	
2.6 x10 ⁶ g/mol M _w		1 wt. %	3:2 mixture of 1 x10 ⁶ g/mol and 5 x10 ⁶ g/mol M _w respectively	
5 x10 ⁶ g/mol M _w		1 wt. %	P&G, UK	

* Decon 90 is a liquid detergent

4.3. Material properties

Measurement of mechanical properties of the test specimens and lubricants was conducted using a Biomomentum for solid materials and a rheometer for liquids.

4.3.1. Biomomentum

The Biomomentum Mach-1™ (Biomomentum Inc., Canada) was used to measure mechanical properties of skin mimic materials. It is a multiple axis tester that can evaluate the mechanical properties of soft materials.

Cylindrical samples were bored from the material to be tested, approximately 10 mm diameter, 6 mm height. These were then placed into the Biomomentum, with silicone oil between the sample and loading plates to remove friction effects (Figure 4.5a). Samples were compressed by 10 % (Figure 4.5b), and this strain value was chosen as elastic properties are only valid for very low strain rates. Three samples were taken for measurement from each material, and for each sample three compressions were conducted. Figure 4.6 shows three repeats from one sample of 10 wt. % gelatine gel. These results were then processed and averaged to provide mechanical properties. The results are shown in section 4.2.3.1 Gelatine, Figure 4.3.

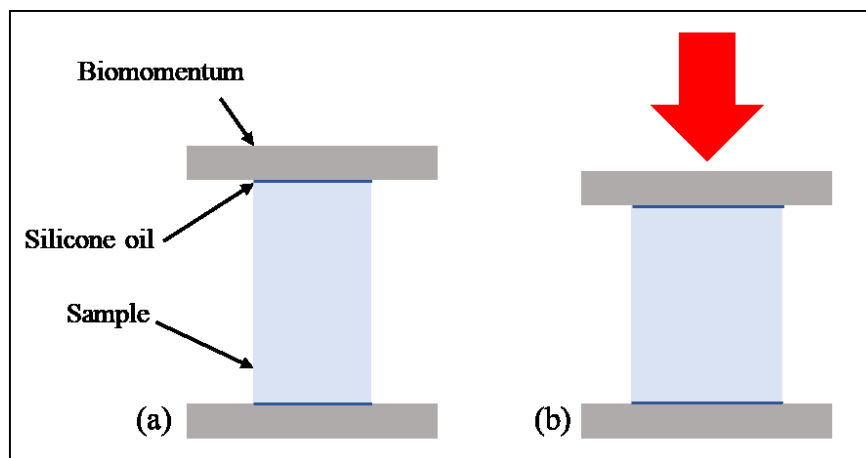


Figure 4.5: Material sample in Biomomentum (a) before loading (b) after 10 % compression

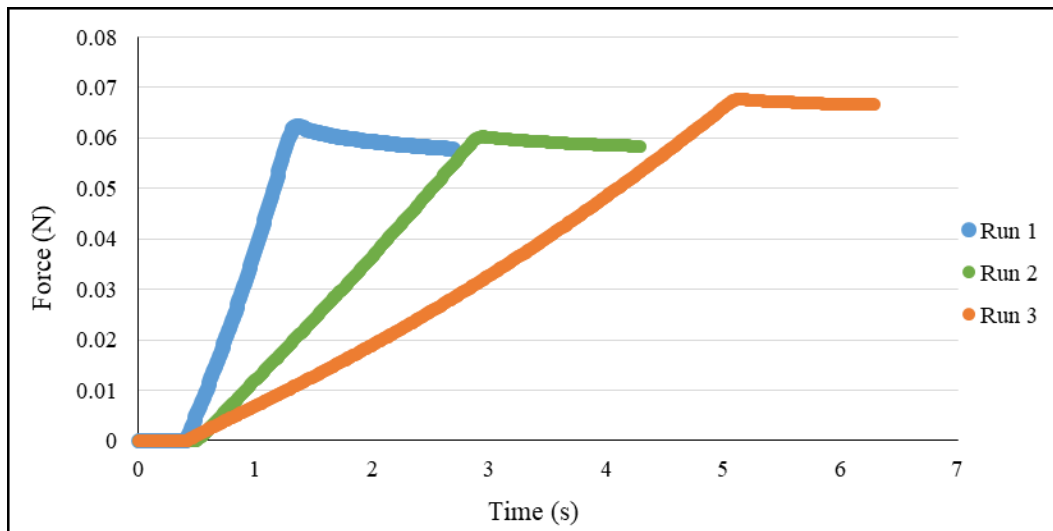


Figure 4.6: Biomomentum raw data for 10 wt. % gelatine gel

4.3.2. Rheometer

A HR-1 rheometer (TA Instruments, U.S.A.) was used to measure the rheology of the test fluids. The lubricants were tested at 25 °C under a shear rate ramp from 1000 s^{-1} to 3000 s^{-1} . Figure 4.7 shows the results from the shear rate sweep with respect to lubricant viscosity. It shows that the Newtonian fluids show a small decrease viscosity as shear rate increases and significant shear thinning is seen for xanthan gum.

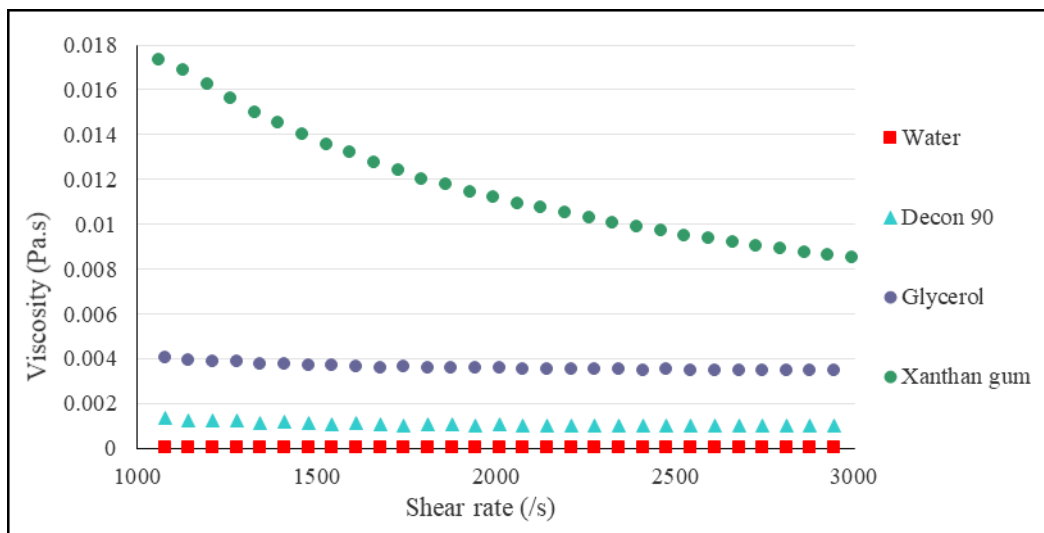


Figure 4.7: Viscosity of reference fluids for shear rate sweep

Figure 4.8 shows the viscosity results for PEO solutions at increasing shear rate. The majority of elastic liquids are polymers and therefore shear thinning [22]. Shear thinning is generally attributed to a structural breakdown in the fluid, but there is also a close association with viscoelasticity [23]. Within the viscoelastic properties, the influence of the shear thinning viscosity dominates the effects due to fluid elasticity [24], which agrees with the increasing shear effects for increased molecular weight.

Liquid elasticity is related to extension of polymer chains and Brownian motion of the solvent [22]. Brownian motion is the random motion of particles suspended in a fluid, which results in collisions between said particles and the molecules within the liquid. This opposes stretching and alignment of chains by acting to keep them in random configurations, and in fluid flow the level of extension is determined by the extent to which viscous forces dominate the forces due to Brownian motion [22] i.e. the greater the fluid viscosity, the less influential Brownian motion is on the extension of polymer chains. This is shown in Figure 4.6 for 5×10^6 g/mol M_w PEO: as the viscosity influence reduces, data becomes more scattered as the elasticity becomes more dominant. When an applied stress is removed, the polymer chains relax to their equilibrium state and this is visible at macroscopic level as elastic recoil. The rate of stress relaxation is determined by the fluid's relaxation time, which is a measure of fluid elasticity [22].

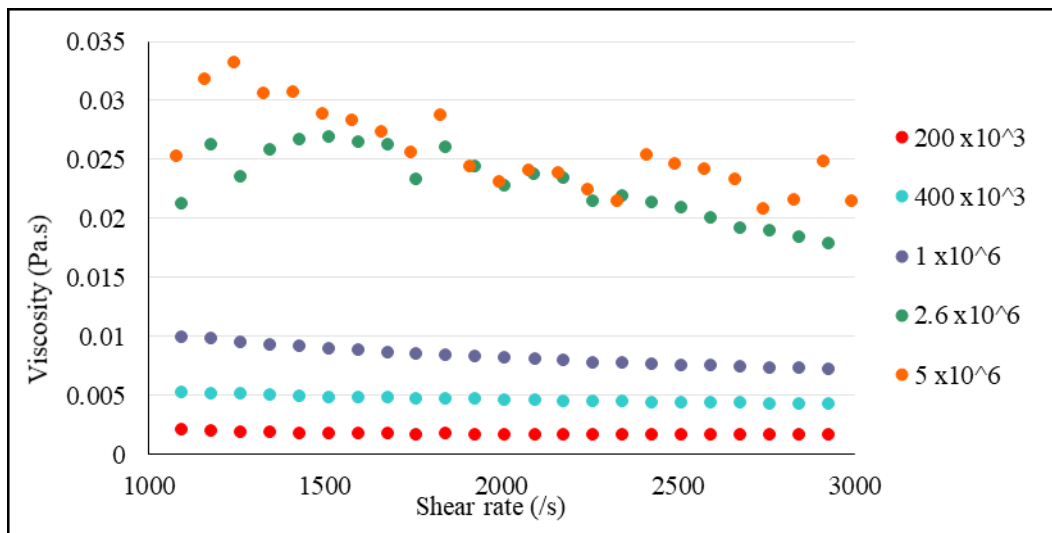


Figure 4.8: Viscosity of PEO solutions for shear rate sweep

2.6×10^6 and 5×10^6 g/mol M_w PEO shear thin with increasing shear rate, but the thinning is erratic and linked to the strong viscoelastic properties. This is because fluid elasticity also causes shear flow

instability, whereas simple shear flow of a Newtonian fluid is stable at all speeds (until inertia becomes relevant) [25, 26]. An apparent increase in viscosity is seen at a shear rate above that of the critical shear rate of a viscoelastic fluid [25, 26], and this behaviour is strongly linked to instability [27]. Instability is created by the normal stress from the polymer in the direction of shear, causing the local adverse pressure gradient to increase and resulting in secondary or unstable flow [22]. This behaviour is not seen in Newtonian fluids, and is therefore caused by fluid elasticity [27]. As the molecular weights of the PEO solutions decrease, so do the elastic effects and the fluids appear to behave more like Newtonian fluids than viscoelastic.

Table 4.7 lists the viscosity for each lubricant at 1000 s^{-1} and 3000 s^{-1} , which are approximated to the low and high shaving speeds used in this project (50 and 150 mm/s). This simplified approximation was made using the average assumed film thickness for $1 \times 10^6 \text{ g/mol}$ M_w PEO solution in the razor cartridge/skin contact of $50 \text{ }\mu\text{m}$ (P&G) in Equation 4.1.

$$\gamma = \frac{u}{h} \quad (4.1)$$

The effect of speed on viscosity is important during shaving as any changes in viscosity can affect the lubrication behaviour. The results from the shear speed sweeps show that all of the experimental lubricants show shear thinning effects when exposed to increasing shear rates.

Table 4.7: Viscosity measurements for experimental solutions

Solution	Viscosity at 1000 s ⁻¹ (mPa.s)	Viscosity at 3000 s ⁻¹ (mPa.s)	Change in viscosity (%)
Distilled water	0.89	0.71	25
Decon 90	1.28	0.97	32
Glycerol	4.05	3.45	17
Xanthan gum	17.32	8.53	103
200 x10 ³ g/mol M _w	2.17	1.63	33
400 x10 ³ g/mol M _w	5.35	4.25	26
1 x10 ⁶ g/mol M _w	10.25	7.16	43
2.6 x10 ⁶ g/mol M _w	25.02	17.99	39
5 x10 ⁶ g/mol M _w	31.81	21.50	48

The viscosity of Decon 90 solution is not significantly greater than distilled water despite the presence of detergent molecules, and is due to slip at the wall from these molecules. Slip occurs in a two-phase lubricant due to the displacement of the disperse phase away from the walls, resulting in a lower-viscosity, depleted layer of fluid at this boundary [28]. Dilute surfactant solutions such as Decon 90 solution are very sensitive to shearing [29], and a shear induced phase can induce slip in these solutions [30].

4.4. Cleaning methods

Before testing all samples were cleaned thoroughly to standardise results and remove any surface contamination. Samples were treated depending on the material properties.

All materials were washed first with boiling water, followed by an aqueous solution of Decon 90 (2 wt. %) and then rinsed with deionised water. Stainless steel, PTFE, glass and silicone elastomer surfaces were then cleaned with isopropanol, submerged in isopropanol and placed into an ultrasonic bath for 15 minutes. PDMS was submerged in deionised water and placed into an ultrasonic bath for 15 minutes. The materials were then patted dry and plasma cleaned using an Atto Plasma Laboratory Unit (Diener

Electronic, Germany) to remove any remaining organic contamination and increase hydrophilicity. Increased hydrophilicity encourages water-based fluid entrainment into the contact and reducing wetting effects on lubricant supply.

Plasma cleaning removes impurities and contaminants from a surface, using a dielectric barrier discharge (DBD) plasma created from gaseous species such as argon and oxygen. This process changes the surface chemistry of PDMS and produces silanol terminations (SiOH) on its surface, making PDMS hydrophilic for approximately thirty minutes [1]. Increasing the hydrophilic surface properties encourages fluid entrainment into the contact, and the improved properties can be demonstrated by measuring the contact angle of a drop of water on its surface: the contact angle of PDMS before plasma cleaning is 75°, and 26° after cleaning.

4.5. Friction measurements

Friction was measured using an MTM, and test profiles were developed to assess the potential suitability of lubricants to a shaving contact and identify lubricant properties. One reason for developing a friction measurement technique is to provide P&G with an improved method for screening shaving lubricants. P&G currently use an MTM, so using the same rig in this research project will both make the findings more relevant to P&G, and allow them to adopt the techniques for their own development. The MTM can operate across a range of sliding-rolling ratios, as well as in pure sliding. Although shaving is a pure sliding contact, it may be beneficial to use both contacts to analyse the lubricant behaviour.

4.5.1. MTM data processing

Chapter 5 shows the results for MTM friction tests between a steel ball or Lubrastrip and a PDMS disc (test conditions are described in further detail in Chapter 5). For each contact condition, 12 repeat runs were conducted. Figure 4.9a shows repeat runs for Decon 90 solution lubricating a sliding-rolling ball/disc contact. Three runs only have been shown for clarity, and variation between runs was typical for all lubricants. The sliding speed and friction coefficient data were each averaged and plotted against each other to produce the results presented in Chapter 5, an example of which is shown in Figure 4.9b.

Averaging the data made it simpler to identify lubricant behaviour, and allowed for clearer comparisons between lubricants.

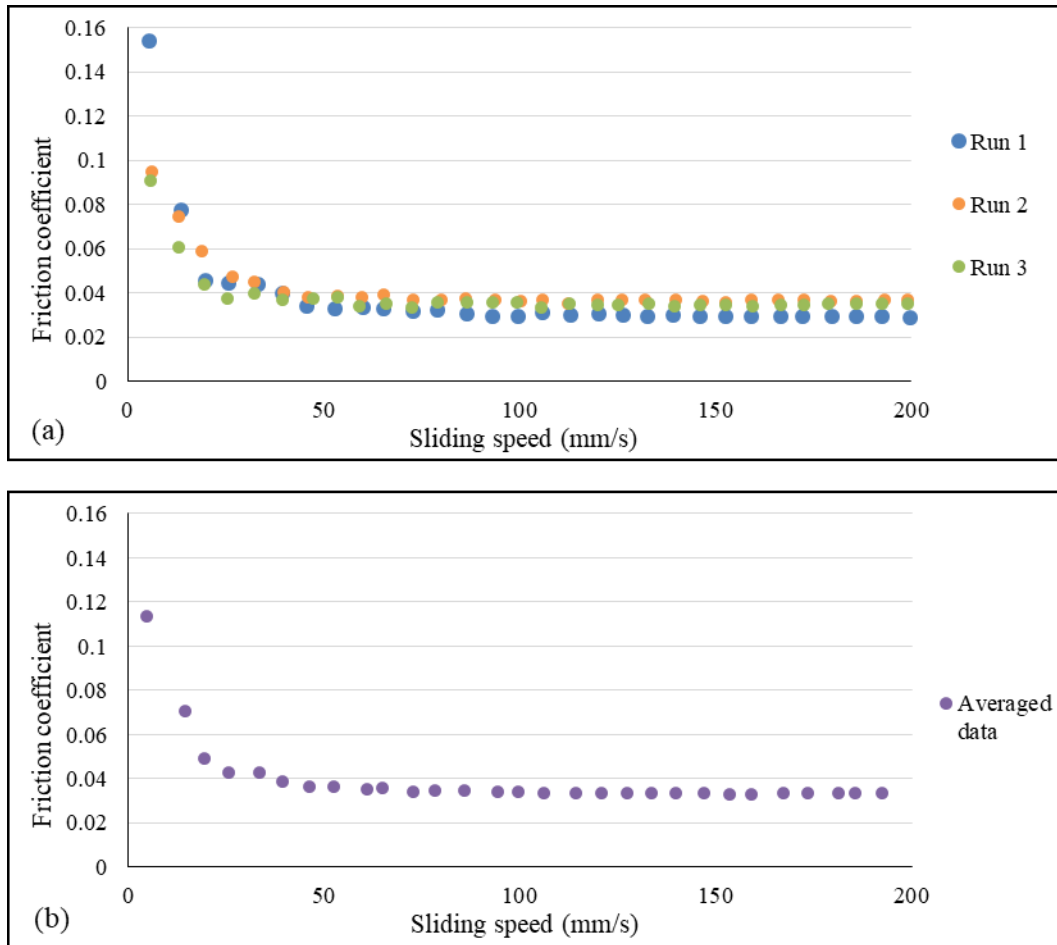


Figure 4.9: Raw data and averaged results for 2 wt. % Decon 90 solution lubricating a sliding-rolling contact

4.6. Theoretical lubricant film thickness

The razor cartridge contact geometry is highly complex, and as a result very simple theoretical calculations can only be used as a guide to the lubrication level and as to the validity of experimental results. The majority of previous experimental investigations into I-EHL have focused on the frictional characteristics within the compliant contact, rather than the film thickness [31]. Although this has demonstrated how lubrication regimes can be controlled by varying contact parameters, without knowing the film thickness it is difficult to determine the shear rate acting on the fluid film or the true tribological mechanisms controlling the lubrication regime boundaries [31].

One method of estimating the film thickness in the contact is to use Hooke's I-EHL central film thickness equation (Equation 4.2) [32], which can be applied to situations where the compliant materials in the contact produce elastic deformation, but maintain such a low pressure in the contact that pressure thickening of the lubricant does not occur [33].

$$h = 4.18 \frac{(u\eta)^{0.6} R^{0.67}}{W^{0.18} E'^{0.47}} \quad (4.2)$$

The equation demonstrates the dependence of film thickness on speed, as well as viscosity. This is relevant because the speed at which a user shaves is likely to change depending on which part of their face they are shaving i.e. more difficult areas such as the chin and jaw bone will require a lower speed than the large flat area of the cheek. However, EHL theory assumes continuum mechanics and ignores effects of wear, wear debris and chemical interactions [34], which may have an effect on lubrication of the shaving contact.

4.7. Contact pressures

MTM and initial LIF experiments use a ball on disc contact to measure friction and film thickness respectively. Contact area is calculated using JKR Theory (Equation 4.3) for a ball on plate contact, where the radius is related to the applied load and surface energy. Maximum theoretical contact pressure for a ball-on-disc setup can be calculated using the Hertzian contact equation (Equation 4.4).

$$a_{JKR} = \left\{ \frac{3R}{4E'} \left[W_{appl} + 3\pi R\Delta\gamma + \left(6\pi\Delta\gamma R W_{appl} + (3\pi R\Delta\gamma)^2 \right)^{\frac{1}{2}} \right]^{\frac{1}{3}} \right\} \quad (4.3)$$

$$P_{max} = \frac{3W}{2\pi a^2} \quad (4.4)$$

4.8. References

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5. MTM FRICTION MEASUREMENTS OF SHAVING PREPARATION FLUIDS

Summary

A conventional ball-on-disc test device was used to measure traction properties of shaving preparation fluids. Comparison is made between Newtonian, shear thinning and viscoelastic fluids, the latter of which are used in the razor cartridge on-board lubrication system. The shaving contact was simulated by a steel ball sliding against a silicone disc. Two lubricant supply levels were investigated: excess and restricted which was designed to simulate shaving prep use. Measurements were also made for Lubrastrip friction and to study the effect of skin surface chemistry (by use of an artificial sebum coating on the skin mimic). Pure sliding tests produced poor repeatability and some fluids showed surface wetting problems in this condition. Load was found to have an effect on both the magnitude of friction and response to sliding speed. Restricting the lubricant quantity with a scraper reduced starvation in high viscosity fluids by replenishing lubricant back into the track. All test fluids were found to lubricate in the full film regime; low viscosity fluids showed a decrease in friction with increased sliding speed, high viscosity fluids showed an increase in friction with increased sliding speed that was not caused by starvation. Surface chemistry can have implications for lubrication, and higher molecular weight PEO solutions were the only test fluids where friction did not increase with sebum presence. Decon 90 detergent solution was very effective at removing sebum from the disc surface. Optimum Lubrastrip lubrication occurred with hydration at 150 mm/s sliding speed. For all conditions (dry/hydrated, 50 and 150 mm/s sliding speed) minimum friction was reached after 25 m.

5.1. Introduction

Friction between the skin and razor cartridge has a significant impact on perceived comfort during shaving. It is therefore important to understand the effect of shaving prep fluid quantity and speed (two factors which can change considerably during shaving) on the friction coefficient and lubrication. The

friction coefficient for different shaving lubricants will be measured using a Mini Traction Machine 2 (MTM) (PCS Instruments, UK) for a range of operating conditions. The razor cartridge/skin contact is simulated by a stainless steel ball loaded against a PDMS disc. Although this is a poor simulation of the cartridge contact, it is a simple interface currently used by P&G for the screening of potential shaving lubricants. The intention of this Chapter is to understand the friction response of different prep fluids and study the effect of different test protocols, developing an improved methodology. Previous studies [1-5] have used the MTM device for measurement of compliant surfaces lubricated by aqueous solutions. Myant et al. [1] and Vicente et al. [5] studied the properties of compliant contacts lubricated by Newtonian fluids. Other studies have had applications in cosmetics [2], oral processing [3] and biological contacts [4].

The MTM measures fluid traction in the contact interface, outputting a friction coefficient, and it can simulate a variety of different contact conditions. In a standard set up (Figure 5.1) the contact is between a 19.05 mm diameter ball and a 46 mm diameter disc. The ball is loaded against the disc and both ball and disc are driven independently to create a mixed rolling-sliding contact. The friction force within the contact is measured by a force transducer, whilst additional sensors measure the applied load and temperature. The control software runs on a PC and allows the user to define test profiles [6], which set the load, speed, slide-roll ratio and temperature conditions.

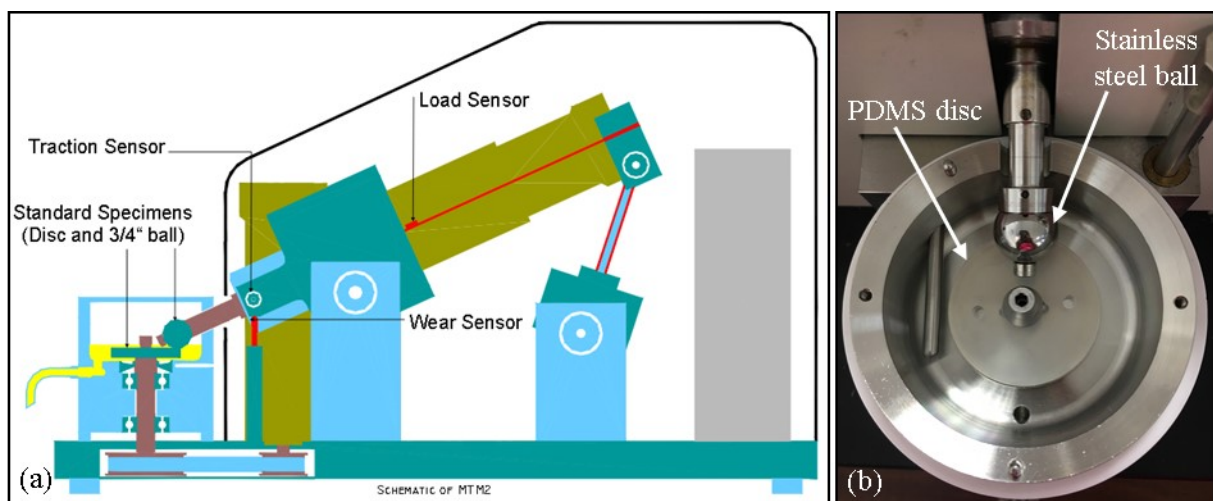


Figure 5.1: MTM setup: (a) schematic [6] (b) specimen layout

However issues with repeatability of results can occur when a pure sliding profile is used [1]. In pure sliding, the ball remains stationary whilst the disc moves, which can contribute to an offset in load cell (attached to the ball drive shaft). In a slide-roll-ratio profile, friction measurements are averaged from two successive measurements from the load cell at the same entrainment speed: one with the ball travelling faster than the disc and a second with the disc travelling faster than the ball. This cancels any offset in the load cell.

5.2. Contact conditions

5.2.1. MTM specimens

In these experiments a stainless steel ball (stainless so as to resist corrosion by aqueous lubricants) was used as a razor blade mimic, and the counterface disc is made of PDMS (PDMS LSR 4330 A/B), as described in Chapter 4, which acts as a skin mimic (Figure 5.1 (b)). This PDMS is an elastomer particularly suited for use as a skin mimic as its mechanical properties are comparable with skin (mechanical properties are listed in Chapter 4). It is manufactured by Bluestar Silicones, and supplied by PCS Instruments UK.

5.2.2. MTM test profiles

Procter & Gamble, UK (P&G) have two standard MTM test profiles designed to screen potential shaving lubricants for their suitability (Table 5.1).

Table 5.1: P&G MTM test profiles

Test profile	Fluid quantity	SRR* (%)	Sliding speed (mm/s)		Load (N)	Temperature (°C)	Contact pressure (MPa)
			Min.	Max.			
P&G 1	Excess fluid	200	10	500	5	25	536.30
P&G 2	Excess fluid	200	150	150	5	25	536.30

*Slide/Roll Ratio (SRR) is defined in Equation 5.1, and in pure sliding SRR = 200 %.

$$SRR = 200 \times \frac{|u_1 - u_2|}{(u_1 + u_2)} \quad (5.1)$$

Although these profiles allow simple comparison between different lubricants, the test conditions do not represent a “real life” simulation of shaving. Some differences are outlined below:

- A razor cartridge creates a line contact with the skin, not a point contact, as seen in the typical ball-on-disc arrangement.
- Lubricant supply levels are restricted by the guard, and as a result fully flooded bulk fluid conditions rarely occur (aside from the initial stroke).
- Cartridge load may vary across different areas of the face, as opposed to a static load.
- Speed changes across different areas of the face.
 - The speed range is typically between 10-200 mm/s sliding speed, with an average shaving speed of 150 mm/s.
- Temperature is difficult to quantify, as factors such as presence of water (hot or cold), room temperature and skin temperature will affect this.

To produce more realistic test profiles, P&G’s profiles were built up in complexity to produce three new test profiles relatable to “real life” shaving. Four parameters were chosen for improvement, which are listed below. For simplicity, the contact remains a point contact and temperature is maintained and 25 °C.

1. Two lubricant supply levels were used:

- Excess fluid
 - Represents the shaving lubricant when first applied, during the initial razor stroke
- b) Restricted fluid
 - This replicates the effect of the guard on a razor cartridge, which reduces film thickness of the lubricant entering the razor cartridge contact
- 0.5 ml of lubricant is applied to the disc using a pipette
- A scraper is incorporated into the MTM setup (Figure 5.2), which restricts the film thickness to 100 μm before entering the contact

- The scraper also channels lubricant back onto the track after it has passed through the contact, reducing starvation effects

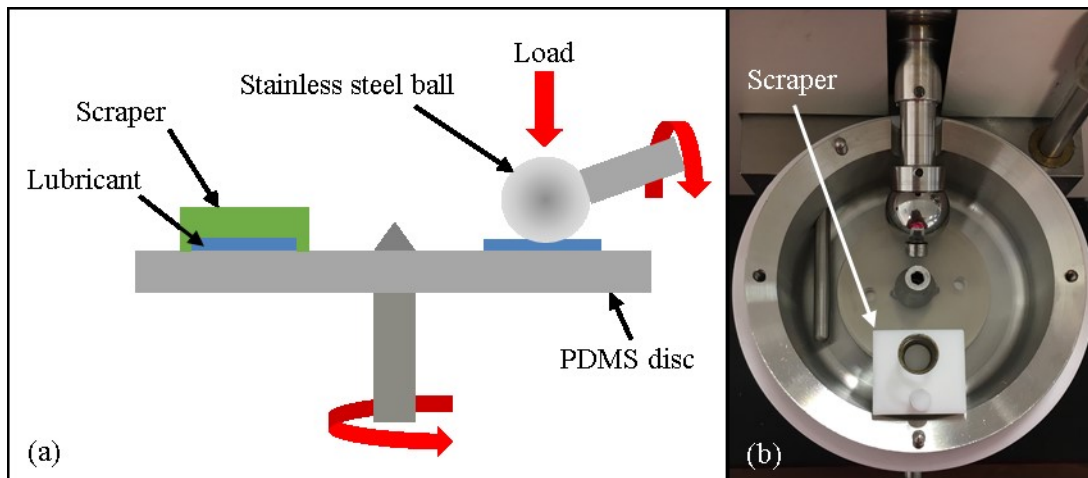


Figure 5.2: MTM setup with scraper (a) schematic (b) layout in MTM pot

2. Consideration of skin surface chemistry

- Artificial sebum has been developed for application to the PDMS disc (detailed in Chapter 4), which will mimic skin surface chemistry

3. Speed sweeps (10-200 mm/s) to analyse lubrication regimes across a representative speed range.

- This included the addition of a 100 % SRR profile

4. The Lubrastrip friction was measured directly by replacing the steel ball with a Lubrastrip.

- Further details on Lubrastrip experimental setup are provided in section 5.2.3.

Ideally, the ball would also be replaced with a line contact, to better represent a razor blade. A decision was made to maintain the ball-on-disc contact for comparability with other studies and to create a simple contact for initial analysis of the PEO solutions.

The three modified test profiles are described in Table 5.2. These profiles were designed to be more representative of shaving than P&G's previous standard profiles, and using both pure sliding and sliding/rolling contacts will indicate the suitability of each contact for shaving prep screening. Each

profile contained 6 repeat runs, with a 5 minute pause between run 3 and run 4 – this pause was to allow the lubricants to relax before the subsequent three repeats – and each profile was run twice.

Table 5.2: MTM test profiles

Test profile	Fluid quantity	SRR (%)	Sliding speed (mm/s)		Load (N)	Temperature (°C)	Contact pressure (MPa)
			Min.	Max.			
1	Excess fluid	200	10	200	2.5	25	268.15
2	Restricted fluid	200	10	200	2.5	25	268.15
3	Excess fluid	100	10	200	2.5	25	268.15

5.2.3. Lubrastrip

The Lubrastrip is the on-board lubrication system for the razor cartridge and the material that it deposits will affect the friction between skin and cartridge. The lubricant present in the Lubrastrip is PEO (1×10^6 g/mol Mw), held by a polystyrene matrix.

To measure friction, the stainless steel ball was replaced with a Lubrastrip on a specially designed mount (Figure 5.3). This was angled such that the Lubrastrip would align in parallel with the disc surface. Hydration was achieved with a drip feed, depositing 0.1 ml of distilled water once a minute. This volume and flow rate of water was sufficient to maintain hydration of the Lubrastrip for the duration of the experiment. A time dependent experiment was conducted at two speeds (50 mm/s and 150 mm/s), with a temperature and load of 25 °C and 0.2 N (average load on the Lubrastrip during shaving). The Lubrastrip was not pre-soaked before testing, but placed in surface water already present on the PDMS disc to replicate shaving.

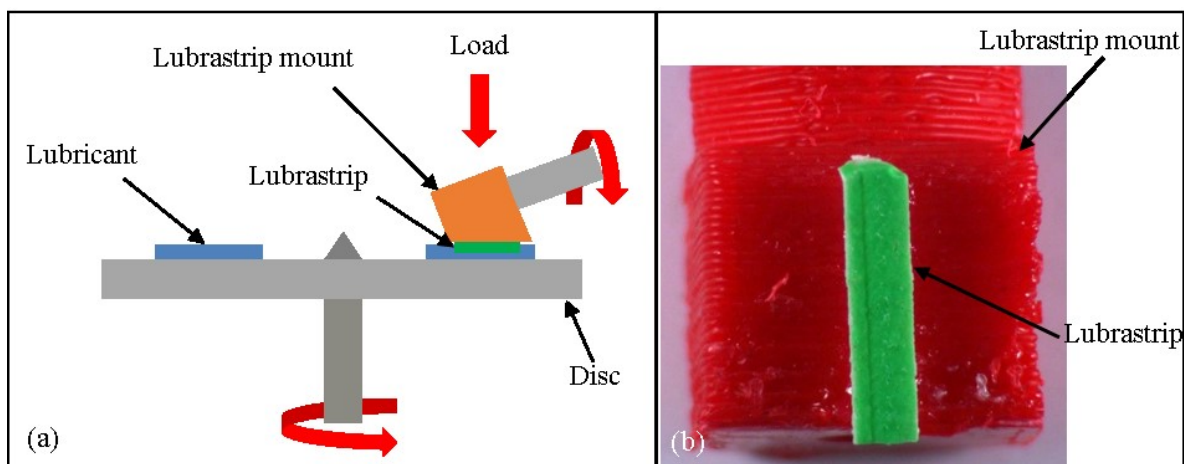


Figure 5.3: Lubrastrip mounted for MTM tests (a) schematic (b) Lubrastrip on mount

5.2.4. Lubricants

Three groups of experimental solutions were identified from their rheological properties: Newtonian, shear thinning and viscoelastic. Using a range of characterised Newtonian and shear thinning reference fluids helps understand the behaviour of viscoelastic PEO solutions and how the lubrication properties may be suited to the application of shaving. Further detail on the lubricants used in this study can be found in Chapter 4.

5.3. Results: P&G profiles

Figure 5.4 shows the results for P&G's MTM test profiles, comparing 1×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO solutions. Below 200 mm/s sliding speed (in the shaving speed range), 5×10^6 g/mol M_w PEO solution has a lower friction coefficient, but this then increases with speed to exceed 1×10^6 g/mol M_w PEO solution. Figure 5.5 (b) shows that PEO lubrication does not significantly change with time.

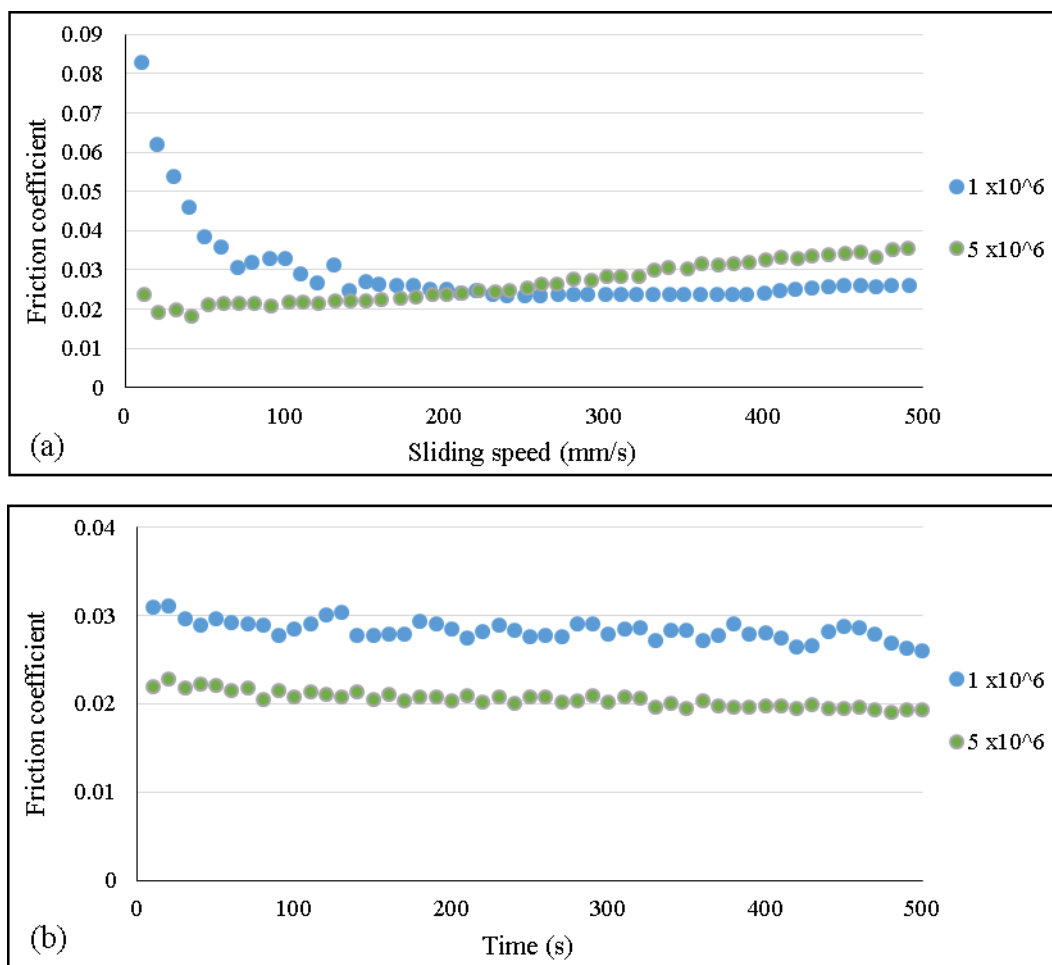


Figure 5.4: P&G profiles for 1×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO solutions (a) speed sweep (b) time dependent test at sliding speed 150 mm/s

5.4. Results: reference fluids speed sweep

Results from the reference fluid friction tests are shown in this section. The graphs compare averaged results from each contact condition: excess fluid, pure sliding; restricted fluid, pure sliding; excess fluid, sliding/rolling.

At sliding speeds above 115 mm/s, distilled water (Figure 5.5) produces a similar friction coefficient for all three conditions. At low speeds friction is higher for the sliding/rolling contact than for pure sliding contacts.

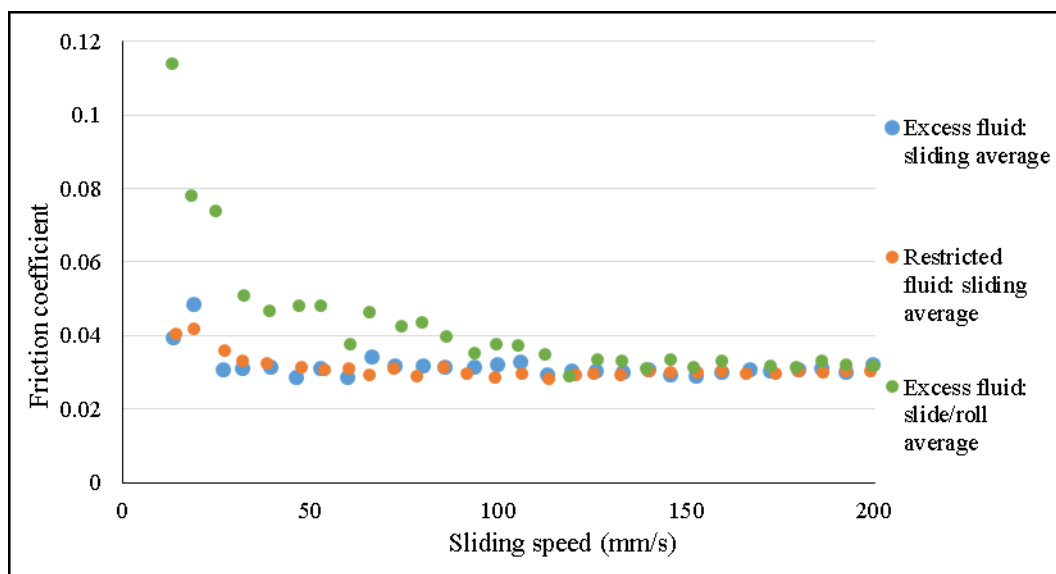


Figure 5.5: Distilled water friction results for each contact condition

The results for Decon 90 solution are shown in Figure 5.6. The coefficient of friction for distilled water is larger than that of Decon 90, despite similar viscosities.

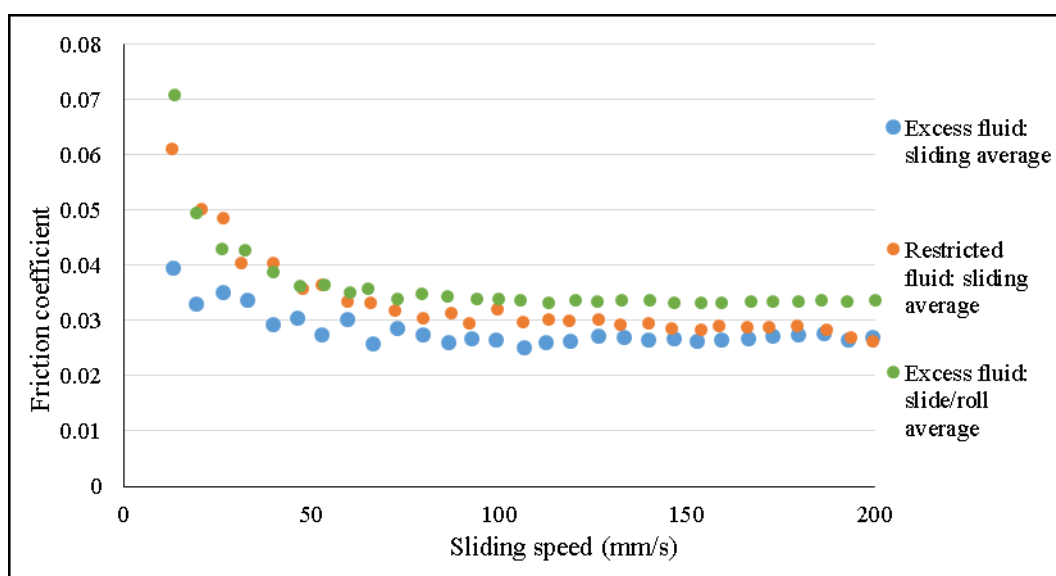


Figure 5.6: 2 wt. % Decon 90 solution friction results for each contact condition

Figures 5.7 and 5.8 show the similar response of glycerol and xanthan gum solutions to the different contact conditions. The highest friction was seen for the excess fluid, sliding contact condition – xanthan gum in particular produced very scattered and high friction results. For both lubricants, reducing the fluid quantity with the scraper or using a sliding/rolling contact produced a drop in friction. This is discussed in section 5.8.

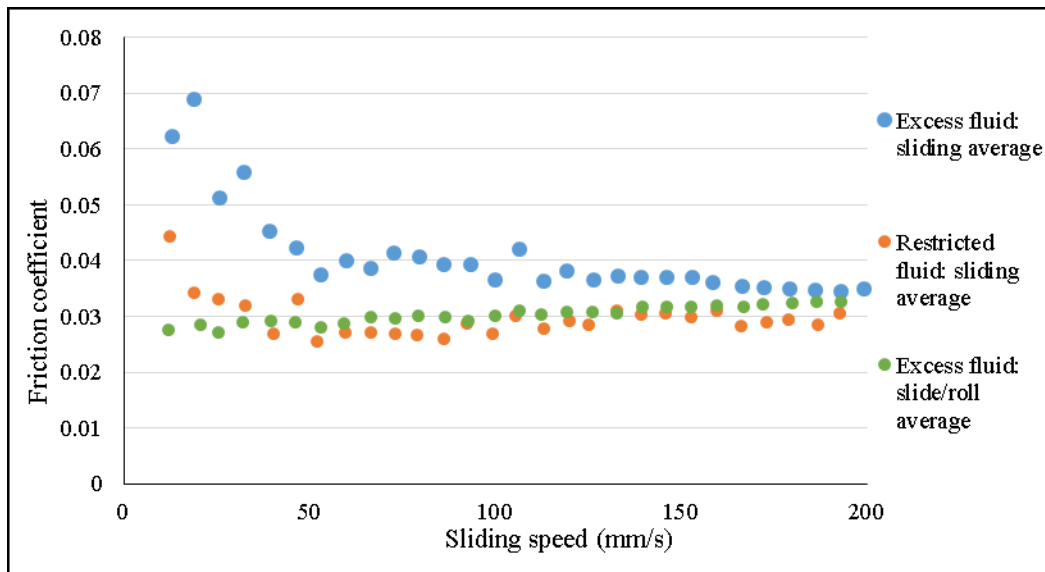


Figure 5.7: 60 wt. % glycerol solution friction results for each contact condition

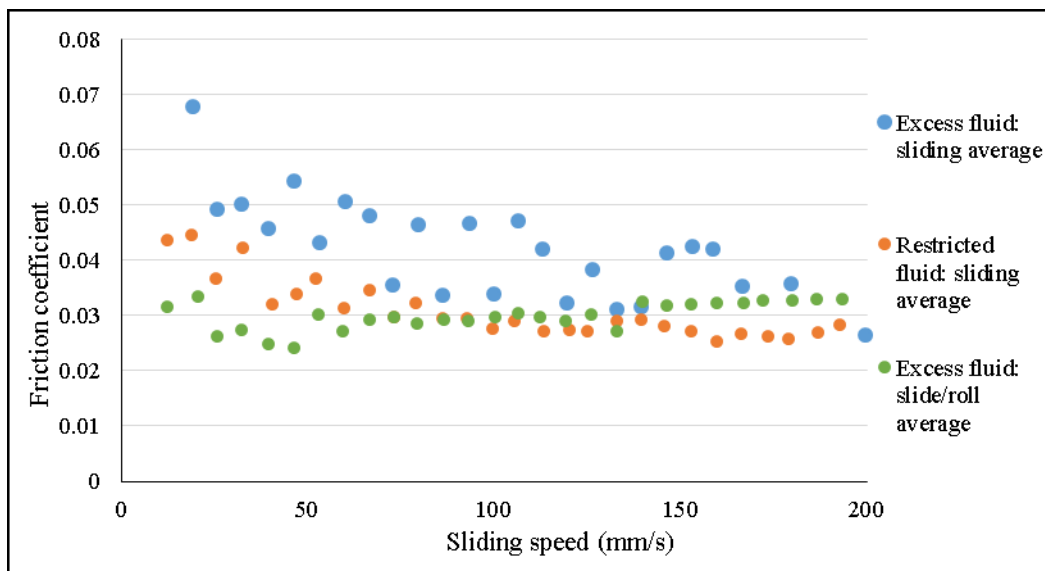


Figure 5.8: 1 wt. % xanthan gum solution friction results for each contact condition

Figure 5.9 compares the friction results for all reference fluids in each contact condition: excess fluid (sliding), restricted fluid (sliding) and excess fluid (sliding/rolling). The effect of incorporating the scraper in pure sliding conditions is to reduce the friction coefficient and results scatter of glycerol and xanthan gum solutions (those with high viscosities). Under this condition all reference fluids follow a similar friction trend. The sliding rolling results show differences between the fluids at low speeds, with distilled water and Decon 90 solution producing significantly higher friction than glycerol and xanthan gum solutions at sliding speeds below 100 mm/s.

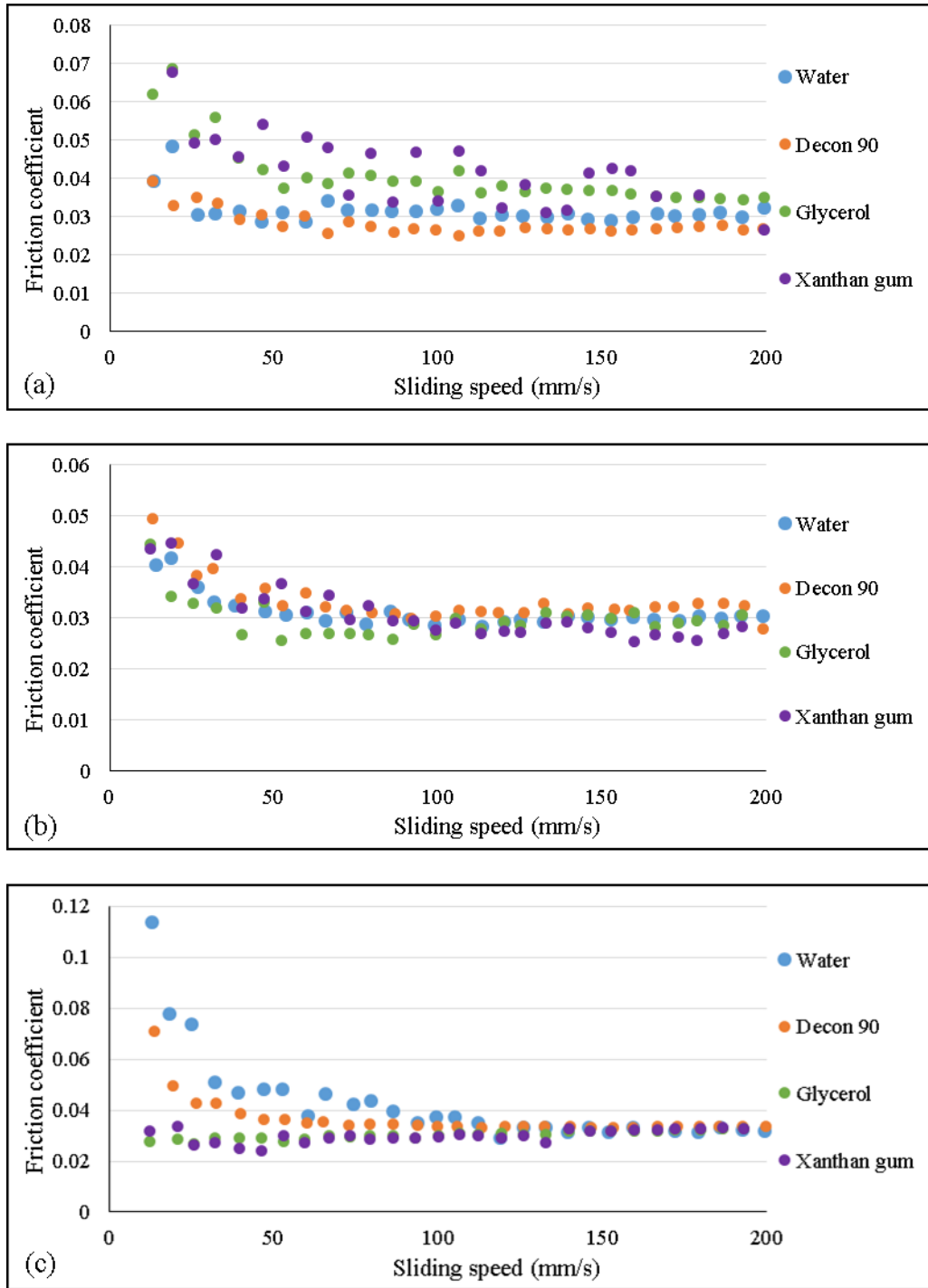


Figure 5.9: Showing friction results for reference fluids lubricating the following conditions: (a) excess fluid, sliding contact; (b) restricted fluid, sliding contact; (c) excess fluid, sliding/rolling contact

5.5. Results: PEO solutions speed sweep

Coefficient of friction is plotted against sliding speed for each PEO fluid for different test conditions (excess fluid, restricted fluid, 100% SRR) this is shown in Figure 5.10 for 200×10^3 g/mol M_w PEO

solution). The restricted fluid condition produces the lowest friction response, which is also seen for 400×10^3 g/mol M_w PEO solution (Figure 5.11).

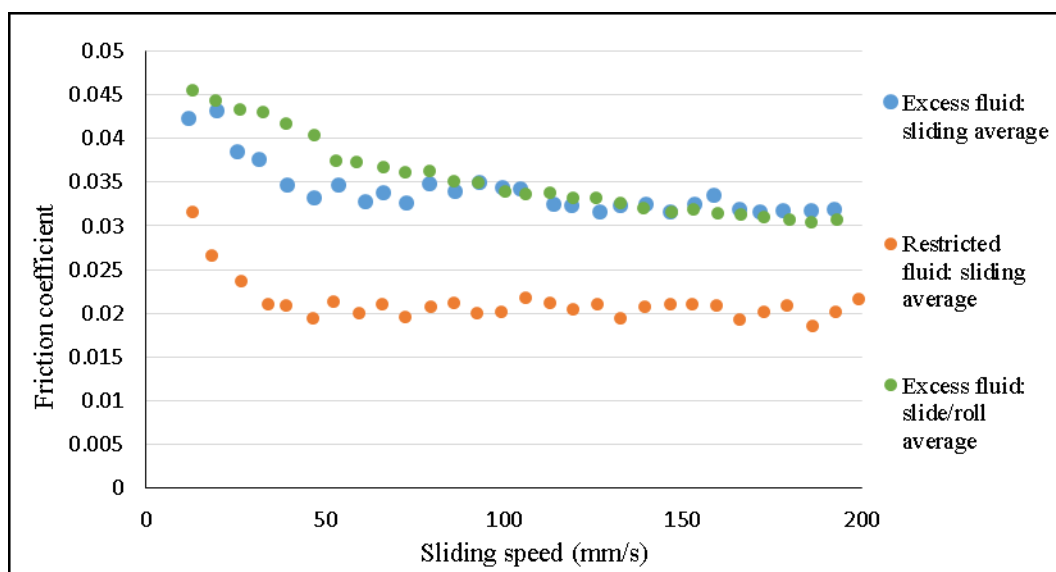


Figure 5.10: 200×10^3 g/mol M_w PEO solution friction results for each contact condition

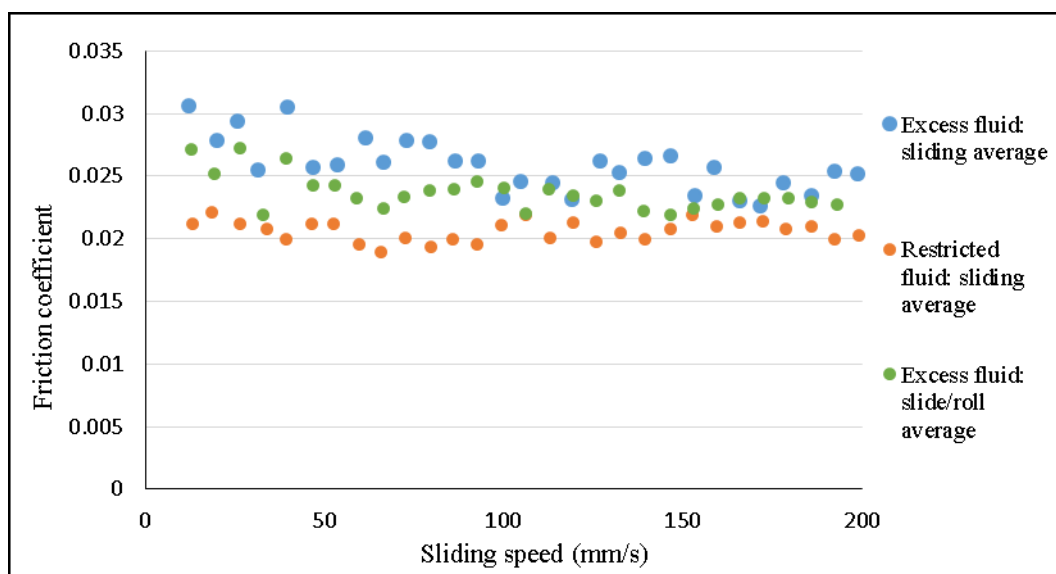


Figure 5.11: 400×10^3 g/mol M_w PEO solution friction results for each contact condition

1×10^6 g/mol M_w PEO solution (Figure 5.12) produced similar friction coefficient values for both pure sliding conditions. A drop in friction occurred for the sliding/rolling contact.

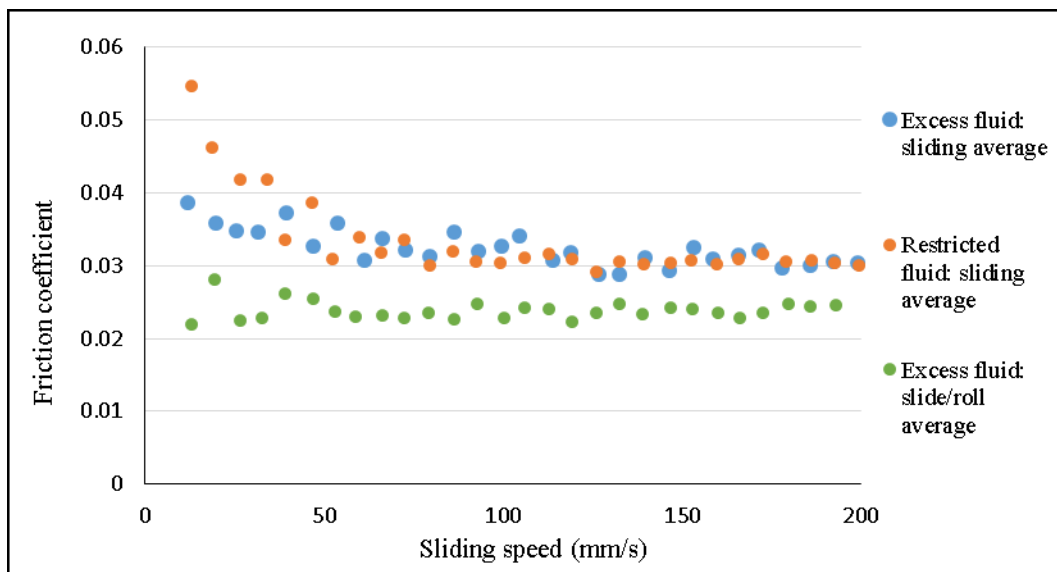


Figure 5.12: 1×10^6 g/mol M_w PEO solution friction results for each contact condition

2.6×10^6 g/mol M_w PEO solution (Figure 5.13) friction increases with sliding speed, which is not seen for PEO solutions below this molecular weight. Restricting the fluid reduces friction.

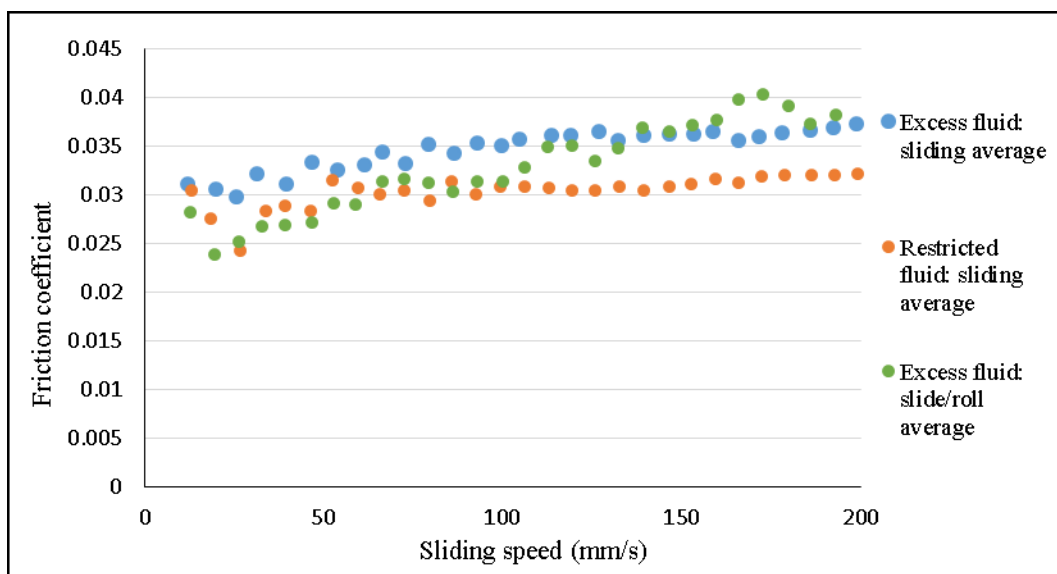


Figure 5.13: 2.6×10^6 g/mol M_w PEO solution friction results for each contact condition

Results for 5×10^6 g/mol M_w PEO solution are shown in Figure 5.14. The friction coefficient is low for the both excess fluid conditions, but results for restricted fluid are very unstable at high speeds, which may be due to lubricant starvation.

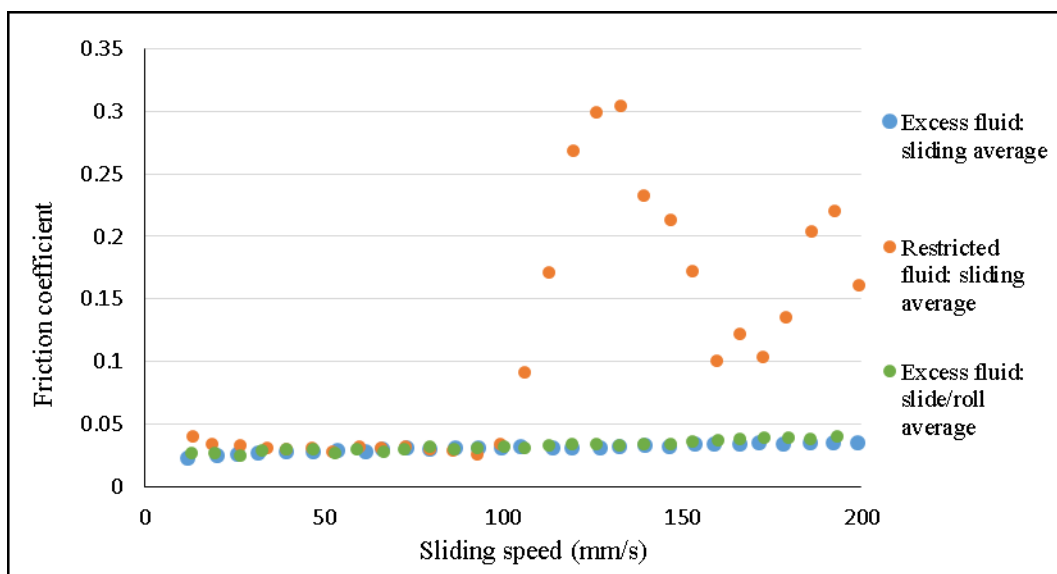


Figure 5.14: 5×10^6 g/mol M_w PEO solution friction results for each contact condition

Figure 5.15 shows the friction results for all PEO solutions in each contact condition: excess fluid (sliding), restricted fluid (sliding) and excess fluid (sliding/rolling). The effect of restricting the fluid is to reduce scatter in the results. All solutions maintain a similar friction value compared to the excess fluid (sliding) results, except for 200×10^3 g/mol M_w PEO solution where the friction coefficient decreases from ~ 0.04 to ~ 0.03 with restricted fluid.

The excess fluid (sliding/rolling) results show good definition between the PEO solutions, not present in the pure sliding results. The effect of molecular weight on friction is such that:

- 200×10^3 g/mol M_w PEO solution friction decreases with increasing sliding speed.
- 400×10^3 g/mol and 1×10^6 g/mol M_w PEO solutions maintain friction across the speed range (~ 0.24)
- 2.6×10^6 g/mol and 5×10^6 g/mol M_w PEO solutions friction increases with increasing sliding speed.

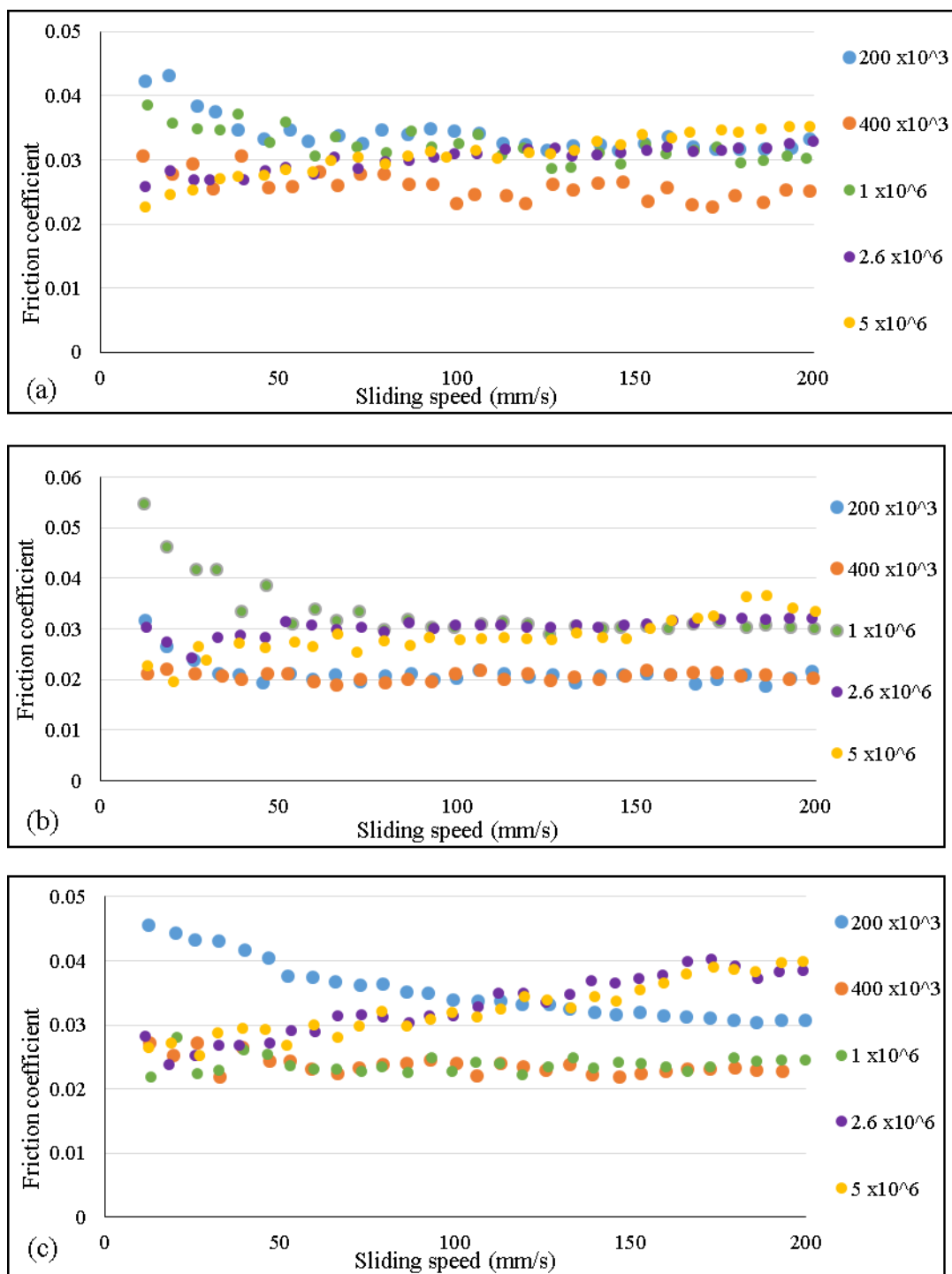


Figure 5.15: Showing friction results for PEO solutions lubricating the following conditions: (a) excess fluid, sliding contact; (b) restricted fluid, sliding contact; (c) excess fluid, sliding/rolling contact

5.6. Results: skin surface chemistry

The PDMS disc was coated with sebum (detailed in Chapter 4) to create a surface more chemically similar to skin. The results in this section show the friction response for an artificial sebum coated disc,

and an artificial sebum coated disc lubricated by the test lubricants. Figure 5.16 shows the results for artificial sebum only. The coefficient of friction increases proportionally with sliding speed ($R^2 = 0.99$).

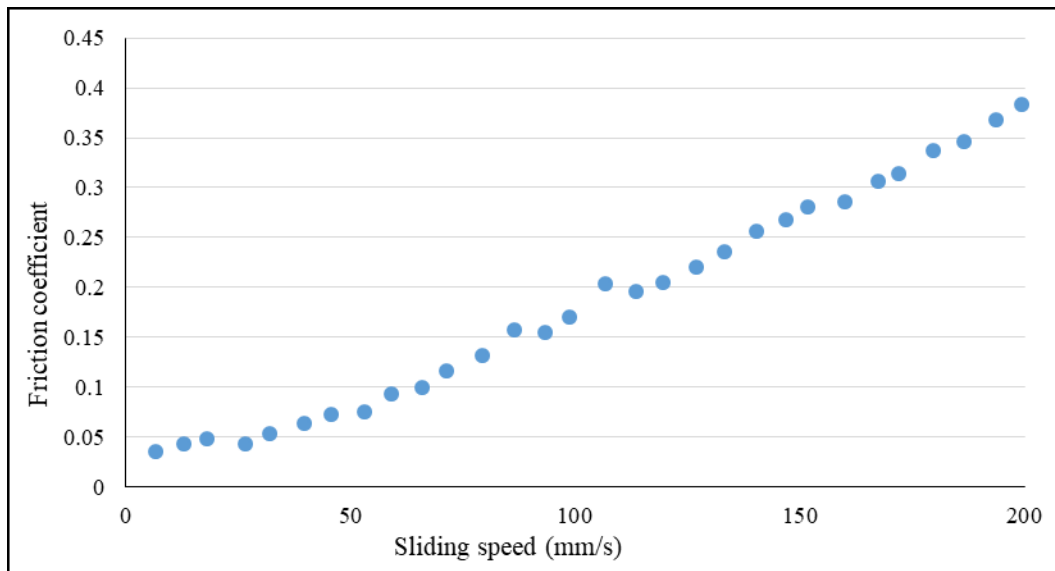


Figure 5.16: Speed sweep friction results for artificial sebum

Results shown below compare the friction coefficients for lubricants in the restricted fluid condition with a sebum coated disc and without a sebum coated disc. Glycerol and xanthan gum solutions have not been included as these are not used as shaving preps. Figures 5.17 and 5.18 show the effect of lubricating the sebum coated disc with water and Decon 90 solution respectively. The addition of distilled water to the contact produces a friction response that is relatively unaffected by sliding speed, but is approximately four times larger than when sebum is not present and the results are very variable. Decon 90 solution, however, produces the same friction response with and without sebum present. This may be due to Decon 90 removing sebum from the disc surface, showing why soap solutions are used as shaving preps.

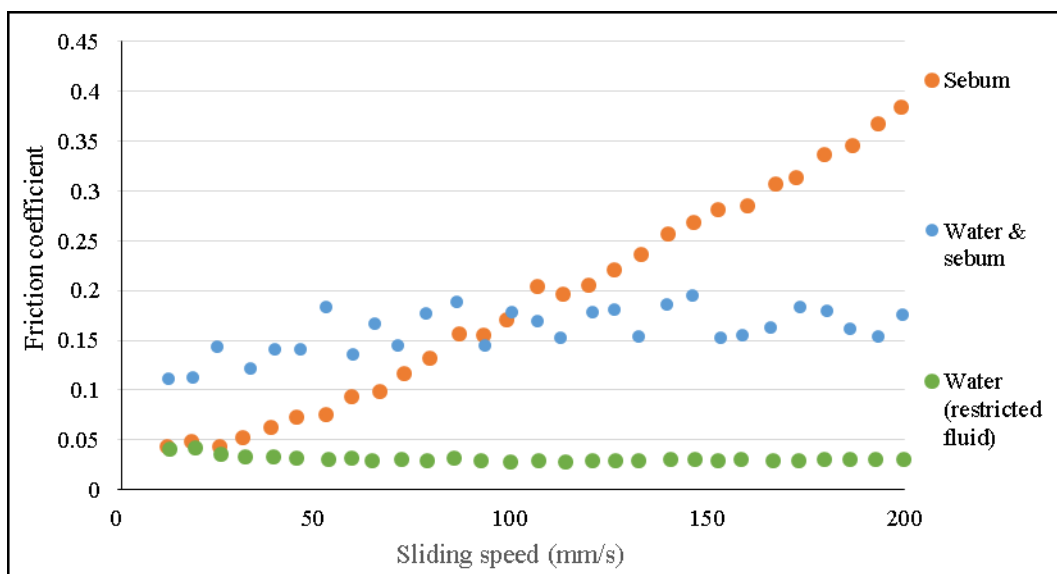


Figure 5.17: Speed sweep friction results for artificial sebum with distilled water

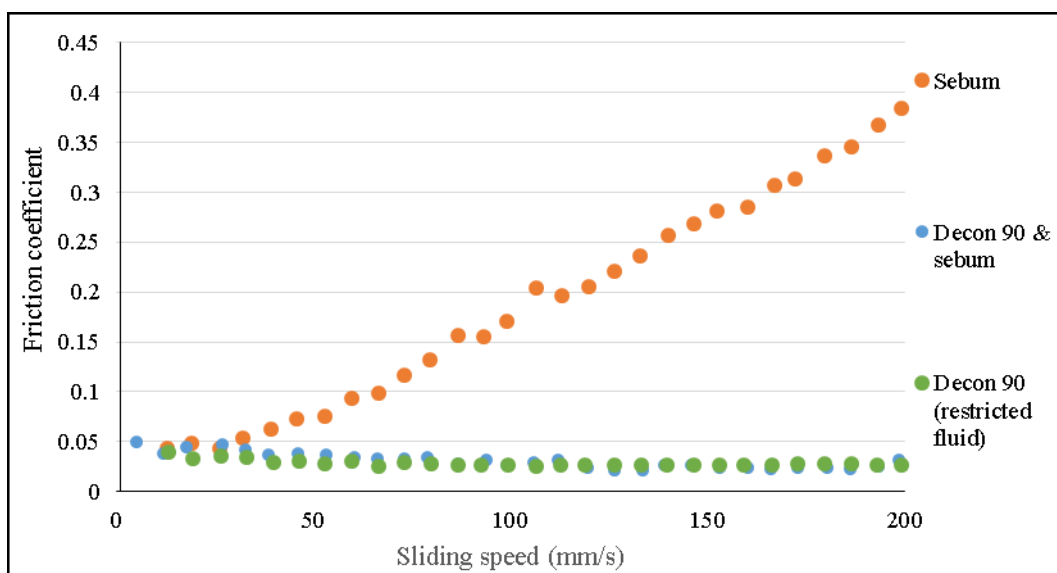


Figure 5.18: Speed sweep friction results for artificial sebum with Decon 90 solution

Figures 5.19-5.23 show the effect of artificial sebum on a PEO solution lubricated contact. The addition of sebum to the 200×10^3 g/mol M_w PEO lubricated contact (Figure 5.19) produces significant scatter and an increase in friction of up to almost four times larger than when sebum is not present.

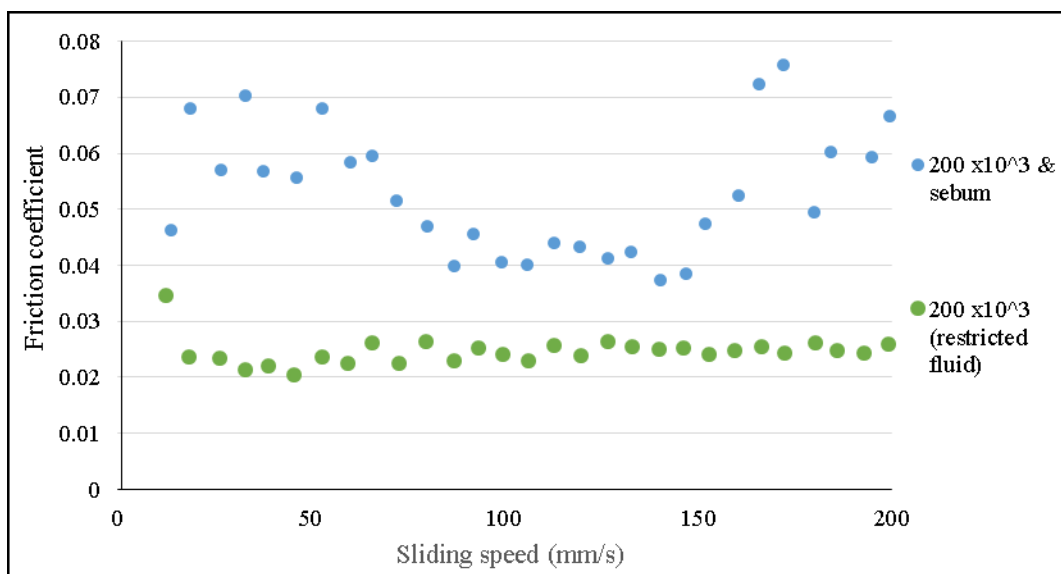


Figure 5.19: Speed sweep results for artificial sebum with 200×10^3 g/mol M_w PEO solution

For PEO solutions of 400×10^3 g/mol and 1×10^6 g/mol M_w (Figures 5.20-5.21), the presence of sebum approximately doubles the friction coefficient.

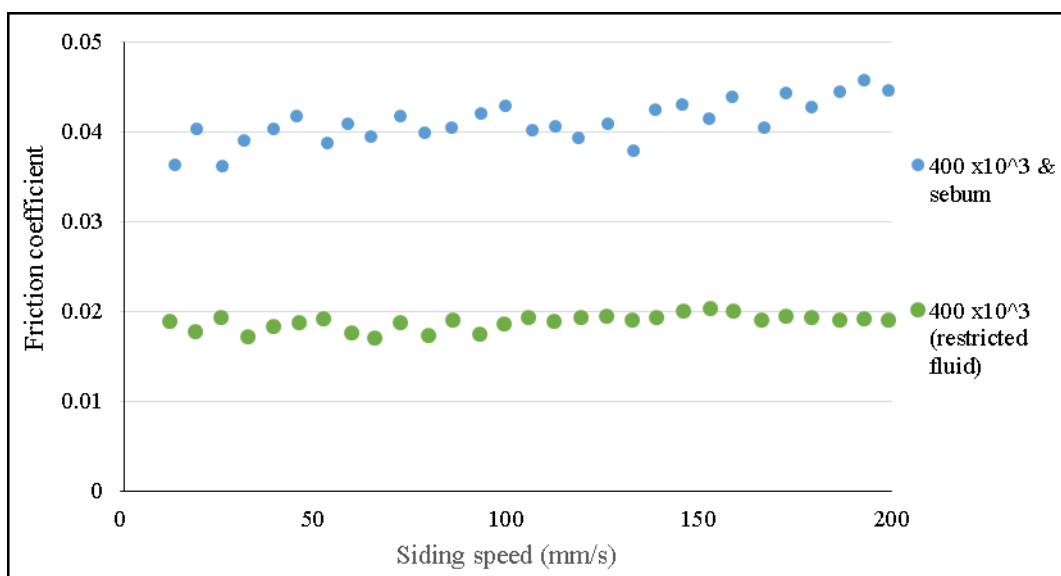


Figure 5.20: Speed sweep results for artificial sebum with 400×10^3 g/mol M_w PEO solution

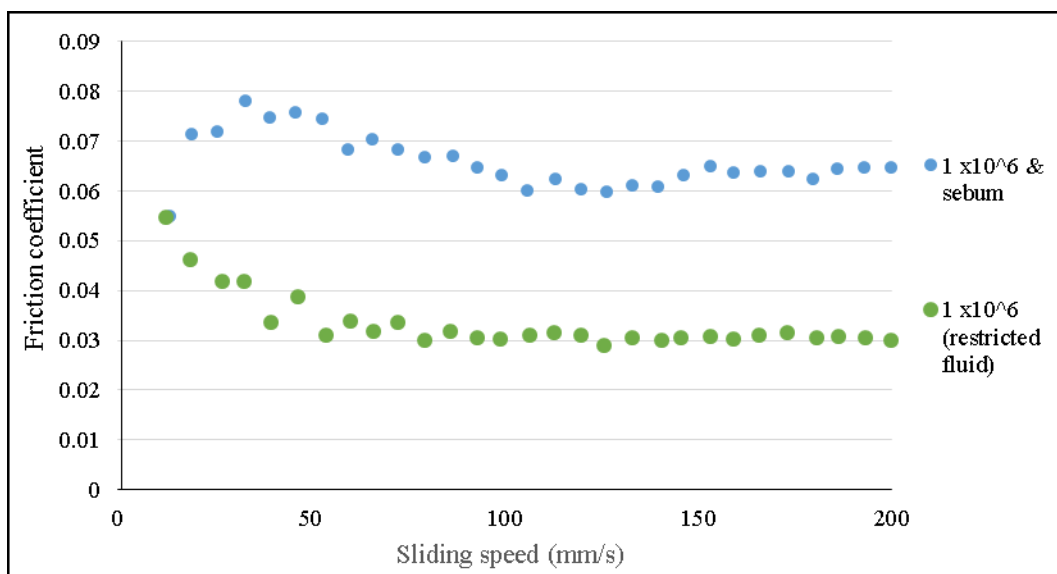


Figure 5.21: Speed sweep results for artificial sebum with 1×10^6 g/mol M_w PEO solution

Figure 5.22 shows the results for 2.6×10^6 g/mol M_w PEO solution. Here, the friction coefficient is lower with the presence of sebum, although results are variable.

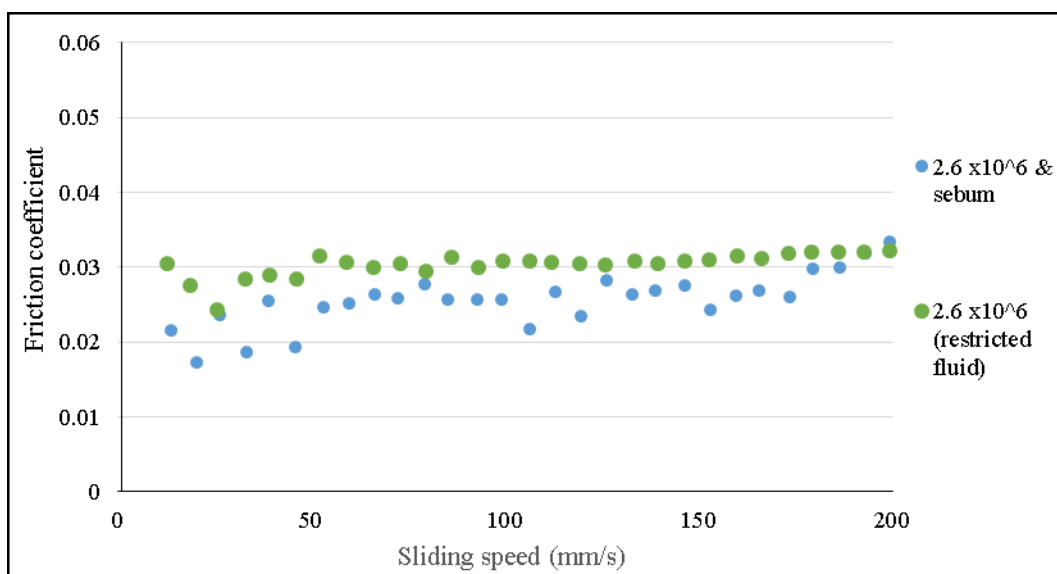


Figure 5.22: Speed sweep results for artificial sebum with 2.6×10^6 g/mol M_w PEO solution

The results for 5×10^6 g/mol M_w PEO solution are shown in Figure 5.23. Results from the excess fluid condition without artificial sebum have been presented for comparison due to starvation in the restricted fluid results (Figure 5.14). The addition of sebum reduces friction coefficient variability and at higher sliding speeds (above approximately 150 mm/s), the friction coefficient is lower than for when sebum is not present in the contact.

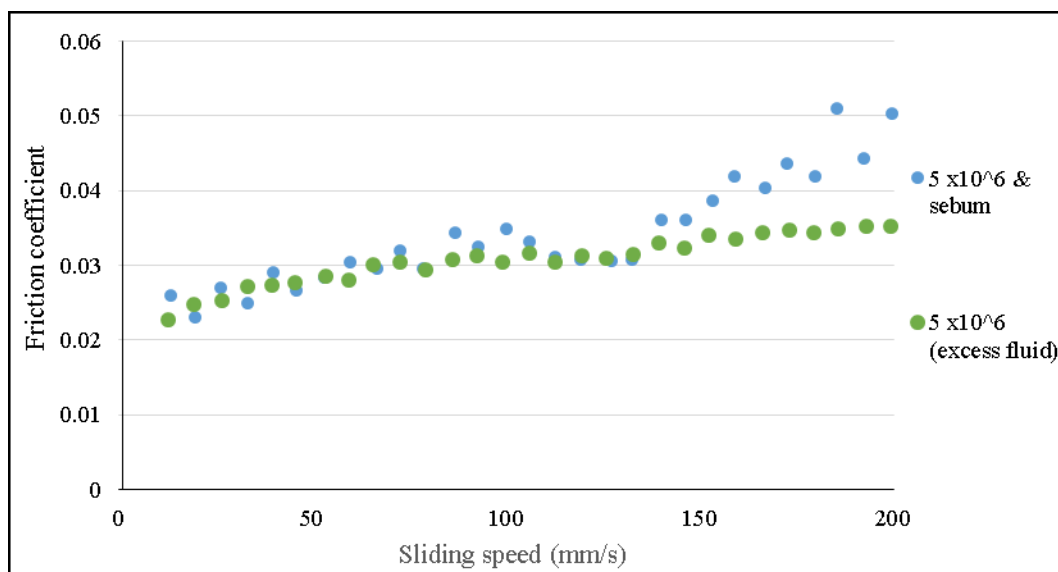


Figure 5.23: Speed sweep results for artificial sebum with 5×10^6 g/mol M_w PEO solution

5.7. Results: Lubrastrip

To measure the effect of the Lubrastrip performance on the overall cartridge friction coefficient, a time dependent test was carried out at 50 mm/s and 150 mm/s. The Lubrastrip was tested under hydrated and dry conditions. Figure 5.24 shows the effect of speed and hydration on the Lubrastrip friction. The results are plotted against sliding distance to display lubrication through the Lubrastrip's predicted lifetime. A Lubrastrip is currently required to lubricate for 10-15 shaves, which equates to approximately 10-25 m. The lowest friction is seen for the hydrated Lubrastrip at sliding speed 150 mm/s, and for all conditions the lowest friction coefficient is reached after 25 m.

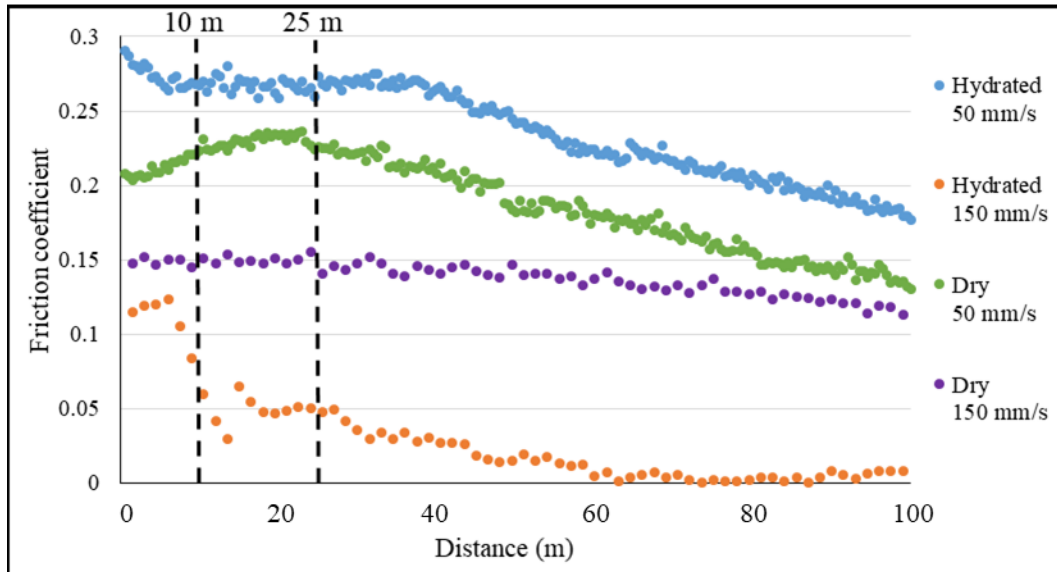


Figure 5.24: Effect of speed and hydration on Lubrastrip friction coefficient

5.8. Discussion

5.8.1. P&G profiles

The excess fluid, pure sliding condition and P&G's speed sweep test are similar in that they both employ bulk fluid, pure sliding conditions for a stainless steel ball/PDMS disc contact. The modifications made to P&G's profile were to reduce load from 5 N to 2.5 N (to align with total load on the cartridge) and cap the speed range at 200 mm/s, as speeds greater than this are irrelevant to shaving. Although these contact conditions are not directly comparable with a cartridge line contact, the results may show identifiable lubricant properties, which when paired with panel tests could be used to screen for potential shaving lubricants. Figure 5.25 shows the comparison between results from these two test profiles. Results up to sliding speed 200 mm/s only are shown for clarity.

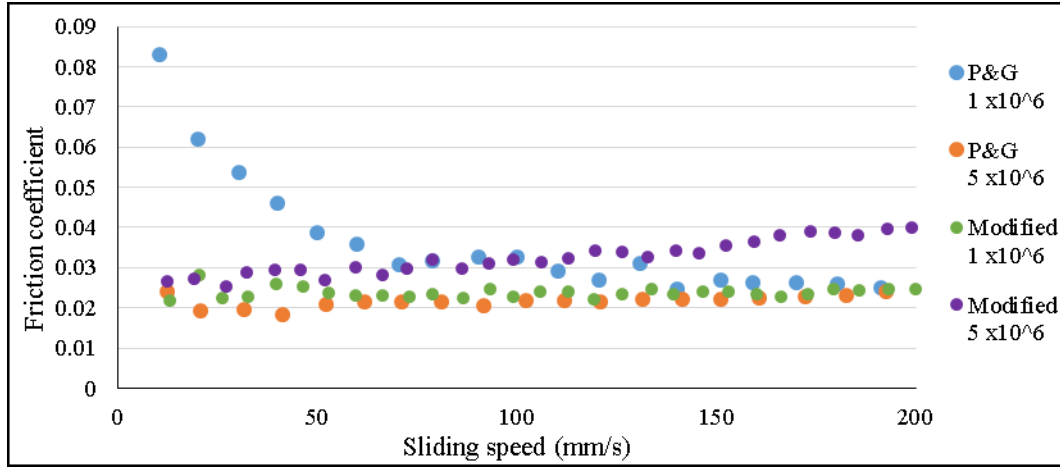


Figure 5.25: Comparison of results between P&G test profiles and modified test profiles

Although the change in contact pressure is halved (536 MPa (5 N) vs. 268 MPa (2.5 N) by reducing the load, and causes the friction coefficient for of 1×10^6 g/mol M_w PEO solution to become constant across the speed range, although some scatter is seen at low speeds. Overall, the friction is lower for 2.5 N load, especially at speeds below 150 mm/s (which is within the shaving speed range). For 5×10^6 g/mol M_w PEO solution, reducing load causes friction to increase with increasing sliding speed. As a result friction is higher for a 2.5 N load across the speed range even though initial values for both profiles are similar.

Friction is strongly dependent on load across all lubrication regimes [1] and a decrease in load causes an increase in film thickness [7] – this is illustrated by the film thickness equation, Equation 5.2 [8].

$$h = 4.18 \frac{(u\eta)^{0.6} R^{0.67}}{W^{0.18} E^{0.47}} \quad (5.2)$$

Although differences in lubricant behaviour cannot be attributed to load/film thickness alone as predicted film thickness values for these PEO solutions were not significantly different for each load:

- 1×10^6 g/mol M_w (10-200 mm/s):
 - 2.5 N: 0.4-2.2 μm
 - 5 N: 0.3-1.9 μm
- 5×10^6 g/mol M_w (10-200 mm/s)
 - 2.5 N: 0.9-4.2 μm
 - 5 N: 0.8-3.7 μm

It has been shown previously [9] that the load capacity of a viscoelastic film is lowered (compared to Newtonian fluids), and the coefficient of friction is increased by viscoelastic effects. This is shown in the 1×10^6 g/mol M_w PEO solution results where a 5 N load at low speeds (where the lubricant film is thinner) produces a friction coefficient up to four times larger than that of a 2.5 N load.

5×10^6 g/mol M_w PEO solution's predicted film thickness is approximately double that of 1×10^6 g/mol M_w PEO solution (due to increased viscosity), and the thick film contributes to increased friction with increasing speed. This is explained in further detail in Section 5.8.3.

5.8.2. Pure sliding contact lubrication

The modifications to P&G's original MTM test profiles were intended to allow for screening of potential shaving lubricants and to identify desirable lubricant characteristics. Although a pure sliding contact is representative of shaving, the 100 % SRR profile produces smoother friction curves with clear definitions between each test fluid. There are however differences in friction coefficients between the pure sliding and sliding/rolling profiles, particularly at low speeds. One of the reasons for this and the increased scatter in the sliding measurements is the required use of the pin-on-disc test profile, which measures friction in one direction only [1]. Figure 5.26 shows an example of poor repeatability in the pure sliding profiles, between results from two repeat first runs for 400×10^3 g/mol M_w PEO solution.

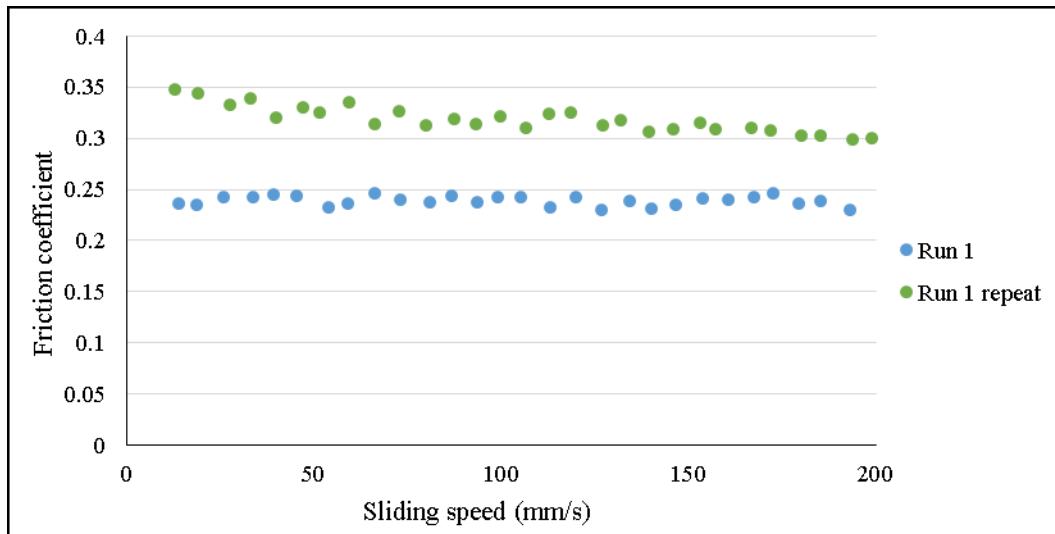


Figure 5.26: Repeated test results for 400×10^3 g/mol M_w PEO solution for excess fluid, pure sliding conditions.

Surface wetting problems were seen for glycerol solution in the excess fluid, pure sliding condition (Figure 5.27). At low speeds in particular, the friction coefficient is very high at 0.069 compared to 0.027 for the sliding/rolling contact at the same speed. This was also observed by Myant et al. [1] for a glycerol solution speed sweep in a steel ball/PDMS disc contact at low speeds, although no explanation was given other than that the lubricants were in the boundary and mixed regimes, and increased friction at low speeds was therefore a result of increased contact area due to elastic conformation of the PDMS disc.

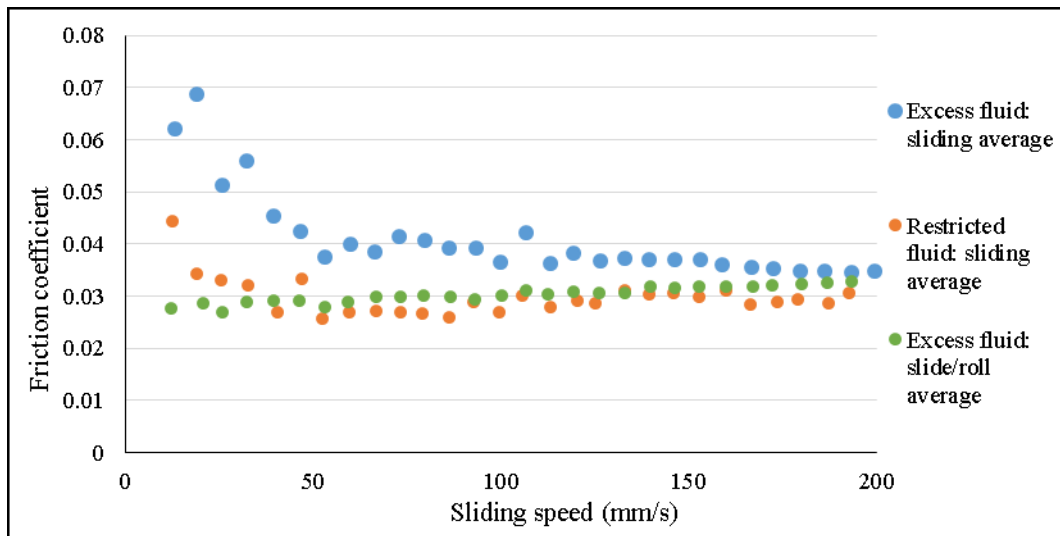


Figure 5.27: 60 wt. % glycerol solution friction results

Starvation for high viscosity fluids is reduced with the inclusion of the scraper, which assists lubricant replenishment into the track due to its geometry (Figure 5.28). However, for 5×10^6 g/mol M_w PEO solution including the scraper causes friction instability at higher sliding speeds, and this behaviour does not occur for any other lubricants in these results. Relaxation time is the characteristic time required by the polymer coils to relax from a deformed state to their equilibrium configuration, and is a key parameter for characterising viscoelastic fluids [10]. 5×10^6 g/mol M_w PEO solution has a relaxation time of 500 ms, and time elapsed between the scraper and contact is 352.2 ms at 150 mm/s sliding speed. Therefore there is not sufficient time for the PEO solution to recover between the scraper contact and the ball contact. Calculations show that at sliding speeds above 105.7 mm/s, time between the scraper and ball is less than 500 ms and starvation will therefore start to occur. This is illustrated in Figure 5.29, where starvation effects are first measured at 106.1 mm/s.

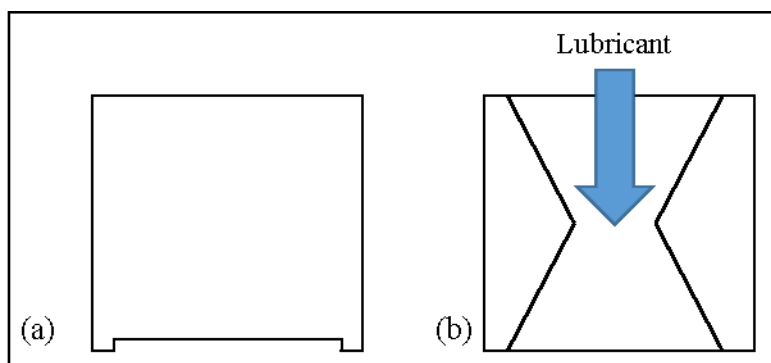


Figure 5.28: Scraper geometry (a) front and rear view (b) lubricant channel on underside of scraper

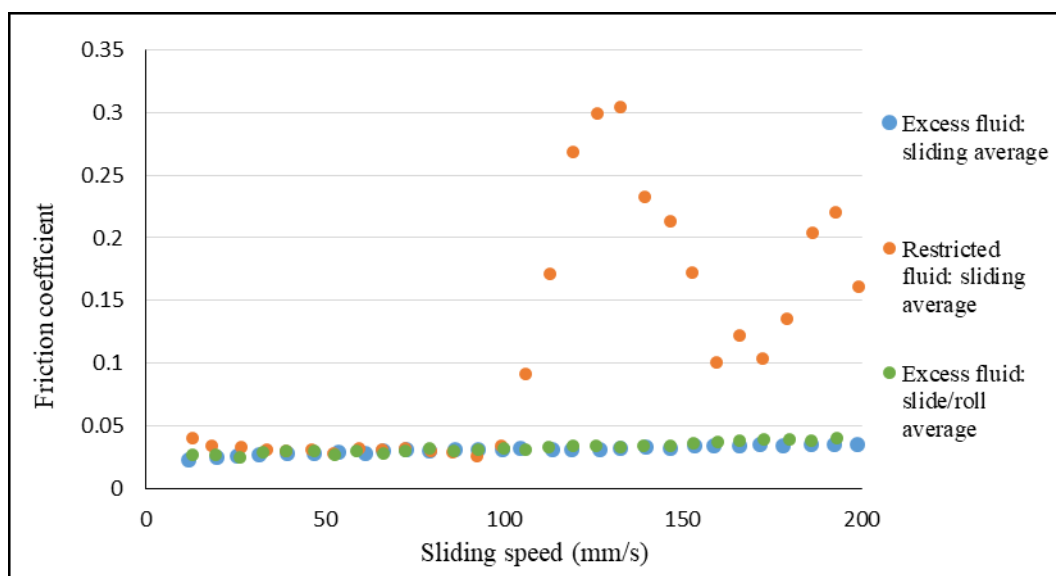


Figure 5.29: 5×10^6 g/mol M_w PEO solution friction results

5.8.3. Sliding/rolling contact lubrication and calculated film thickness results

The sliding/rolling test profile provides a quick and convenient screening method for potential shaving lubricants. Although it is not the pure sliding contact found in shaving, it does mimic the sliding speed, initial bulk fluid quantity and overall load. Additionally, friction values are similar to the pure sliding results, and clear trends between lubricants can be identified. Results were repeatable with little variability, and previous problems with surface wetting and starvation did not occur. For these reasons lubricant analysis has been carried out using the sliding/rolling results.

Calculated film thickness for this hard/compliant contact is relatively high (Figure 5.30), and it is therefore expected that a full film is formed in the contact. This can be further quantified by calculating the lambda ratio.

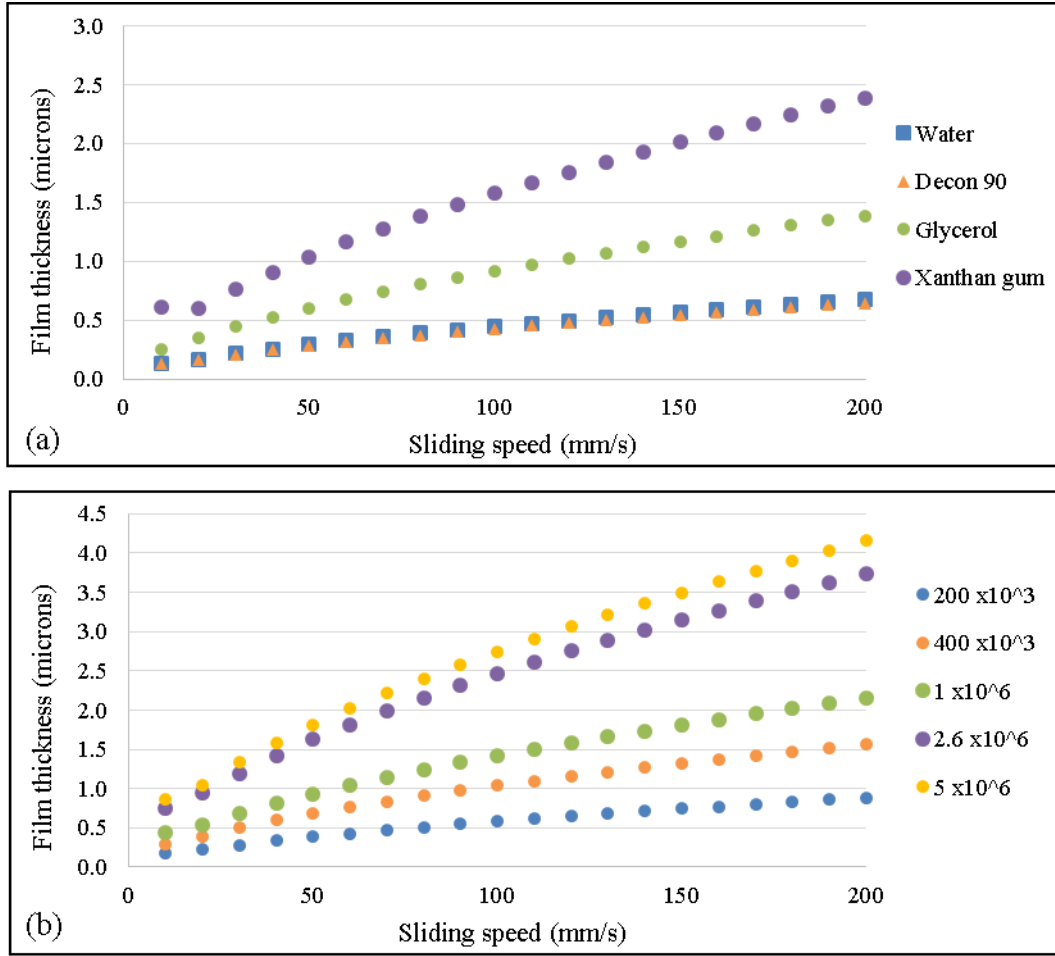


Figure 5.30: Calculated film thickness for (a) reference fluids (b) PEO solutions

The lambda ratio, λ , (Equation 5.3 [11]) relates the film thickness to surface roughness, and therefore shows whether a contact is lubricated in the fully flooded regime:

$$\lambda = \frac{h}{RMS} \quad (5.3)$$

where h is lubricant film thickness, and RMS (Equation 5.4) is the root mean square surface roughness, Ra , of the two contacting materials: stainless steel (11 nm) and PDMS (800 nm).

$$RMS = \sqrt{Ra_1^2 + Ra_2^2} \quad (5.4)$$

The resulting lambda ratio indicates which lubrication regime will occur in the contact [12]:

- Boundary lubrication, $\lambda < 1$
- Mixed lubrication, $1 < \lambda < 5$
- EHD lubrication, $3 < \lambda < 10$

- Hydrodynamic lubrication, $5 < \lambda < 10$

However, lambda ratio was originally derived for hard materials [11], assuming no surface deformation. When lambda was calculated using this method, all test fluids were found to lubricate in the boundary and mixed regime across the speed range (Figure 5.31). At 50 mm/s sliding speed, low viscosity test fluids (water, Decon 90, 200 x10³ g/mol M_w PEO and 400 x10³ g/mol M_w PEO solutions) produce boundary lubrication, and high viscosity solutions (glycerol, xanthan gum, 1 x10⁶ g/mol M_w PEO, 2.5 x10⁶ g/mol M_w PEO and 5 x10⁶ g/mol M_w PEO solutions) are in the mixed regime. At 150 mm/s sliding speed 200 x10³ g/mol M_w PEO solution maintains boundary lubrication, but all other fluids lubricate in the mixed regime.

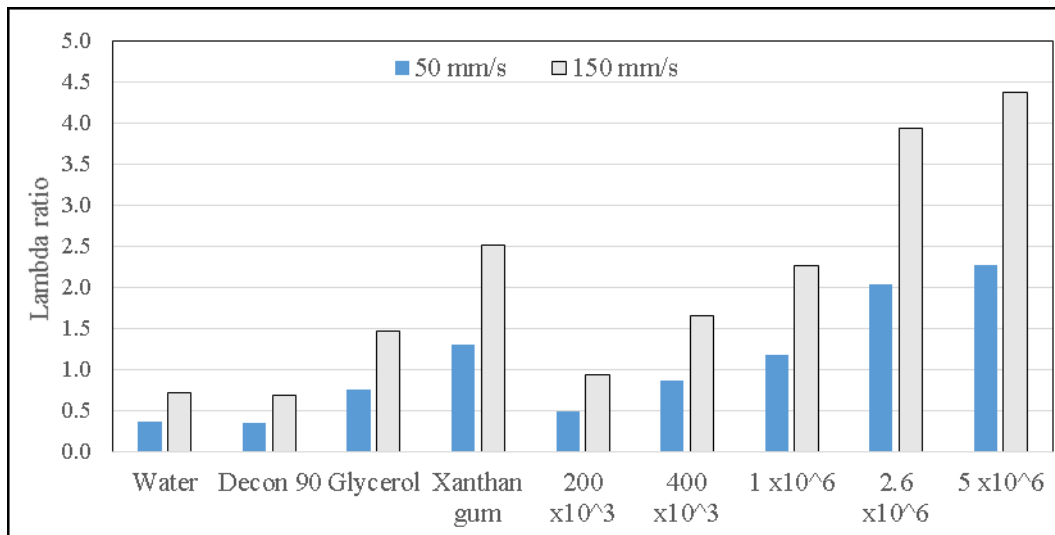


Figure 5.31: Lambda ratios for test fluids in a stainless steel ball/PDMS disc contact

Compliant contacts do not behave in the same way as hard contact [1]: elastic conformation occurs rather than plastic deformation at asperities. Taking this into account the lambda ratio for test fluid speeds sweeps was recalculated to assume zero surface roughness of the PDMS disc (resulting from surface deformation). The results are shown in Figure 5.32, where lambda ratio increases with viscosity and sliding speed. As lambda must be greater than 5 for full film lubrication to occur, even when accounting for simplification of surface deformations in the PDMS it can be assumed that all test fluids form a surface separating film across the speed range – Decon 90 solution has the lowest lambda ratio of 11.5 at a sliding speed of 10 mm/s.

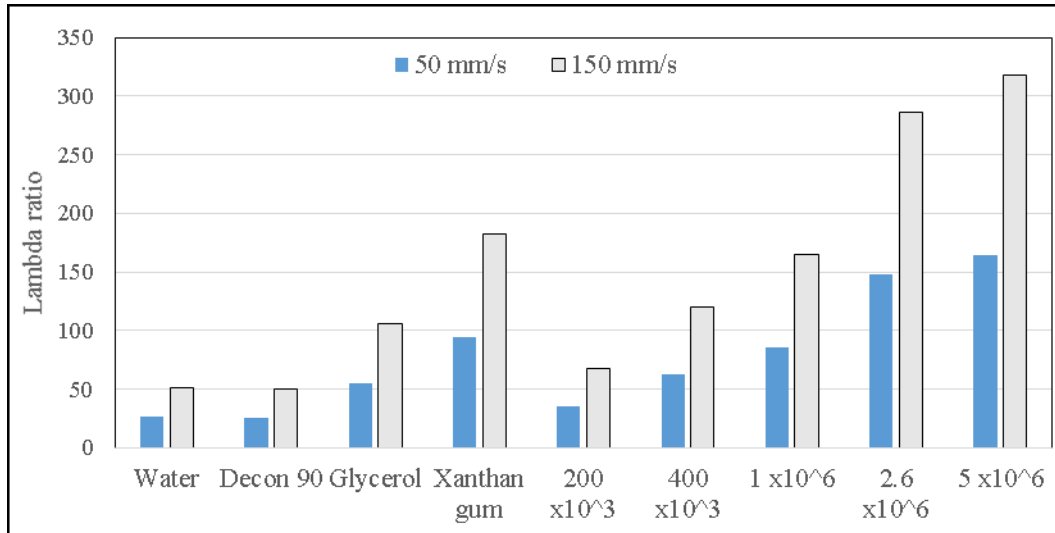


Figure 5.32: Lambda ratios for test fluids in a stainless steel ball/PDMS disc contact assuming compliant surface deformation

Figure 5.33 shows Stribeck curves for the test fluids in the excess fluid, sliding/rolling condition. Water and Decon 90 solution produce similar curves, although the friction coefficient for Decon 90 solution is lower than that of water. This is due to the soap molecules present in the Decon 90 solution, which create slip at the wall (as described in Chapter 4) and result in a lower viscosity, depleted layer of fluid at the contact boundaries [13].

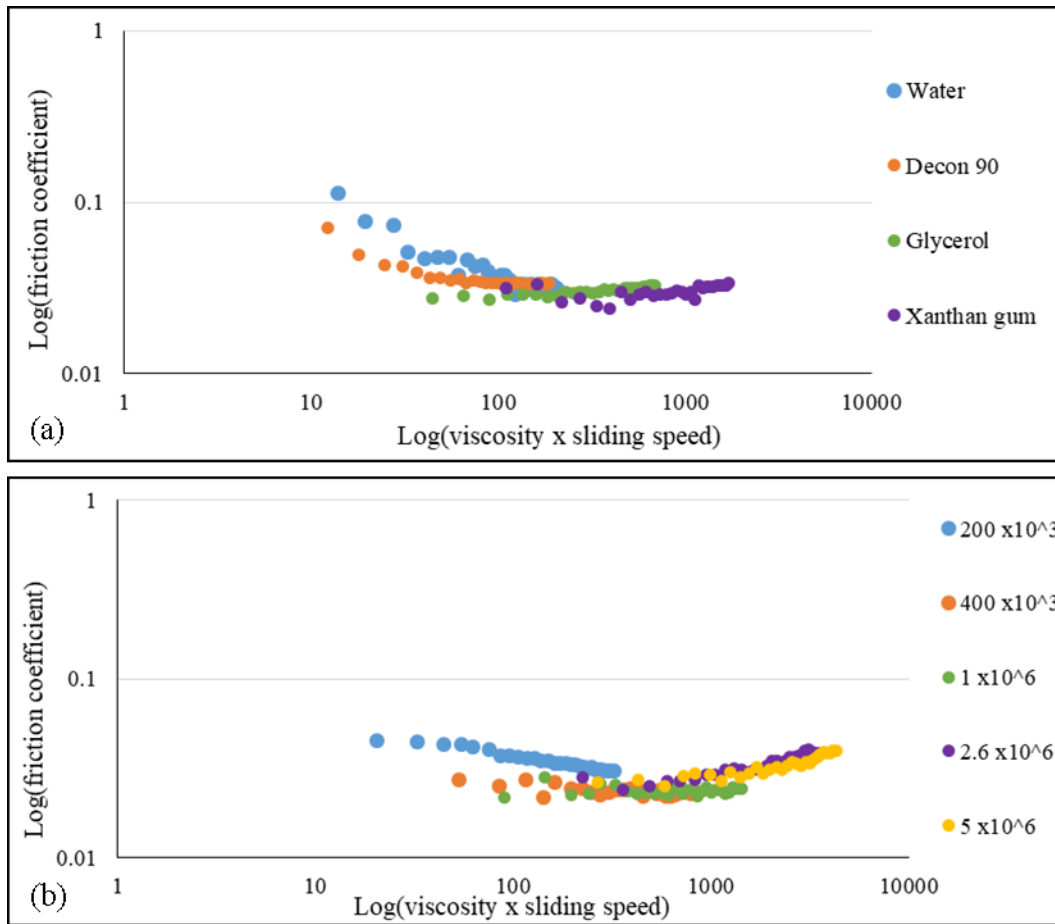


Figure 5.33: Stribeck curve showing excess fluid, sliding/rolling results for (a) reference fluids (b) PEO solutions

As sliding speed increases, more lubricant is entrained into the contact, which produces a thicker lubricant film and reduces friction [7, 14]. However, lubricants with higher viscosities (glycerol, xanthan gum, 2.6×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO solutions) produce a friction increase with increasing sliding speed that cannot be attributed to starvation. Higher viscosity fluids produce thicker lubricant films [7], and the friction increase occurs due to shearing of this progressively thick lubricant film [15]. Although this has been observed in high contact pressure systems (> 10 MPa), the principle that friction is a measure of lubricant shear stress still applies. This effect also explains the smoother (and sometimes) lower friction curves for pure sliding restricted fluid speed sweeps compared to excess fluid: film thickness is reduced, and therefore shear forces are lower.

1 x 10⁶ g/mol M_w PEO solution, which is the PEO currently used on the Lubrastrip, does not produce a significant change in friction across the speed range, despite the film thickness increase from 0.44-2.15 μm. This may be a reason as to why it is the preferred lubricant by users (P&G)

5.8.4. Surface chemistry

The results showed that there is a linear increase in friction for artificial sebum lubrication with increase in speed ($R^2 = 0.99$). However these results are not directly comparable to those quoted in the literature, which are from studies with live skin. There are differences between PDMS structure (single layer, constant mechanical properties, relatively smooth surface etc.) and surface chemistry coating (artificial sebum film thickness > 12.5 times greater than for naturally occurring sebum).

Figure 5.34 shows the effect of artificial sebum presence on the friction coefficient for a stainless steel ball/PDMS disc contact lubricated by the test fluids. At 50 mm/s sliding speed the difference between sebum presence and absence is more pronounced, compared to 150 mm/s – increased sliding speed will encourage lubricant entrainment into the contact, reducing the effect of sebum presence. At this lower speed the most effective lubricants (i.e. those where friction coefficient is similar with and without a sebum coated surface) were 2.6 x 10⁶ g/mol M_w and 5 x 10⁶ g/mol M_w PEO solutions, followed by Decon 90 solution.

In previous tests without the sebum layer, distilled water and Decon 90 solution produced similar friction results. However, friction coefficient for Decon 90 solution when artificial sebum is present is significantly lower than that of water. The friction coefficient for water increases over five times that of when sebum is not present, and at 50 mm/s its friction coefficient is more than double that of sebum alone. Coating the PDMS disc with artificial sebum increases the surface lipid content and therefore also hydrophobicity [16]. Further hydrophobicity can also occur to the steel ball due to adherence of lipids to this surface [16]. This separation of lipids (adhering to the steel ball) and water-based components (from sebum and lubricant) will create conditions where surface wetting properties are very poor and entrainment into the contact is reduced [17]. With reduced lubricant at the contact interface, there is an increased contribution from the bulk viscoelastic properties of PDMS, and its effect on shear

strength and contact area [18]: as velocity increases, the force to shear the interface and break adhesive bonds between the PDMS disc and steel ball increases, causing an increase in friction [19]. This behaviour is most notable for distilled water, as there is no solute present to reduce hydrophobic effects.

In contrast to distilled water, the difference between Decon 90 solution's friction coefficient with and without sebum present is small: it increases by ~ 0.01 at 50 mm/s, and decreases by ~ 0.001 at 150 mm/s. This demonstrates why soap solutions are used as shaving preps; they are able to “clean” the surface and emulsify sebum [20].

At sliding speed 150 mm/s, the friction coefficient for water with sebum remains unchanged at ~ 0.16 , despite increased entrainment and film thickness. This also occurs for all PEO solutions of 1×10^6 g/mol M_w and below. However, increasing sliding speed to 150 mm/s sees the friction for 2.6×10^6 g/mol M_w and 5×10^6 g/mol M_w PEO solution fall to lower values than when sebum is not present.

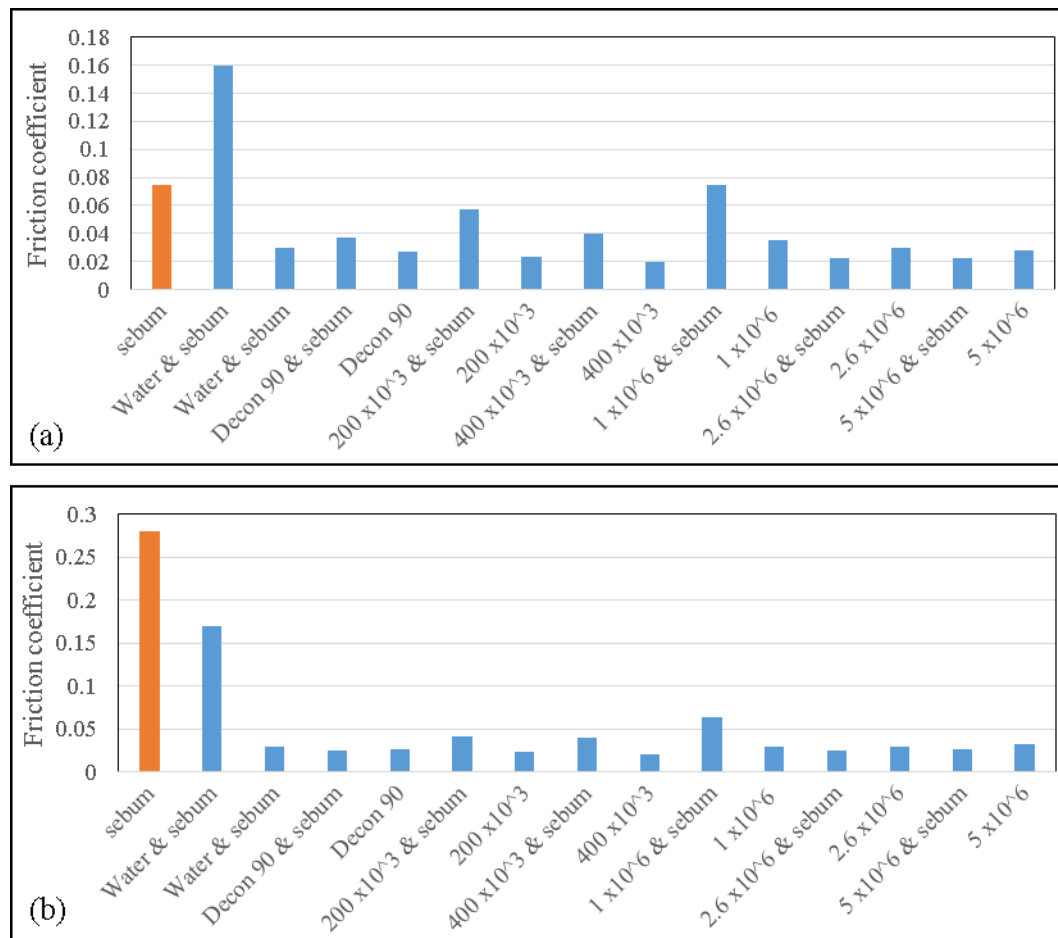


Figure 5.34: Effect of artificial sebum presence on friction coefficient for lubricated contact at sliding speed (a) 50 mm/s (b) 150 mm/s

5.8.5. Lubrastrip friction tests

The friction results from these tests are unlikely to be representative of the friction experienced by the user, as the Lubrastrip is sliding against a relatively smooth PDMS surface. If there were a considerable surface roughness (such as skin furrows or facial hair), this minimum value of friction would likely be higher and be achieved much sooner as the increased surface roughness would contribute to the degradation of the polystyrene matrix. The results show that the most effective method for Lubrastrip lubrication is a combination of a higher sliding speed (150 mm/s) and hydration.

A reduction in friction with speed is shown for dry conditions, but this is not due to significant lubricant release from the Lubrastrip (although some polymer may be present on the counterface). Figure 5.35 shows the effects of hydration on the Lubrastrip after use. Pitting can be seen on the surface of the hydrated Lubrastrip where degradation of the PEO/polystyrene matrix has occurred. After dry experiments there is no visible change to the surface of the Lubrastrip, which indicates that hydration is required for effective lubrication.

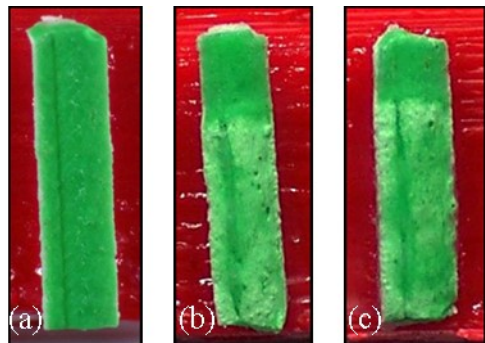


Figure 5.35: Visual condition of Lubrastrip after hydrated testing. (a) unused, (b) 50 mm/s, (c) 150 mm/s

5.9. Conclusion

The results from these experiments have shown the following:

- Pure sliding test profiles can produce results with poor repeatability and surface wetting problems. A sliding/rolling contact improves the quality of results.

- Comparison between original P&G profiles and modified profiles illustrated the effect of load on friction for two PEO solutions. The load capacity of a viscoelastic film is lowered (compared to Newtonian fluids), and the coefficient of friction is increased by viscoelastic effects. The friction coefficient of the model tests should be determined by matching that of 'real life' shaving.
- Using a scraper can reduce starvation in pure sliding conditions for high viscosity fluids, providing there is enough time for the lubricant to recover between the scraper and the contact.
- All test fluids lubricate in the full film regime.
- For fluids with lower viscosities (distilled water, Decon 90, 200×10^3 g/mol M_w PEO, 400×10^3 g/mol M_w PEO solutions) friction coefficient decreases with increasing sliding speed. This is due to increased entrainment into the contact creating a thicker lubricant film.
- The friction coefficient for high viscosity fluids (glycerol, xanthan gum, 2.6×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO solutions) increases with increasing sliding speed. This is due to increased shearing of the lubricant film as it increases in thickness.
- 1×10^6 g/mol M_w PEO solution, which is the PEO currently used on the Lubrastrip, does not produce a significant change in friction across the speed range, despite the film thickness increase from 0.44-2.15 μm . This may be a reason as to why it is the preferred lubricant by users.
- With sebum presence, distilled water is a very poor lubricant, and at 50 mm/s its friction coefficient is more than double that of sebum alone.
- Decon 90 solution is very effective at removing sebum from a surface.
- 1×10^6 g/mol M_w PEO solution produces a comparatively high friction coefficient with sebum present.
- 2.6×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO solutions were the test fluids with the lowest friction coefficient when sebum was present. This is in contrast to the action of Decon 90, which is to remove sebum from the contact area.
- Optimum Lubrastrip lubrication occurs when it is hydrated and at high sliding speeds.

5.10. References

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6. FLUID FLOW MEASUREMENTS:

DEVELOPMENT OF FLUORESCENT IMAGING METHOD

Summary

A laser induced fluorescence (LIF) technique has been developed to measure lubricant film thickness and distribution in compliant contacts, notably against a skin mimic. LIF employs a fluorescent fluid to lubricate the contact between a ball and transparent disc. A laser is shone into the contact, exciting the fluorescent dye and a camera measures the intensity level of photons emitted. This intensity measurement is then calibrated to find film thickness values. The technique can measure film thickness down to $2 \pm 0.4 \mu\text{m}$ for compliant/hard contacts, and $2^{+3.1}_{-2} \mu\text{m}$ for compliant/compliant contacts. Fluorescent intensity was successfully calibrated for film thickness measurements. For all systems, film thickness increased with speed and higher film thickness levels were seen in compliant/compliant contacts compared to compliant/hard contacts. PEO solutions formed thicker lubricating films than the reference fluids, and for these PEO solutions film thickness increased with molecular weight. $2.6 \times 10^6 \text{ g/mol } M_w \text{ PEO}$ produced unusual results that did not match the trend shown by other PEO solutions.

6.1. Introduction – film thickness measurements

The film thickness and distribution of the shaving lubricant within the cartridge will profoundly affect the friction experienced during shaving. Measuring film thickness in a razor cartridge/glass contact would be relatively simple to accomplish, as many established film thickness measurement techniques already employ a glass counterface. One of the main considerations of this work is to mimic the “real life” razor cartridge contact as closely as possible, which involves the use of a compliant counterface to mimic skin. Therefore, a compliant skin mimic material has been identified and incorporated into a film thickness measurement technique suitable for compliant contacts. The effect of skin deformation on cartridge lubrication (Figure 6.1) can therefore also be obtained.

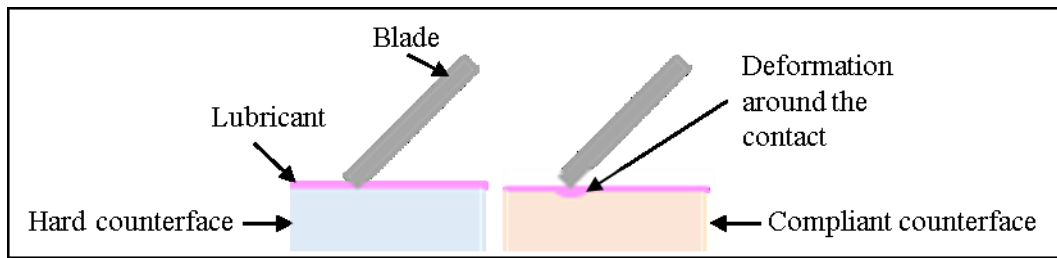


Figure 6.1: Surface deformation in a razor blade contact for a hard surface and a compliant surface

6.2. Measurement of film thickness in compliant contacts

There are three groups of techniques available to measure lubricant film thickness within a contact [1, 2]:

1. Electrical techniques (e.g. electrical capacitance and resistance measurement)
2. Electromagnetic radiation-based techniques (e.g. optical interferometry, Raman spectroscopy and laser fluorescence)
3. Ultrasonics and direct displacement

Electrical techniques are best suited to electrical conducting and reflective materials, such as metals, as film thickness measurement is reliant upon obtaining an electrical property of the lubricant film (typically resistance, capacitance or inductance) [3]. Optical interferometry [4-7], magnetic resistance [8] and Raman spectroscopy [9] have been used to measure film thickness in elastomer (e.g. seals) contacts.

6.2.1. Electrical and magnetic techniques

Electrical techniques for film thickness measurement rely on obtaining an electrical property of the lubricant film, which is then linked to film thickness [1]. Contact materials are typically metallic, with a non-conductive lubricant, so that when direct contact is made between them there is a short circuit. This reduces the potential or capacitance to zero, producing a zero film thickness result. When a lubricant film is present, the electrical signal gives an indication of contact separation [1]. However, due to the requirement of an electrical circuit to calibrate for film thickness, this method is not suited to a compliant contact, which is typically a non-metallic material.

A method involving magnetic flux was developed [8] with the aim of measuring film thickness up to hundreds of microns within a compliant I-EHL contact. In this case, the contact was a rotary lip seal. Magnetite particles were mixed into the lubricant and a magnetic circuit was constructed with the magnetic flux directed through the seal contact. Because of the high permeability of magnetite, the induction and impedance of the coil providing the magnetic potential could be calibrated to show the quantity of fluid present.

A significant advantage of using magnetic flux is that no optical window is required for this method, and the test specimen's original optical microgeometry remains unchanged (as there is no optical transparency required), which allows investigation of opaque and rough surfaces [7]. However, the necessity of a magnetic field limits both the range of lubricants that can be studied and the lowest measureable film thickness. It is also not possible to measure contact profiles, unless by axial displacement of the sample or test rig, which makes film thickness maps difficult to obtain [7]. Film thickness maps are a desirable output of this study to visualise the lubricant flow and distribution through the razor cartridge contact.

6.2.2. Ultrasonic and mechanical methods

As early as 1886, techniques for measuring lubricant film thickness with mechanical methods such as direct displacement were in use [10]. This technique has been developed substantially and now uses laser detection methods, which significantly increases the accuracy of results [11]. A different approach uses ultrasonic sound waves sent through the lubricated contact [1]. The reflected pulses are captured and digitalised with either an oscilloscope or a PCI digitising card in a PC. Film thickness values are then calculated from a coefficient amplitude spectrum, and as such ultrasonic measurement is constrained by needing to match the acoustic properties of the contact mediums. Although film thickness mapping is possible, it can be time consuming [12].

6.2.3. Electromagnetic radiation

Whilst all of the above methods have the advantage of not requiring an observation window to measure film thickness, making it easier to capture in-situ, real-time measurements, they lack the ability (or it is

impractically time consuming) to map film thickness over the entire contact. For this to be possible, one or both of the contact surfaces must be transparent to some form of electromagnetic radiation, and emitted or transmitted radiation be used to probe film conditions [13].

Techniques using electromagnetic radiation include X-ray transmission[13], Infrared (IR) absorption spectroscopy [14], IR emission [15] and Raman spectroscopy. All of these methods measure film thickness [16], but some also have the ability to measure lubricant temperature [17], rheology [18], composition [9] and molecular alignment [19]. It is possible to measure film thickness by using a confocal method, but the accuracy is only as good as the focussing resolution.

Confocal Raman spectroscopy has been successfully used to measure film thickness within a compliant contact lubricated with simple Newtonian fluids and stabilised oil/water emulsions [9]. This technique can show lubricant composition within the contact as well as being able to measure the film thickness of emulsions and opaque lubricants. However, water has a poor Raman signal, so aqueous solutions require an additional bulk solvent component added to the polar phase. This makes low viscosity aqueous solutions difficult to study. It is also only possible to measure film thickness at single locations, making film thickness maps difficult and time-consuming to acquire.

6.2.4. Optical interferometry

Optical interferometry was first developed in the 1960's to quantitatively measure lubricant film thickness within a contact down to 100 nm [20]. As EHL film thickness is the same order of magnitude as the wavelength of visible light [20], interferometry has the potential to study this lubrication regime. It has been used in the investigation of both hard [21] and compliant [22] contacts with the spacer layer method, and hard contact lubricant films down to ~ 1 nm thick can be measured.

A lubricated contact is typically formed between a steel ball and glass disc. White light illuminates the contact region through the glass window and is reflected from the steel ball and the underside of the glass disc [1]. A phase difference is created between the two beams, as one beam must pass through the lubricant twice. Optical interference occurs on recombination [20]. White light creates complex interference maps and the perceived colours vary continuously, requiring a time-consuming film

thickness/perceived colour calibration before film thickness measurements can be calculated from interferograms [1].

In a compliant/hard contact [23], monochromatic light has been used to acquire interference images. Early work with compliant contacts was limited to static loading and observed fluid film squeezed from the contact area over time [23-25] and could be used for film thickness measurements down to 20 nm [4]. Roberts [5] introduced low amplitude, lateral sinusoidal motion and film thickness measurements were recorded over a small entrainment speed range. Monochromatic optical interference was used by Kaneta et al. [26, 27] to measure lubricant film thickness in a reciprocating, compliant, line contact, which represented o-ring seals.

However, the coherence of illuminating light is reduced as the separating gap is increased [1]. Interference image quality reduces proportionally with reducing coherence, until the point at which film thickness measurements are no-longer possible. This critical point is dependent on the interference system, but usually occurs at film thicknesses of $\sim 2 \mu\text{m}$ [1].

6.2.5. Laser induced fluorescence

Laser induced fluorescence (LIF) is based on the photo-excitation of a fluorophore or fluorescent dye. It has advantages over the methods listed above for measuring film thickness, particularly in compliant contacts [1]:

- It has the capability to measure much larger values of film thickness, particularly compared to optical interferometry.
- It has the potential to measure very low levels of photon emission, down to a minimum of emissions from a single molecule.
 - Achieved with the use of extremely sensitive, modern visible light photon detectors.
- It does not require reflective coatings on the contact surface (these coatings are expensive and wear easily, particularly for high surface roughness).

Fluorescence occurs when incident radiation is absorbed and reradiated as a longer wavelength, and Haugland [28] states that fluorescence can be used to characterise any property affecting the

fluorescence of the dye, including film thickness. Measured fluorescence intensity is a function of the dye characteristics and concentration, the exciting light intensity and the property being measured. Upon selecting a dye and concentration, the fluorescence dependent on these factors remains constant [29].

LIF has previously been used to measure thin lubricant films in hard ball-on-disc contacts [30], but was restricted by optical interference and a significant background effect from cavities formed at the film exit. These problems are inherent in all illuminated hard/metallic contacts and few experimental film thickness results were presented [2]. Since this study, photon detection equipment and fluorescent dye technology has advanced considerably. Poll et al. [31] used LIF to investigate lubricant film thickness in rubber rotary lip seals. Limited results were given, but sub-micron film thickness results were measured across a narrow entrainment speed range (10-150 mm/s) and a clear explanation of the technique was provided. Hidrovo and Hart [29] employed a dual dye technique to remove optical interference and reduce background noise. High quality results were obtained, but the upper and lower limits of the system were not proven, nor was the method used on a realistic tribological contact, most likely because optical interferometry already offers an accurate measurement tool.

6.2.6. Summary

The contact that will be measured in this investigation consists of at least one compliant material and (from calculated values) will have film thickness values greater than 1 μm . LIF is able to fulfil the criteria to measure lubrication across the contact in this system as it can be used for compliant contact lubrication, can measure film thickness on a micron scale with a high upper limit (dependent on dye fluorescence properties), and mapping film thickness profiles is not too time consuming. There is also no need for contact materials to be smooth, reflective or electrically conductive, which increases the choice of contact materials that can be used for the compliant skin mimic. The type of laser and fluorescent dye can also be selected to suit the specific application, assisting with achieving a useful sensitivity level.

6.3. Laser Induced Fluorescence

LIF has often been used to visualise 1D, 2D and 3D applications [29], but relatively little development has been made with this method as a quantitative tool [30]. This is primarily because of the difficulty in separating variation in photon excitation, surface reflectivity and optical distortion effects from the fluorescent emission [1].

Fluorescent materials have the ability to absorb light of one wavelength (e.g. green) and emit light of another wavelength (e.g. red) [32] and electron structure determines the wavelengths and intensities at which fluorophores absorb and emit [33]. Fluorescence occurs in three stages (Figure 6.2), which is seen in certain molecules (typically polyaromatic hydrocarbons or heterocyclic) known as fluorophores or fluorescent dyes [28]:

1. **Excitation:** a photon of energy $h\nu_{EX}$ is supplied by an external source (e.g. laser) and is absorbed by a fluorophore, which creates an excited electronic singlet state, S'_1 .
2. **Excited state lifetime:** the molecule remains in this excited state for 1-10 ns. During this period, the fluorophore is subject to an array of possible interactions with its molecular environment and undergoes conformational changes. This has two important consequences:
 - The energy of S'_1 is partially dissipated, which yields a relaxed singlet excited state (S_1) from which fluorescent emission originates.
 - Not all initially excited molecules (Stage 1) return to the ground state (S_0) by fluorescent emission. Depopulation of S_1 can occur due to coalitional quenching, fluorescence energy transfer and intersystem crossing.

The fluorescence quantum yield (ratio of the number of fluorescence photons emitted (Stage 3) to the number of photons absorbed (Stage 1)) is a measure of the relative extent to which these two processes occur.

3. **Fluorescence emission:** a photon of energy $h\nu_{EM}$ is emitted, which returns the fluorophore to its ground state S_0 . Due to the energy dissipation during the excited-state lifetime, the energy of this photon is lower and therefore of longer wavelength than the excitation photon $h\nu_{EX}$.

This change in energy, or wavelength, ($h\nu_{EX} - h\nu_{EM}$) is known as Stokes shift. The Stokes shift is essential to the sensitivity of fluorescence applications as it allows emission photons to be detected against a low background, separated from the excitation photons.

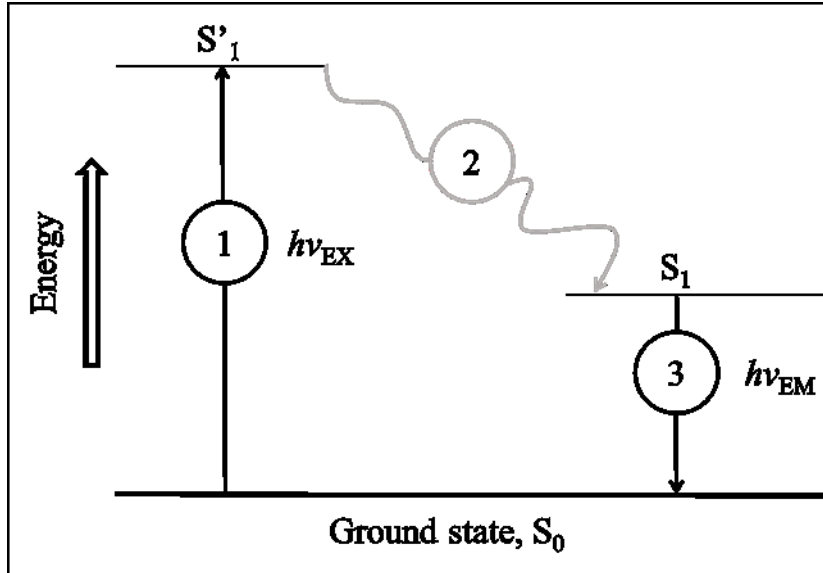


Figure 6.2: Fluorescence principle [28]

Photofluorescence can be used to characterise any scalar that affects the fluorescence of the dye [34]. Fluorescence is a function of the dye characteristics and concentration, the exciting light intensity, and the measured scalar. Selecting a single specific dye and concentration renders the fluorescence dependence on these factors as constant, although problems will persist with the irregularity of illumination light intensity; most illumination sources are not uniform and vary in intensity in space and time [1]. Pulsed lasers in particular exhibit this behaviour due to the characteristics of their resonance cavities [29]. Despite this, pulsed lasers are used due to their short pulse duration (and accordingly short fluorescent emission), which allows for nearly instantaneous measurements of the chosen scalar. Long periods of illumination can cause unwanted effects, such as bleaching.

6.4. Experimental Setup

The test device used in this project is a modified EHL optical interferometry rig (PCS Instruments, UK) (Figure 6.3). The standard rig consists of a steel ball (supported by a bearing carriage to allow free rotation of the ball) loaded from beneath onto an uncoated, plain BK7 glass disc (PCS Instruments,

UK). No reflective coatings were used on the glass disc. The glass disc has a Young's modulus of 65 GPa, Poisson's ratio of 0.24 and refractive index of 1.52. A solid-state, diode-pumped pulsed laser generates lubricant excitation, with a wavelength of 532 nm green light (Laser2000 LTD., UK). It has a maximum power output of 40mW at 3 kHz.

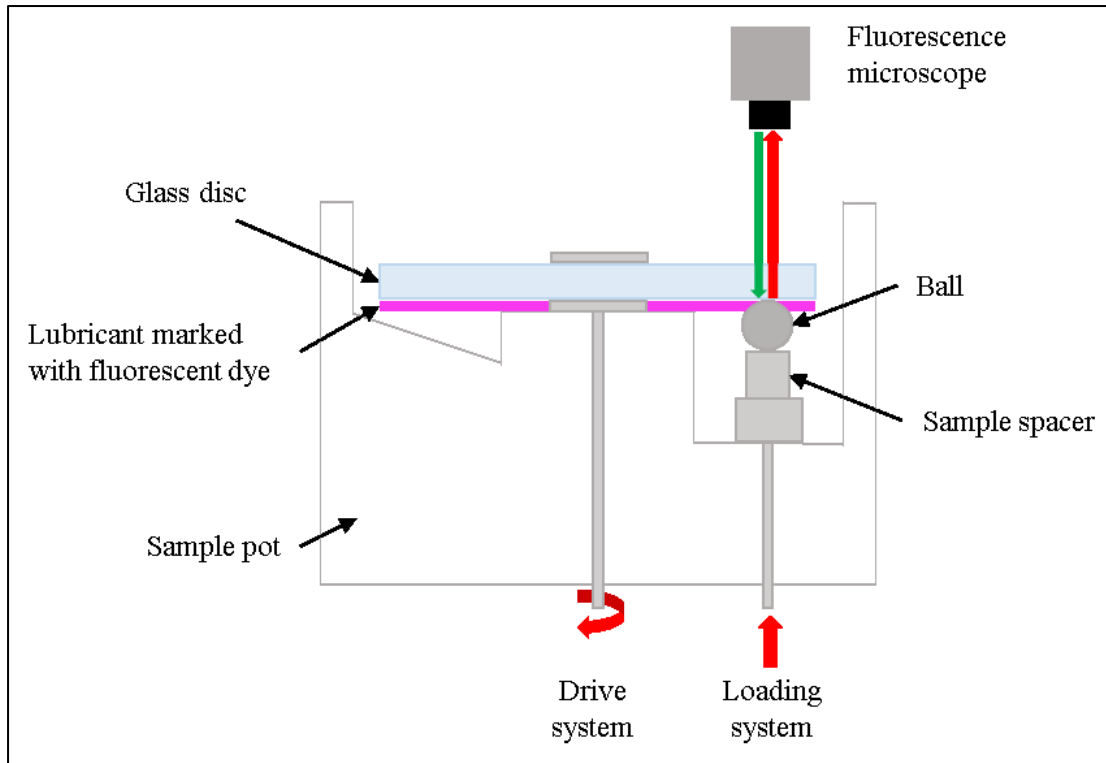


Figure 6.3: LIF device

6.4.1. Drive and load systems

The standard EHL optical interferometry rig uses a steel ball, supported on a bearing carriage, which allows free rotation of the ball. For this experimental study, the ball and carriage were replaced by an elastomer ball, elevated to a similar height as the original steel ball using a spacer (Figure 6.4). The elastomer ball was held in a static position using fixing screws, which allowed tests to operate in pure sliding conditions. This was important as the objective is to represent shaving, which is a sliding contact. Lubricant was entrained into the contact by rotation of the glass disc, which was coated in lubricant.



Figure 6.4: Sample spacer with fixing screws

The drive system used was standard as supplied with the PCS Instruments EHL rig. The disc was driven by a DC electrical motor, and a 25:1 reduction gear box was attached in series with the disc drive motor. This enabled accurate control of entrainment speed down to very low speeds (3-0.1 mm/s). The entrainment speed, u , is defined as the mean speed of the two surfaces. And as in a sliding contact one surface is stationary, entrainment speed is half the disc speed (Equation 6.1):

$$u = \frac{(u_b + u_d)}{2} = \frac{u_d}{2} \quad (6.1)$$

Where u_d is the disc speed, and u_b is the speed of the ball (in this case, $u_b \equiv 0$). The ball is mounted onto the spacer and loaded against the disc from below. The standard displacement load system designed for hard/metallic contacts was used, but low loads are achievable ($W < 1$ N). However, at low loads the system is not sensitive or responsive enough to correct fluctuations in load generated by mechanical vibrations. To determine the real applied load, JKR Theory (Equation 6.2) was fitted to the load-dependent contact area obtained from captured images of a static contact. JKR Theory states that for a ball on plate contact, the radius is related to the applied load and energy by:

$$a_{JKR} = \left\{ \frac{3R}{4E'} \left[W_{appl} + 3\pi R\Delta\gamma + \left(6\pi\Delta\gamma R W_{appl} + (3\pi R\Delta\gamma)^2 \right)^{\frac{1}{2}} \right]^{\frac{1}{3}} \right\} \quad (6.2)$$

where $\Delta\gamma$ is the specific energy of adhesion between the two surfaces and R the radius of the ball. This load was then used for film thickness calibration. The operating load, when a lubricant film is present, was taken to be the static load minus the adhesive force.

6.4.2. Optical equipment

Fluorescence intensity images were captured with an Axiotech Vario microscope (Zeiss, Germany), adjustable along the Z axis. The mechanical rig was situated on X and Y platforms, which allowed image capture of the tribological contact along both axes. Magnification of 2x was found to be sufficient for observing the contact area with a field of view of 3 mm. No eyepiece was required for the experimental setup as a live image display is relayed to the camera's operating PC.

Fluorescent light emitted from the contact in this setup is of a longer wavelength than the excitation wavelength of the laser (532 nm). The two light beams can therefore be separated by a dichroic mirror, 532 nm (Chroma, USA), which is positioned between the objective and camera (Figure 6.5).

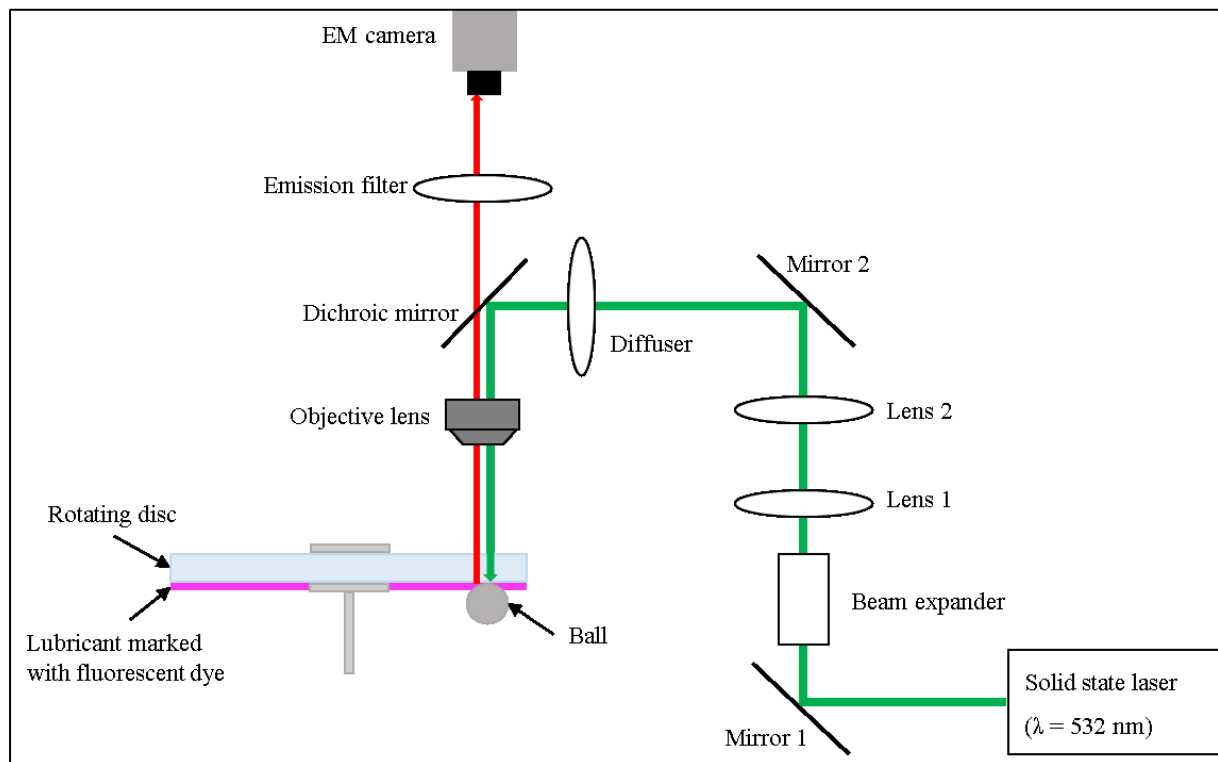


Figure 6.5: Optical setup

An emission filter (Chroma, USA) situated above the dichroic mirror filters any light not produced by the excited fluorescent dye. The optical setup was designed such that fluorescent dyes emitting within 580-640 nm will be observed by the camera, and a diffuser is located before the dichroic mirror to reduce irregularity in the illuminating light. The laser beam intensity distributions of both light sources in this study are Gaussian and to flatten the intensity distribution, the beam was expanded *ca* 30x using

lenses 1, 2 and the beam expander. Tilting mirrors 1 and 2 were used for laser beam alignment. These components were mounted on a shared rail and fully adjustable on the xyz axis. The light source was mounted on its own Z stage at the end of the optical setup.

Images were captured using a Rolera MGi B/W EMCCD camera (QImaging, UK) with a frame rate of 40 ms. As this is a digital camera, it does not have a physical shutter and therefore no shutter speed. A computer processing technique was used to analyse captured images pixel by pixel, creating film thickness maps based on grey-scale intensity. Images were captured as 16 bit tiff files, in a 512x512 array.

6.4.3. Dye selection

There were several factors considered in the selection of an appropriate fluorescent dye, which included:

- Excitation peaks that coincide with the laser wavelength (532 nm).
- Compatibility between emission wavelengths and the emission filter wavelength range.
- The quantum yield must be high enough to result in clearly defined images of the contact.
- Solubility of the dye in aqueous solutions.
- Commercial availability.

For thin films or low dye concentrations, the relationship between film thickness and emission intensity is linear [28]. It is therefore preferable to minimise dye concentration to increase the chances of even a thick film thickness falling within the linear range of fluorescence output. However, the dye concentration (and resulting emission intensity) must be high enough to overcome background noise from the EMCCD [33]. For this reason it is also important to select a high quality EMCCD with low background noise.

For this study, Sulforhodamine G (dye content 60 %) (Sigma-Aldrich, UK, # 230561) was chosen because:

- Its absorption peak coincides with the laser excitation wavelength (532 nm).
- Its quantum yield is sufficiently high to produce bright, clearly defined images of the contact.

- It dissolves in aqueous solutions due to its polar nature.

It has been observed that a small amount of fluorescent dye will sometimes attach to PDMS and glass, but the output intensity from this film was very small when compared to the fluorescent intensity produced by the dye used in test solutions [1]. Therefore, any build-up of dye attached to surfaces during testing can be considered negligible.

6.4.4. Normalisation

There are two forms of noise present in the LIF system used in this investigation:

1. Random fluctuations in the laser light and background noise present within the imaging system. This noise cannot be eliminated by normalisation of the captured fluorescent images.
2. Constant irregularities within the illuminating light. This includes speckle caused by the ND filters, lenses or dust and damage on any of the lens/filter surfaces [33], and the noise increases with film thickness.

A further complication to the second type of noise is the Gaussian distribution, which will skew the emission intensity (and therefore film thickness results) around the Gaussian curve. To reduce this skewing of results, images are normalised against a non-contact background image. Figure 6.6 shows the non-contact image prior to normalisation, where uneven distribution of laser intensity and interference fringes can be seen. Figure 6.6 shows the same non-contact image after normalisation.

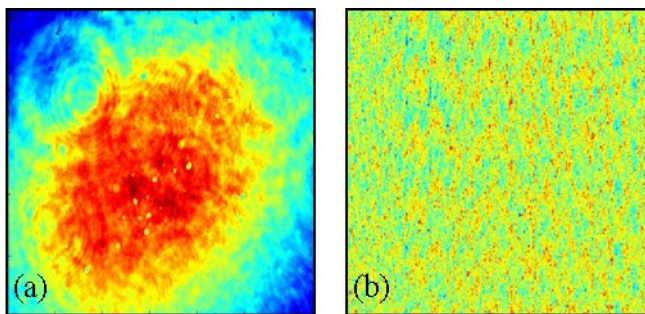


Figure 6.6: Background image of fluorescent, deionised water (a) before normalisation (b) normalised

To obtain the background image, deionised water marked with fluorescent dye is sandwiched between two glass slides, separated by a spacer 0.5 mm thick. The camera is focussed on the water and an image

captured. Irregularities from speckle and the Gaussian intensity can be seen in the background image Figure 6.6 (a), displayed as interference rings and a higher laser intensity in the centre of the image.

Normalisation of all images is completed in a two-step process:

1. The minimum intensity value, I_0 , in each image is identified and subtracted from each pixel, which sets the minimum intensity to zero. This subtraction of I_0 is necessary due to an intensity offset programmed into the camera by the manufacture that ensures no negative values can ever be achieved. The offset value and intensity scale is unique to each value and if the zero intensity value is not set, noise will occur in the contact zone.
 - a. It should also be noted that intensity values between camera types cannot be directly compared. Intensity values should be calibrated to a common scalar, such as film thickness, for comparison.
2. The image is divided by the non-contact image to produce a normalised image.

Finally, intensity values were smoothed to further reduce the effects of background noise in the imaging system and any fluctuations in illuminating light. Intensity was smoothed three successive times using a weighted average in which the intensity at each pixel ($P_{(ij)}$) was determined by Equation 6.3:

$$P_{(ij)} = \frac{(8P_{(ij)} + P_{(i+1j)} + P_{(i-1j)} + P_{(ij+1)} + P_{(ij-1)} + P_{(i-1j-1)} + P_{(i+1j-1)} + P_{(i-1j+1)} + P_{(i+1j+1)})}{16} \quad (6.3)$$

6.4.5. Calibration

Previous fluorescence work has calibrated for film thickness by plotting known film thickness verses fluorescent intensity, and this has been achieved in different ways:

- Film thickness values measured from optical interferometry methods compared to fluorescence intensity curves [30].
- An assumed geometry of a calibration wedge or cylinder [29, 31]. However, there is an effect of reflectivity on emission intensity [29], and an differences between the calibration piece and test specimen will create error when converting intensity to film thickness.

For this project, film thickness calibration was based on intensity images of the contact under static, steady state ($u = 0$) conditions. At the start of each test a ball (the material of which corresponded to the experimental contact material) was loaded against the disc (Figures 6.7 and 6.8) and intensity profiles were taken through the contact centre, which is identified by the computer as the area with lowest emission intensity. For the purpose of this investigation, film thickness profiles were measured along the y -axis.

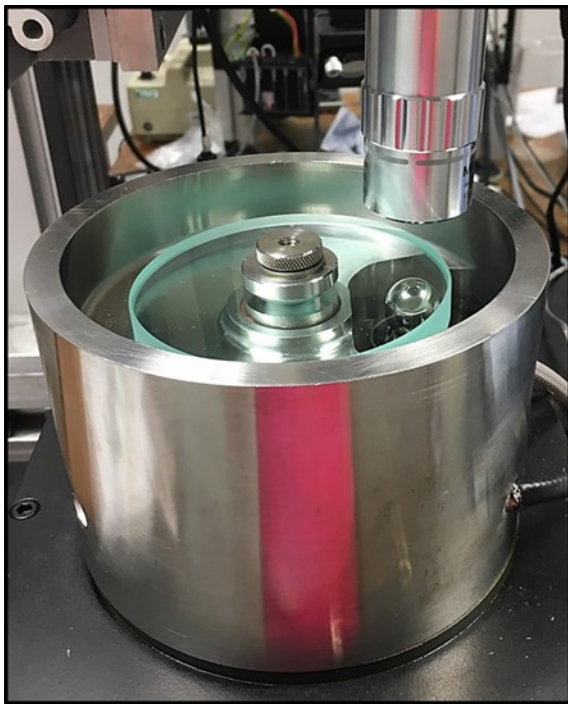


Figure 6.7: Ball loaded against glass disc for calibration

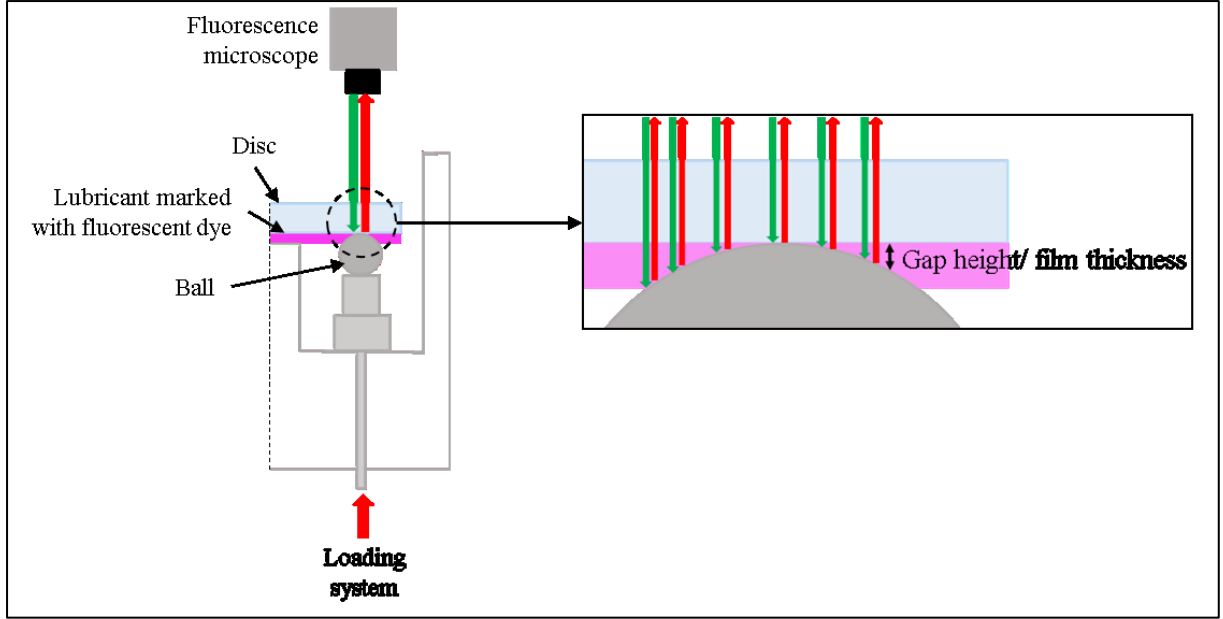


Figure 6.8: LIF calibration ball and disc setup

These intensity profiles were then plotted against the Hertzian equation (Equation 6.4) for the gap outside the central contact region [35].

$$h = \frac{a \cdot P_{max}}{E'} \left[- \left(2 - \frac{r^2}{a^2} \right) \cos^{-1} \frac{a}{r} + \left(\frac{r^2}{a^2} - 1 \right)^{\frac{1}{2}} \right] \quad (6.4)$$

Where maximum pressure is defined as $P_{max} = \frac{3W_s}{2\pi a^2}$, r is the distance from the centre of the contact, a the contact radius, and W_s is the total load present in the static contact.

There are three issues with applying this calibration method to a low load, compliant contact system:

1. The adhesive surface forces provide a significant contribution to the load: $W_s = W_{appl} + W_{adh}$
This must be taken into account when solving for gap height, although it will not be a factor when the surfaces are separated by a lubricant film.
2. The separation profile outside of the static contact area may be changed by the effect of adhesion and of deformation of the compliant material, which would no longer make the gap height equation applicable.
3. The actual value of applied load, W_{appl} , was not controlled due to the inadequacies in the loading system. The error was observed to be up to ± 0.5 N for the compliant disc.

To determine W_s and W_{appl} , the following method was followed: To determine the real applied load, JKR Theory (Equation 6.2) was fitted to the load-dependent contact area obtained from captured images of a static contact.

$$a_{JKR} = \left\{ \frac{3R}{4E'} \left[W_{appl} + 3\pi R\Delta\gamma + \left(6\pi\Delta\gamma R W_{appl} + (3\pi R\Delta\gamma)^2 \right)^{\frac{1}{2}} \right] \right\}^{\frac{1}{3}} \quad (6.2)$$

This load was then used for film thickness calibration.

To find the specific energy of adhesion of PDMS on glass, a PDMS specimen was placed onto a plain glass disc and the contact was viewed from the underneath. The applied load was the weight of the PDMS specimen and an optical interferometric technique using polarised white light and quarter wavelength plates [36] was used to capture the contact area and measure the contact radius. When Equation 6.2 was applied, it was found that the calculated JKR radius matched the observed image contact radius, and the specific energy of adhesion $\Delta\gamma = 0.0356 \text{ Jm}^{-2}$.

This specific energy of adhesion value was used in Equation 6.2 at the start of each test to establish (from the static contact radius) the value of applied load and total static load for use in Equation 6.4. During the experiments, there should be no surface adhesion forces due to a separating film, so the operating load equals the applied load.

A numerical solution for the gap profile between a ball and plate with surface adhesion properties has been derived which uses a “double-Hertz” model [1, 37] (Equation 6.5). This overlaps the original Hertzian contact area with a larger out-of-contact area, over which the adhesive force acts:

$$h = \frac{1+k}{\pi R} \left[a(r^2 - a^2)^{0.5} - (2a^2 - r^2) \cos^{-1} \left(\frac{a}{r} \right) \right] - \frac{k}{\pi R} \left[c(r^2 - c^2)^{0.5} - (2c^2 - r^2) \cos^{-1} \left(\frac{c}{r} \right) \right] \quad (6.5)$$

where k is an arbitrary scaling factor and R the radius of the ball.

Unlike Equation 6.2, fluorescence intensity profiles cannot be compared directly with Equation 6.5 as both k and c are unknown (and would require determining each time applied load, contact materials or contact geometry is changed), which makes calibration using Equation 6.5 difficult. Whilst there is good agreement for calculated film thickness values using Equation 6.5 when compared to experimental

[1], surface energy calculated from these k and c values differed from the measured value above. Contact profiles therefore could not be matched for similar values of surface energy.

Due to complications in using the double-Hertz model and that the difference in film thickness between Hertz and double-Hertz models over the gap height is less than *ca* 5% [2], a simple Hertz model (with load adjusted to include the adhesive contribution) is acceptable for calibration.

It has been noted that reflectivity of the surfaces under illumination has an effect on the fluorescent radiation detected by the imaging system [30, 38]. Light that is from either unabsorbed excitation, or emitted light transmitted through the fluid and reflected off the test specimen, may cause film thickness measurement errors. If contact surfaces have irregular reflectivity, this can create an error in the total intensity output, and therefore film thickness. As a result, individual calibrations were conducted for all lubricants and contact material combinations: different ball materials were used to match different parts of the razor i.e. a stainless steel ball calibration would be applied to the blade film thickness. Disc materials are described in section 6.5, although Figure 6.9 shows a simple illustration for the hard and compliant discs.



Figure 6.9: Calibration setup for (a) glass disc (b) silicone elastomer disc

Calibrations were each repeated three times and matched to the theoretical gap height curves, creating a look-up table. Figure 6.10 shows three calibrations for 1×10^6 g/mol M_w PEO solution in a steel ball/glass disc contact. In Figure 6.11 three calibrations are shown for 1×10^6 g/mol M_w PEO solution in a steel ball/silicone elastomer disc contact, where there is a significantly larger contact area due to increased deformation of the compliant surface.

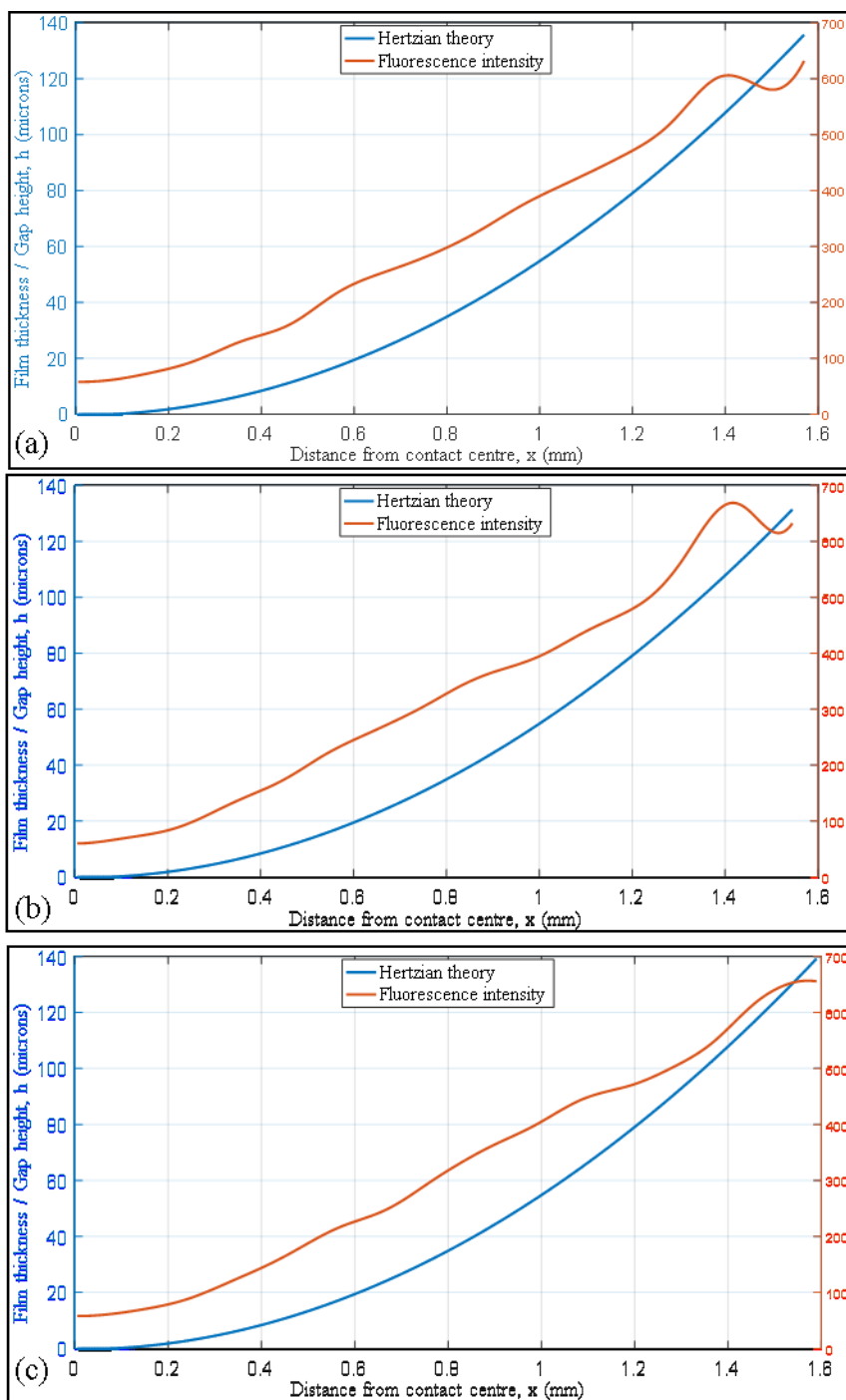


Figure 6.10: Calibration for 1×10^6 g/mol M_w PEO solution in a steel ball/glass disc contact (a) repeat 1 (b) repeat 2 (c) repeat 3

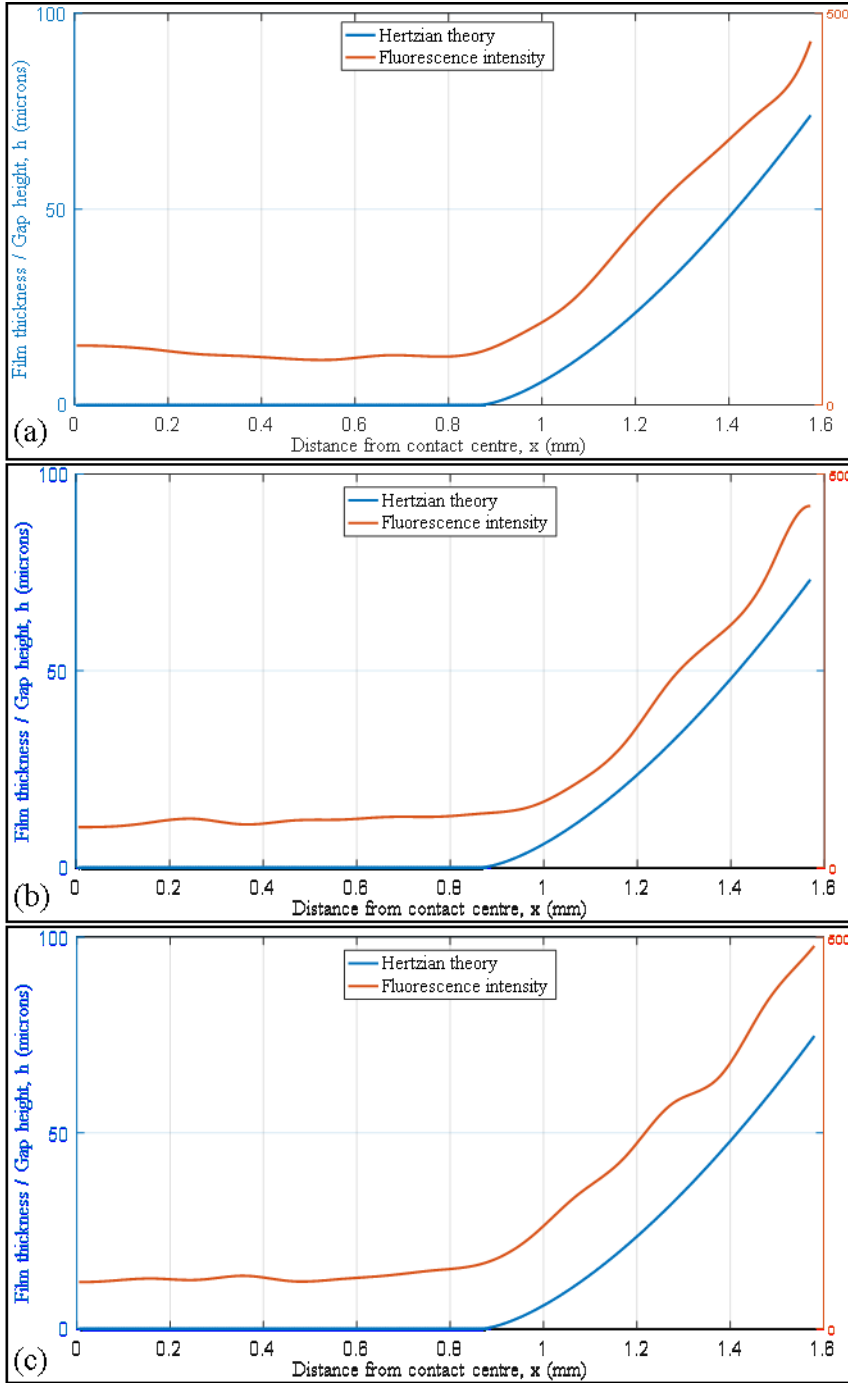


Figure 6.11: Calibration for 1×10^6 g/mol M_w PEO solution in a steel ball/elastomer disc contact (a) repeat 1 (b) repeat 2 (c) repeat 3

For compliant contacts, rapid approach of the contact surfaces creates a “bell” of liquid trapped in the centre of the contact. This trapped lubricant is squeezed out over time under static conditions [23, 24], so to create an accurate calibration curve the static contact was left for 10 minutes before the calibration image was captured. However despite this method occasional bells of liquid persisted within the contact, as shown in Figure 6.11a.

The irregularity created by random fluctuations in the laser light and background noise present within the imaging system prevents the fluorescence intensity data plot from being smooth. This noise cannot be eliminated by normalisation of the captured fluorescent images. The fluorescence intensity values are also never zero, and this is due to a small amount of fluorescent dye sometimes attaching to the contact surfaces.

Using the look-up table from the calibration images average, a polynomial was created to convert fluorescence intensity to film thickness for all subsequent images (Figures 6.12). The maximum fluorescence intensity from calibration is lower for an elastomer surface than for the glass, which is due to the increased thickness of the disc and larger contact area (reducing the amount of fluorescent lubricant in the cameras field of view).

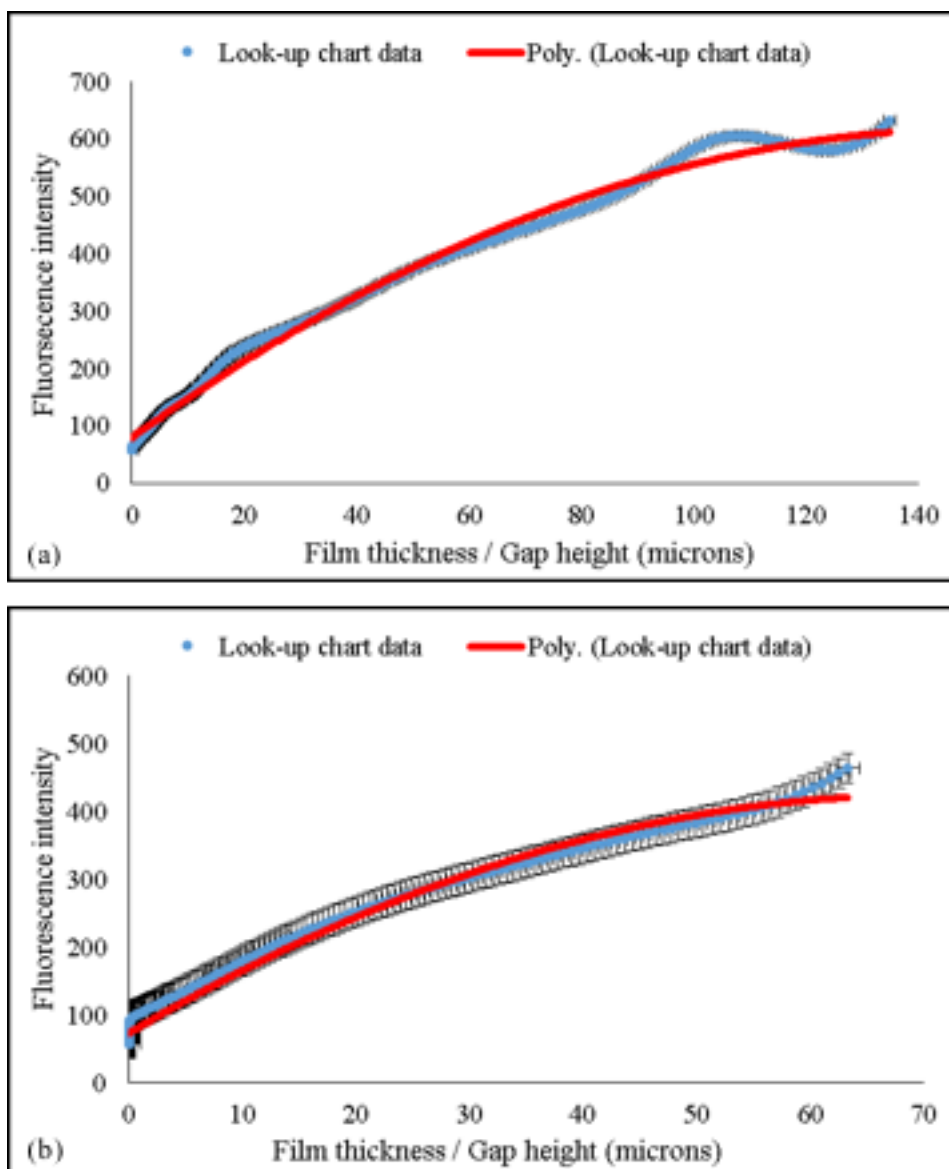


Figure 6.12: Look-up chart with error bars and polynomial (poly.) calibration for 1×10^6 g/mol M_w PEO solution in (a) steel ball/glass disc contact (b) steel ball/elastomer disc contact

Experimental LIF intensity measurements are then converted to film thickness using the calculated polynomial equation calibration curves (Figure 6.13). Experimental maximum measurable film thickness is therefore determined by the fluorescent limitations of the dye.

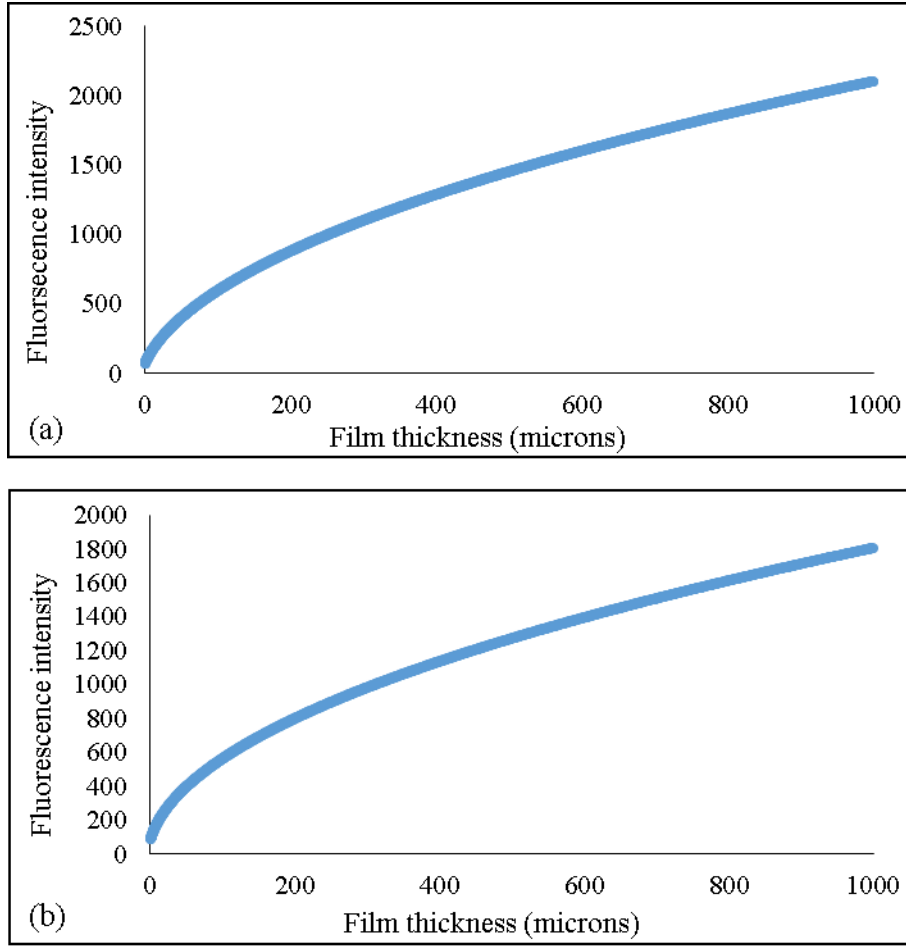


Figure 6.13: Polynomial calibration curve for 1×10^5 Mw PEO solution in (a) steel ball/glass disc contact (b) steel ball/elastomer disc contact

Minimum measurable film thickness was found to be $2 \pm 0.4 \mu\text{m}$ for a glass counterface, and $2^{+3.1}_{-2}$ μm for the silicone elastomer counterface. The measured calibration film thickness range was 2-135 μm . Studies using a similar LIF technique to measure film thickness against a glass disc have achieved minimum measurable film thickness values of 0.2 μm [32] and 0.3 μm [2], and a film thickness range of 50-100 μm [39].

6.5. Contact conditions

LIF has already been shown capable of measuring film thickness in a compliant/hard sliding contact [1, 2, 7], and the aim was to develop this further to measure in-contact film thicknesses for compliant/compliant materials. A sliding contact was selected as this is representative of a razor cartridge/skin contact whilst shaving.

Initially, all lubricants were measured in a sliding PDMS ball/glass disc contact (Table 6.1) (Figure 6.14). This material pair has previously provided film thickness measurements in work carried out by Myant et al. [1, 2, 7]. PDMS is translucent, and as such laser light can be transmitted through it which could interfere with intensity readings due to irregular reflectivity from the specimens and/or sample mounting. To stop this from occurring, the PDMS is coloured black using carbon black.

Table 6.1: Mechanical properties of initial contact materials

Material	Type	Young's Modulus (Pa)
PDMS (coloured with carbon black 0.5 wt. %)	Sylguard 184, PCS Instruments, UK	3.8×10^6
Glass	BK7, PCS Instruments, UK	74×10^9

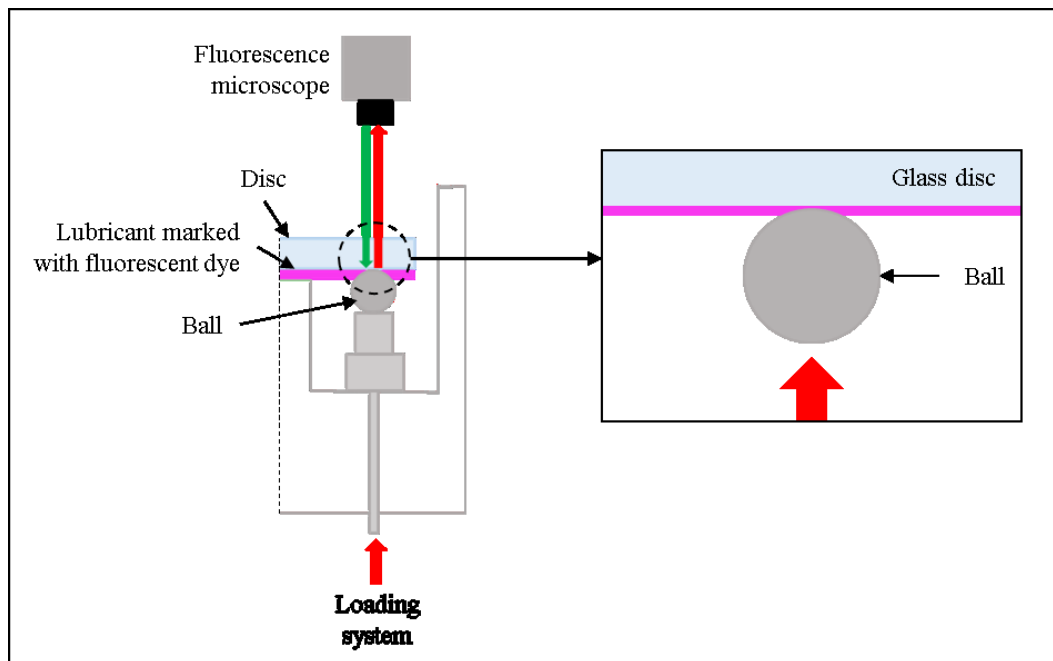


Figure 6.14: PDMS ball/glass disc contact

The second phase was to coat the glass disc in a compliant, skin-like material (Figure 6.15). This was transparent and cast onto the glass disc without any adhesives to bond the two materials. This created an optically clear skin mimic through which the lubricated contact could be visualised.

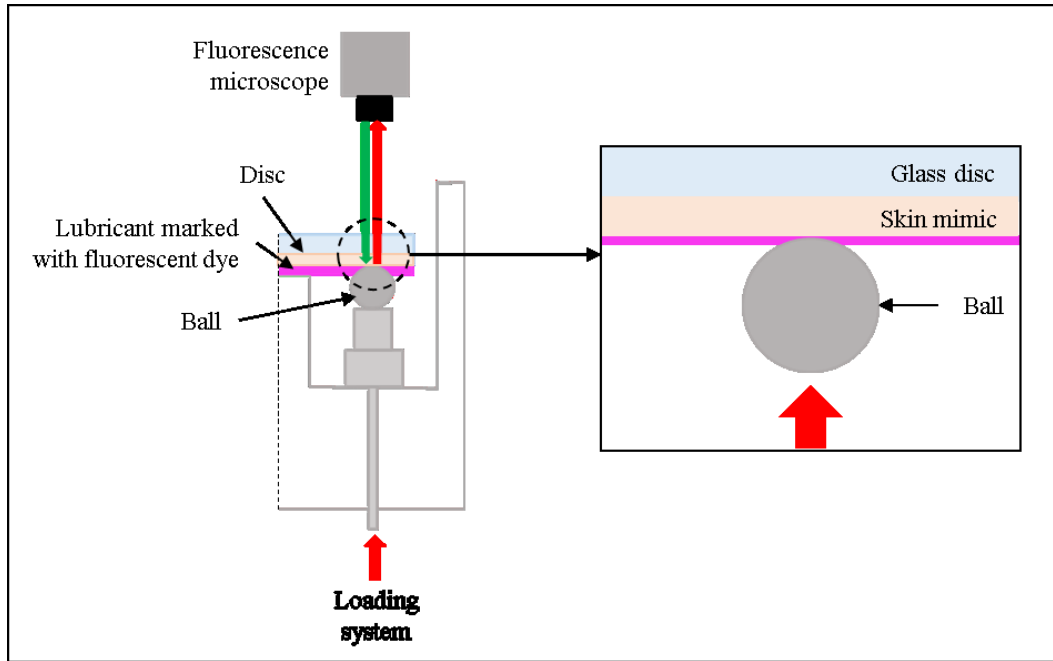


Figure 6.15: PDMS ball/skin mimic coated disc

6.5.1. Skin mimics

The skin mimic used for LIF was required to meet certain criteria in order for visualisation and film thickness measurements to be possible in this experimental setup:

- Optically transparent; clear imaging.
- Non-absorbent; material properties not affected by lubricant absorbance.
- Abrasion resistant; must not degrade during testing.
- Adhere to glass; easily adapted to current imaging techniques.

A review of available skin mimics concluded that the two materials most suitable for this application were gelatine gel and silicone elastomer. Both of these materials had the potential to meet the above requirements, and feasibility studies were conducted to gauge suitability of the potential skin mimics. For simplicity, the study employed a steel ball/compliant contact.

6.5.1.1. Gelatine

Gelatine gel has the advantage of being derived from the selective hydrolysis of collagen [40], and therefore inherently similar to natural skin both mechanically and chemically. Further details of its mechanical properties and formulation can be found in Chapter 4.

An example image of a steel ball/gelatine gel coated disc is shown in Figure 6.16. There is excellent clarity and definition around the edge of the contact, and variations in lubricant quantity can be seen (blue = absence of lubricant, red = excess lubricant).

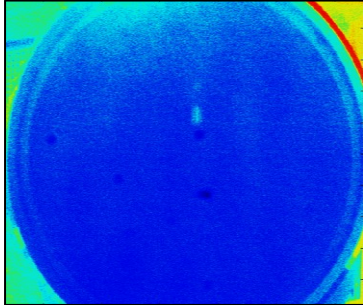


Figure 6.16: LIF image of steel ball/gelatine disc lubricated with 1×10^6 g/mol M_w PEO at 150 mm/s

Unfortunately, due to gelatine's ability to dissolve in water, it also absorbed the aqueous fluorescent solution, which coloured the gelatine gel, becoming more stained as the experiments progressed. There was also some visual damage present on the ball track around the disc. Although not substantial, the progression of this degradation will affect results.

In terms of reproducible samples, one issue with gelatine gel is that it was found to be mechanically very sensitive to temperature, as well as degrading with time. It is therefore very difficult to reproduce identical gels for experimentation, which could affect lubrication behaviour and results.

6.5.1.2. Silicone elastomer

Silicone elastomers are advantageous over other materials such as keratin, gelatine and hydrogels because they are not susceptible to drying and have little sensitivity to ionic content or pH of aqueous solutions [41]. Further details of mechanical properties and formulation can be found in Chapter 4.

Figure 6.17 shows a LIF image from the steel ball/silicone elastomer contact. As with the gelatine gel, changes in lubricant distribution across the contact can be seen.

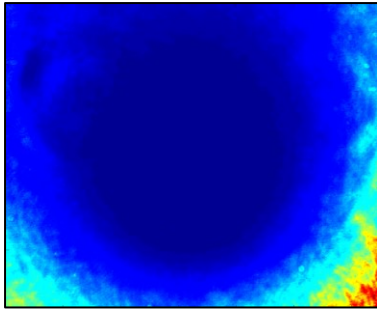


Figure 6.17: LIF image of steel ball/silicone elastomer disc lubricated with 1×10^6 g/mol M_w PEO at 150 mm/s

6.5.1.3. Summary

Both gelatine gel and silicone elastomer are suitable for in-contact imaging using LIF. Gelatine was initially the preferred skin mimic material as it is a natural product derived from collagen, and therefore is inherently similar to skin mechanically and chemically. Although it could be possible to standardise mechanical properties during production, due to the fluorescent dye absorbance and degradation in the track, gelatine gel is not suitable for this experiment. Therefore, the silicone elastomer was chosen for use in the LIF. Although it does not have surface chemical properties similar to skin, its non-absorbance and abrasion resistance mean that it fulfils all of the experimental criteria.

6.5.2. Experimental conditions

Table 6.2 shows the experimental conditions for LIF measurements. These are designed to replicate “real-life” shaving and correspond with the MTM test profiles. Ball and disc specimens were cleaned according to the standard described in Chapter 4.

Table 6.2: LIF experimental conditions

Load	2.5 N
Temperature	25 °C
SRR	200 %
Speed	50 mm/s
	150 mm/s
Ball material	PDMS
Disc material	Glass
	Silicone elastomer

Experimental film thickness values were calculated by averaging data from three separate tests. Within each experiment 25 intensity readings were recorded for every speed range.

6.5.3. Contact pressures

Table 6.3 below shows the change in contact pressures for different contact materials – a steel/glass contact is included as a reference, as this is the standard contact traditionally used. Incorporating compliant materials into the contact reduces contact pressure, and as a result increased film thickness would be expected.

Table 6.3: Contact pressures for different contact material combinations

	Max. Hertzian pressure ($P_{\max}$), Pa
Steel ball/glass disc	2.61×10^6
PDMS ball/glass disc	1.97×10^3
PDMS ball/silicone elastomer disc	259.48

6.6. Lubricants

Reference fluids and PEO solutions used for the experiments in this Chapter are described in Chapter 4.

5 ml of lubricant was pipetted onto the disc, which provided ample lubrication supply during each test. Due to increased hydrophilicity from plasma cleaning of the discs prior to testing (described in Chapter 4), lubricants did not succumb to gravity and leave the disc surface, despite coating the lower face of the disc.

6.7. Results: reference fluids

6.7.1. Hard contact: glass disc

Figure 6.18 shows a fluorescence intensity image of water lubricating the PDMS/glass contact, where blue indicates only a very thin film is formed. Visually similar results were obtained for all the reference fluids due to the experimental film thickness being below the lower film thickness detection limit of the LIF.

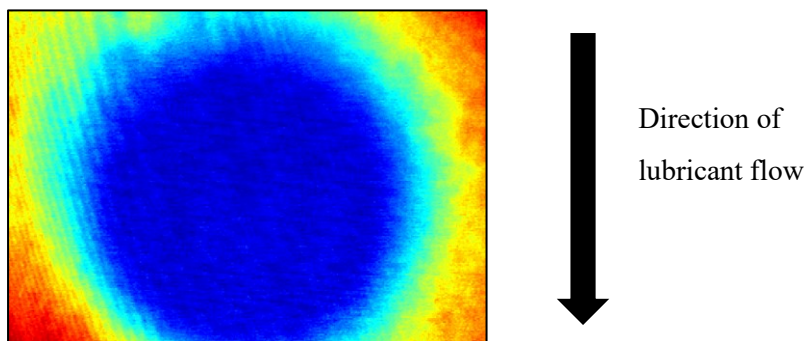


Figure 6.18: LIF image of PDMS/glass disc contact lubricated with water at 150 mm/s

Calculated film thickness values for reference fluids in the glass disc contact are shown in Table 6.4. Considering these results against the lower detectable limit of $2 \pm 0.4 \mu\text{m}$, films are not expected to be measureable for the fluids.

Table 6.4: Reference fluid solution theoretical film thickness for glass disc contact

Reference fluid solution	Film thickness (μm)	
	50 mm/s	150 mm/s
Distilled water	0.35	0.56
Decon 90	0.33	0.54
Glycerol	0.66	1.15
Xanthan gum	1.57	1.99

6.7.2. Compliant contact: silicone elastomer disc

Distilled water and Decon 90 solution in the PDMS/silicone elastomer contact did not form measurable films. Calculated values are shown in Table 6.5. When compared the lower detectable limit ($2 \pm_{-2}^{+3.1} \mu\text{m}$), distilled water and Decon 90 solution should have formed a measurable film at 150 mm/s sliding speeds, although the error at this lower limit is significant for the silicone elastomer contact and may account for the lack of data. However results for glycerol (Figure 6.19) and xanthan gum (Figure 6.20) solutions were recorded.

Table 6.5: Reference fluid solution theoretical film thickness for silicone elastomer disc contact

Reference fluid solution	Film thickness (μm)	
	50 mm/s	150 mm/s
Distilled water	1.48	2.37
Decon 90	1.40	2.28
Glycerol	2.78	4.89
XG	6.66	8.42

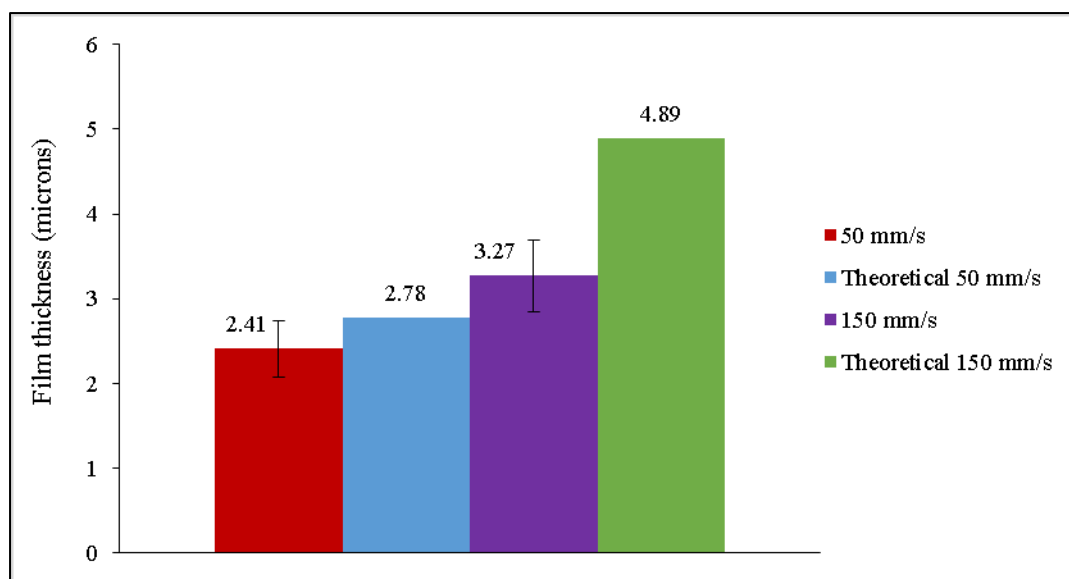


Figure 6.19: Theoretical and experimental film thickness for glycerol solution in a PDMS/silicone elastomer contact

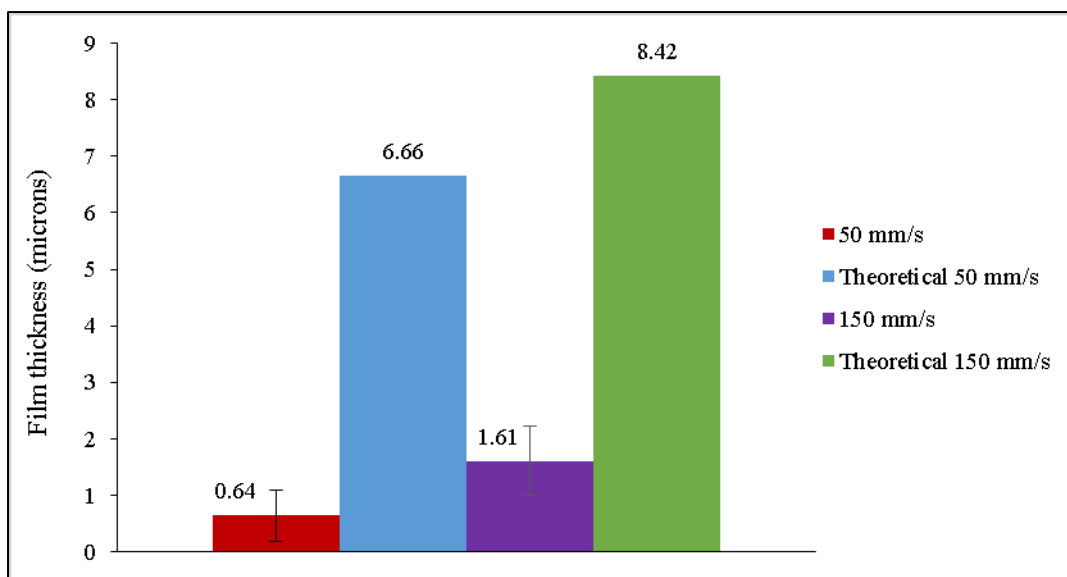


Figure 6.20: Theoretical and experimental film thickness for xanthan gum solution in a PDMS/silicone elastomer contact

6.8. Results: PEO solutions

6.8.1. Hard contact: glass disc

Theoretical film thickness results (Table 6.8) for 200×10^3 g/mol M_w PEO (Figure 6.21), 400×10^3 g/mol M_w PEO and 1×10^6 g/mol M_w PEO solutions are below the LIF lower detectable limit of 2 ± 0.4 μm , and they did not form a measureable film. This is also true of 2.6×10^6 g/mol M_w PEO solution at 50 mm/s sliding speed.

Table 6.6: PEO solution theoretical film thickness for glass disc contact

PEO solution (g/mol M_w)	Film thickness (μm)	
	50 mm/s	150 mm/s
200×10^3	0.45	0.74
400×10^3	0.78	1.31
1×10^6	1.15	1.79
2.6×10^6	1.96	3.11
5×10^6	2.26	3.46

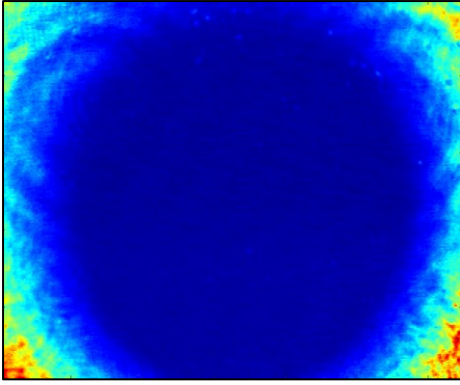


Figure 6.21: LIF image of PDMS/glass disc contact lubricated with 200×10^3 g/mol M_w PEO at 150 mm/s

PEO film thickness increases with speed and molecular weight, and is detectable at 150 mm/s for 2.6×10^6 g/mol M_w PEO solution, and at both speeds for 5×10^6 g/mol M_w PEO solution. Figure 6.22 shows the fluorescence intensity image for the contact lubricated with 5×10^6 g/mol M_w PEO solution, which without calibration appears very similar to Figure 6.21, in which no measurable film was formed. Numerical results for 2.6×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO solutions are summarised in Figures 6.23-6.24.

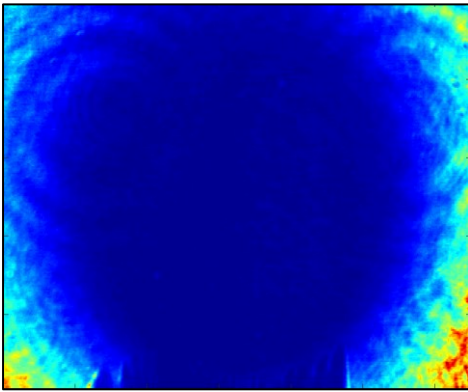


Figure 6.22: LIF image of PDMS/glass disc contact lubricated with 5×10^6 g/mol M_w PEO at 150 mm/s

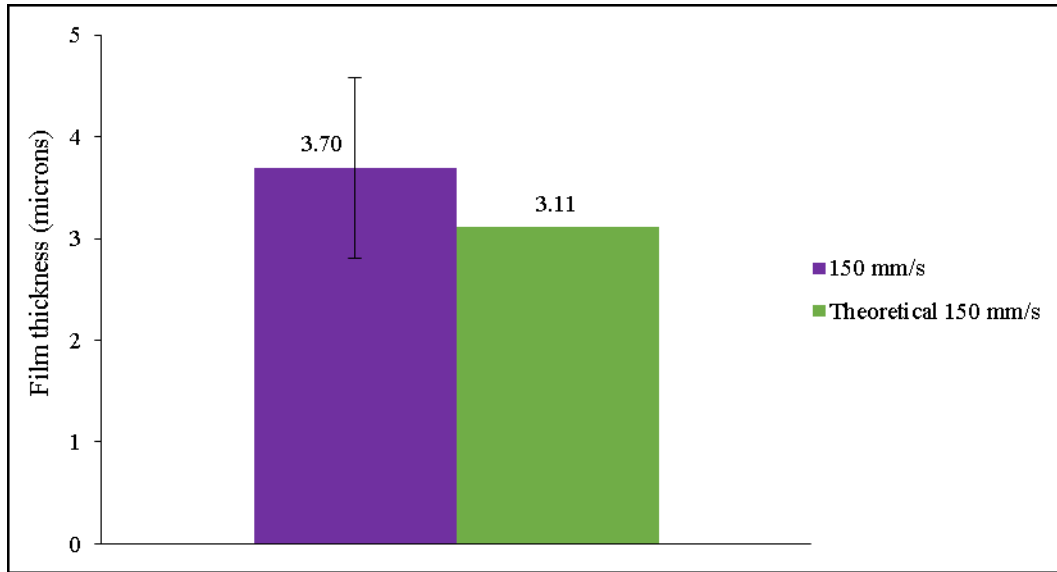


Figure 6.23: Theoretical and experimental film thickness for 2.6×10^6 g/mol M_w PEO in a PDMS/glass contact

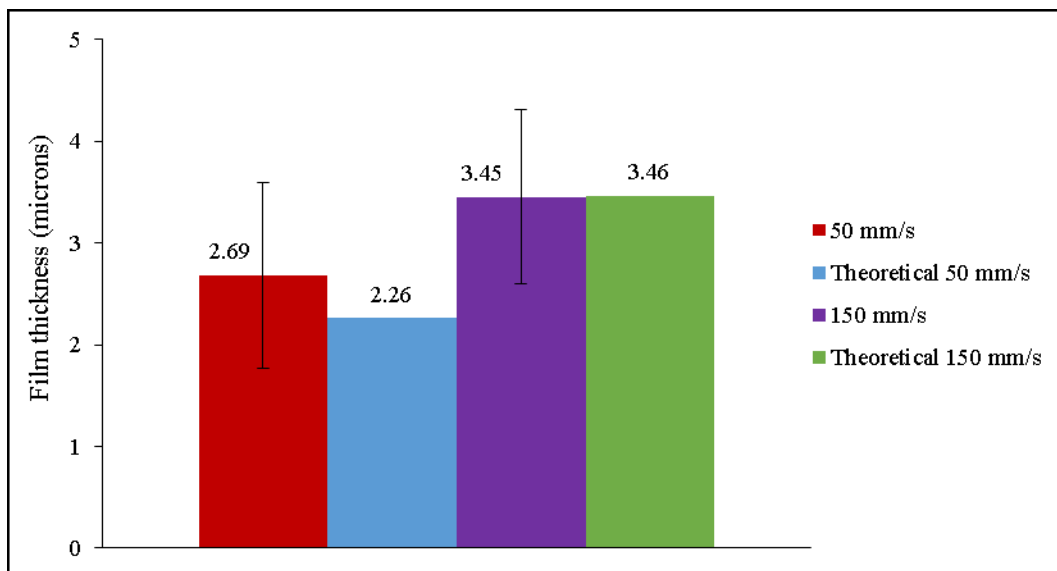


Figure 6.24: Theoretical and experimental film thickness for 5×10^6 g/mol M_w PEO in a PDMS/glass contact

6.8.2. Compliant contact: silicone elastomer disc

All PEO fluids formed a measurable lubricating film in the compliant/compliant contact, although no measurable film was present for the 200×10^3 g/mol M_w solution with a sliding speed of 50 mm/s. Calculated film thickness is $1.92 \mu\text{m}$, which is below the measurable limit of $2 \pm_{-2}^{+3.1} \mu\text{m}$. The average measured film thickness value for 200×10^3 g/mol M_w PEO solution (Figure 6.27) at 150 mm/s was 0.54

μm (calculated film thickness = $3.12 \mu\text{m}$), which highlights the unreliability of results below $2 \mu\text{m}$.

Results for all PEO solutions are shown in Figures 6.25-6.29.

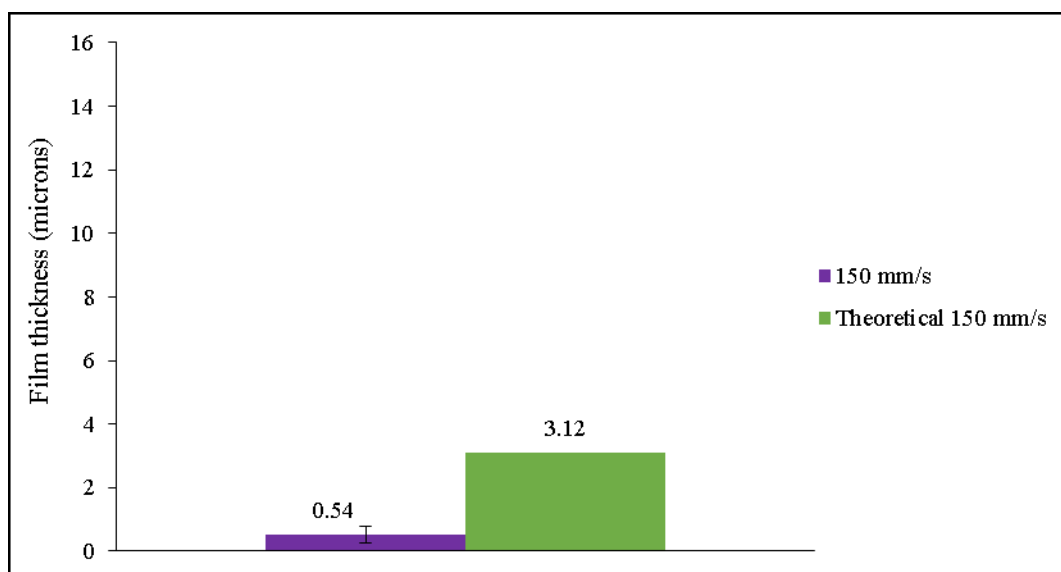


Figure 6.25: Theoretical and experimental film thickness for $200 \times 10^3 \text{ g/mol } M_w$ PEO in a PDMS/silicone elastomer contact

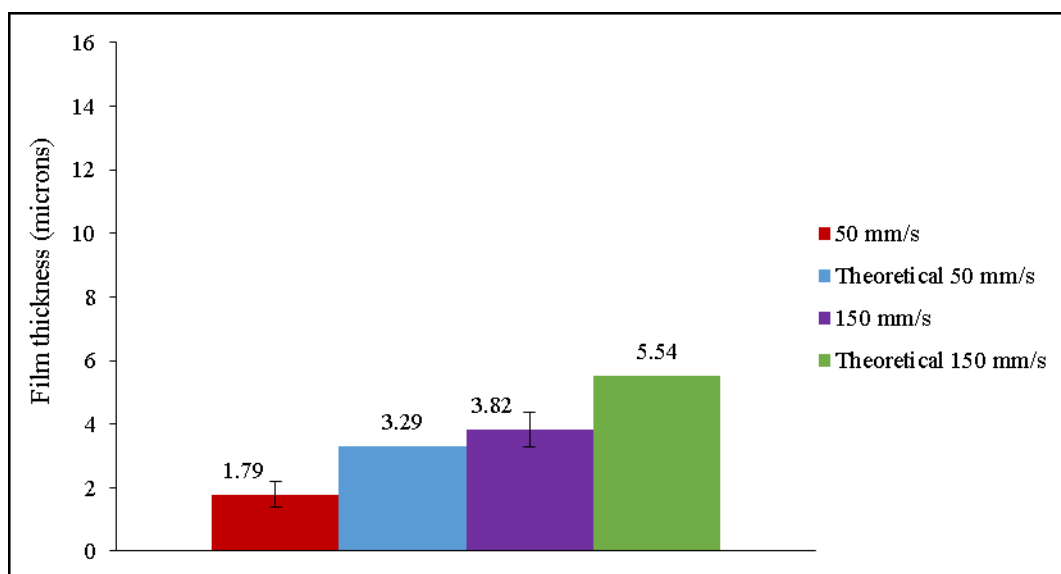


Figure 6.26: Theoretical and experimental film thickness for $400 \times 10^3 \text{ g/mol } M_w$ PEO in a PDMS/silicone elastomer contact

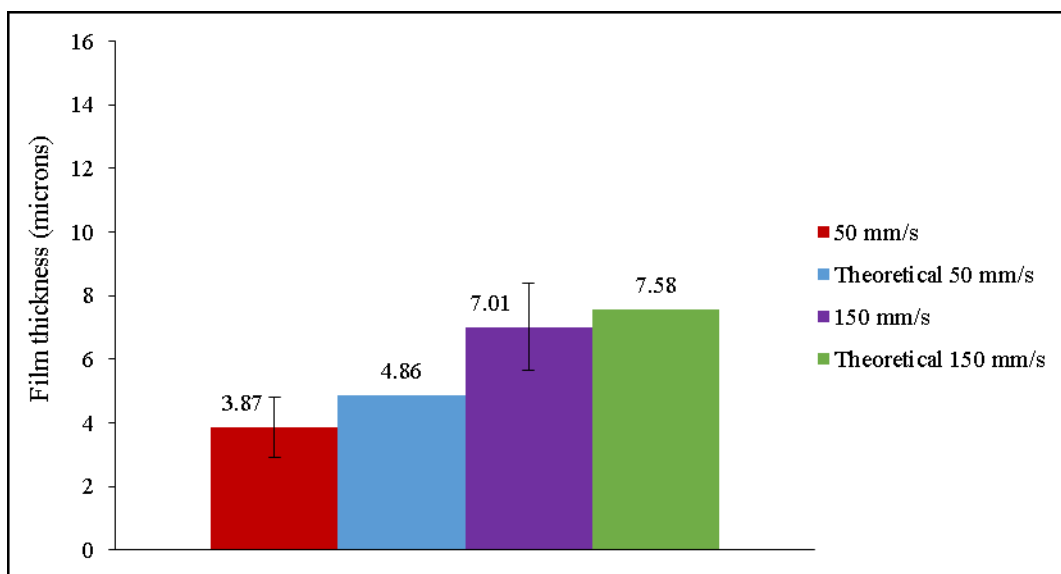


Figure 6.27: Theoretical and experimental film thickness for 1×10^6 g/mol M_w PEO in a PDMS/silicone elastomer contact

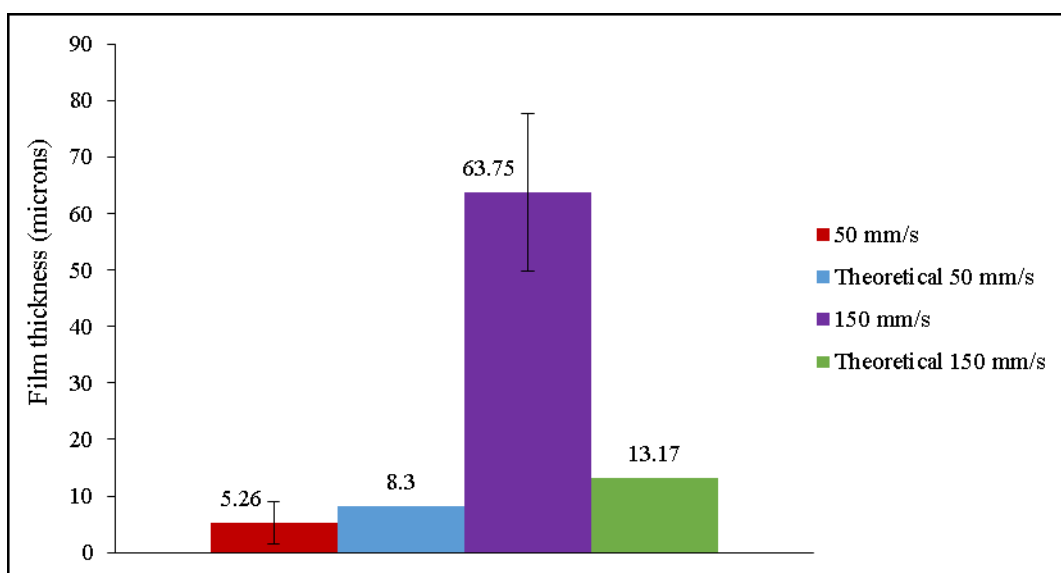


Figure 6.28: Theoretical and experimental film thickness for 2.6×10^6 g/mol M_w PEO in a PDMS/silicone elastomer contact

Figure 6.28 shows the film thickness results for 2.6×10^6 g/mol M_w PEO. This solution consistently produced variable results, with average film thickness at 150 mm/s approximately six times larger than predicted (63.75 μm). This is not in line with results for the other PEO solutions, which show better agreement with theoretical film thickness values. 2.6×10^6 g/mol M_w PEO is a combination of 1×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO. At 50 mm/s sliding speed the film thickness is similar to

that of 5×10^6 g/mol M_w PEO solution (Figure 6.29), although at high speeds the film is approximately 8 times thicker.

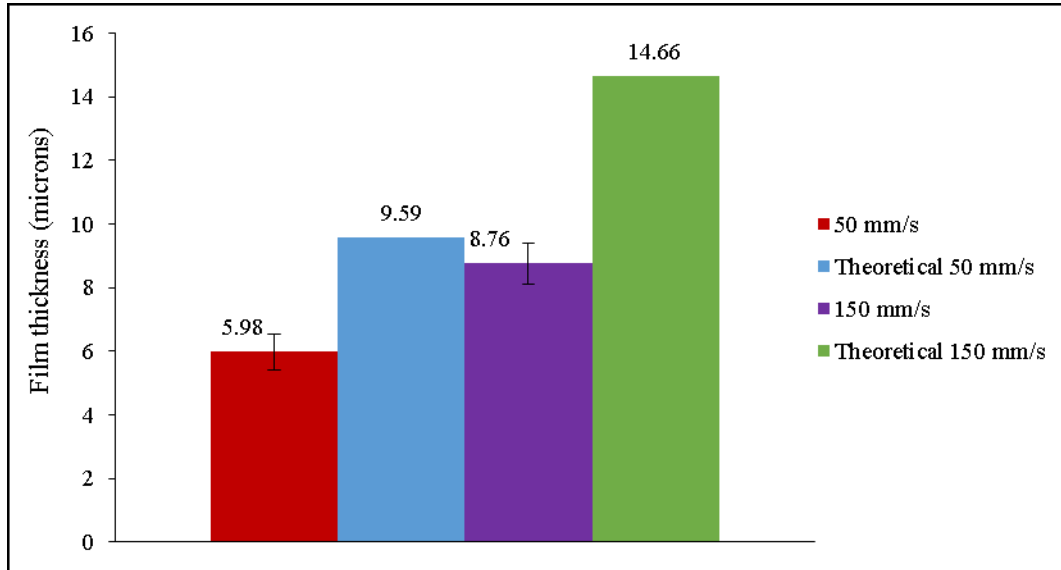


Figure 6.29: Theoretical and experimental film thickness for 5×10^6 g/mol M_w PEO in a PDMS/silicone elastomer contact

6.9. Discussion

6.9.1. Film thickness measurement

The results have shown that this LIF technique can be used to measure film thickness for compliant/hard and compliant/compliant contacts. The minimum measurable film thickness was 2 μm , and the measured calibration film thickness range was 2-135 μm . For results below 2 μm , agreement was poor.

For all reference fluids and PEO solutions (excluding 2.6×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO) no measurable film was formed in the PDMS/glass contact. For the PDMS/silicone elastomer contact, low viscosity fluids (water, Decon 90 solution and 200×10^3 g/mol M_w PEO solution at low speeds) did not form a measurable film. Where a sufficient film was formed, there was good agreement between averaged experimental film thickness results and calculated film thickness (Figure 6.30) for both the glass and silicone elastomer disc.

Greater variability between experimental and theoretical results in the silicone elastomer disc contact than the glass disc contact is not unexpected, as the calibration errors are approximately ten times larger.

Fluctuations in load were also larger for the silicone elastomer disc (≤ 0.5 N), which contributes to the variability in Figure 30b.

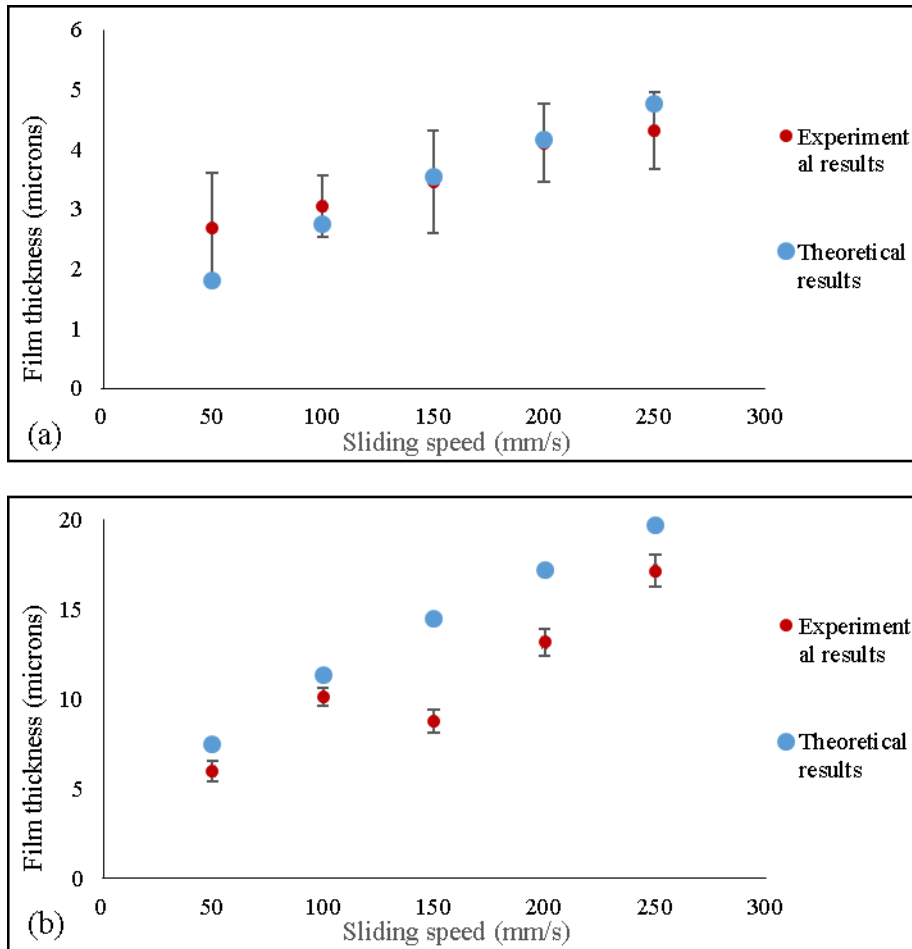


Figure 6.30: Comparison between experimental and theoretical film thickness results for $5 \times 10^6 M_w$ PEO solution in (a) PDMS/glass disc contact (b) PDMS/silicone elastomer disc contact

6.9.2. Reference fluids

Due to the lack of film thickness results for reference fluids it has not been possible to conduct a proper analysis. Results for glycerol solution in the PDMS/silicone elastomer contact showed good agreement with the theoretical calculations at sliding speed 50 mm/s (2.41 μm vs. 2.71 μm theoretical), but did not increase to the predicted value for 150 mm/s (3.27 μm vs. 4.89 μm theoretical). Xanthan gum solution experimental results did not match calculated results at either sliding speed, with values approximately ten times smaller than predicted. Reference fluids were significantly more affected by poor surface wetting than PEO solutions, and when compared to PEO solutions of a similar viscosity, PEO solutions produced greater film thicknesses. For example, xanthan gum solution ($\eta = 8.53$ mPa.s)

and 1×10^6 g/mol M_w PEO solution ($\eta = 7.16$ mPa.s) produced film thicknesses of $1.61 \mu\text{m}$ and $7.01 \mu\text{m}$ respectively in a PDMS/silicone elastomer contact with entrainment speed of 150 mm/s .

6.9.3. PEO solutions

Figure 6.31 shows the relationship between PEO solution molecular weight, film thickness, and the effect of speed. It should be noted that 2.6×10^6 g/mol M_w PEO solution results for sliding speed 150 mm/s have been omitted, as they are approximately eight times larger than the equivalent film thickness results for 5×10^6 g/mol M_w PEO solution and do not fit the trend. The average experimental film thickness for 2.6×10^6 g/mol M_w PEO solution at 150 mm/s was $63.75 \mu\text{m}$ (significantly higher than the calculated value of $11.26 \mu\text{m}$), and across the speed range the errors were as high as 494 %. Even when taking into consideration the “worst case” variability, this is very out of place. However, it occurred for each repeat test with this fluid, and was not seen for any other lubricants. The abnormal lubrication behaviour may be because the 2.6×10^6 g/mol M_w PEO is made up of a combination of 1×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO, which is producing unusual effects. Further investigation into the rheology of this solution is required to reach a conclusion, however that is outside of the scope of this thesis.

Increasing sliding speed increases the in-contact film thickness. This is due to increased entrainment into the contact [42]. Increasing molecular weight also causes an increase in film thickness, which is expected due to higher molecular weight PEO solutions possessing higher viscosities. [42].

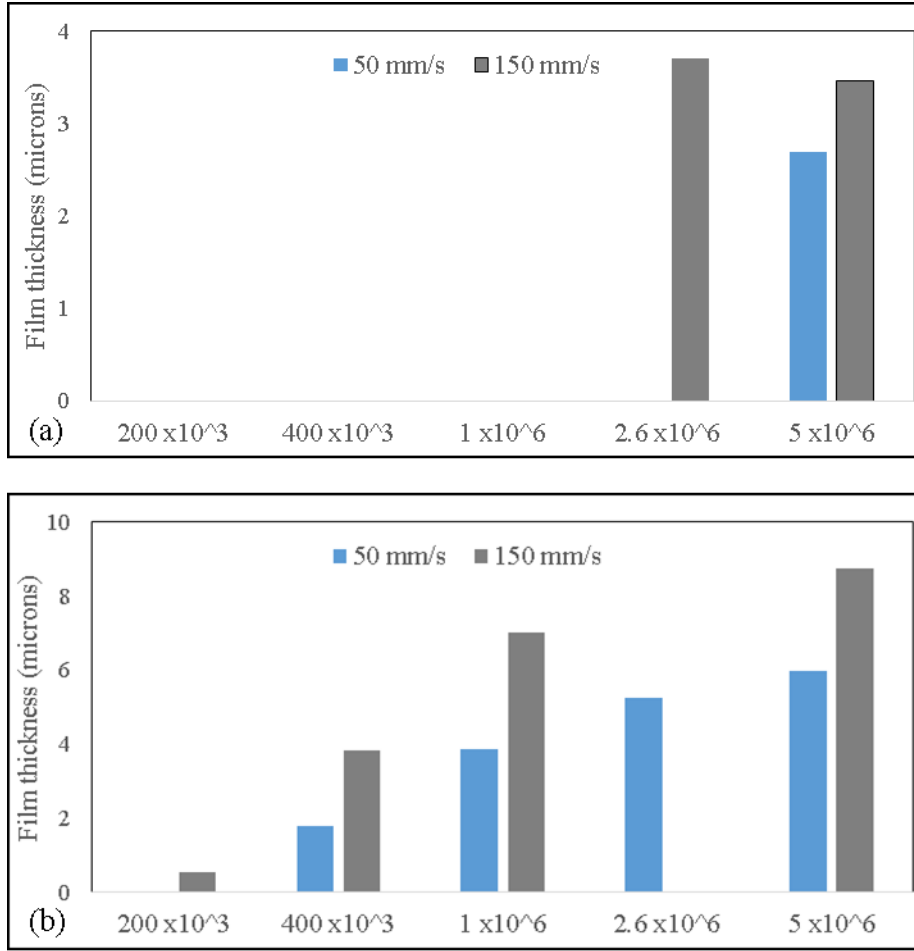


Figure 6.31: Relationship between PEO solution molecular weight and film thickness for (a) PDMS/glass contact (b) PDMS/silicone elastomer contact

Changing the hard glass disc to a compliant silicone elastomer coated disc produced significantly increased film thickness measurements, and reduced the effect of poor surface wetting and entrainment. In many cases it facilitated the formation of a measurable film, which had not been present in the glass disc contact. The silicone elastomer has a much lower Young's modulus than glass (200 kPa compared to 74 GPa), and is therefore able to deform away from the load, reducing contact pressure. The addition of a second compliant material to the contact reduces contact pressure from $\sim 2 \times 10^3$ Pa to ~ 260 Pa, enabling increased contact deformation, which encourages entrainment of lubricant into the contact through increased squeeze flow [43, 44]. The approximate film thickness in squeeze flow can be calculated using Equation 6.6 [44], which shows that as pressure decreases, film thickness increases.

$$h \approx \sqrt{\frac{\eta L^2}{2Pt}} \quad (6.6)$$

Starvation and reflow mechanisms are discussed in more detail in Chapter 9.

6.10. Conclusions

A LIF method has been successfully developed to image fluid flow and measure film distribution in and around a compliant contact with fluorescent images. Initial tests are reported for a simple circular contact using a PDMS ball against a glass or silicone elastomer disc. The results have shown that:

- LIF is an appropriate method for film thickness imaging in either a compliant/hard or compliant/compliant contact.
- Calibration between fluorescent intensity and film thickness was successful
- The minimum measurable film thickness was $2 \pm 0.4 \mu\text{m}$ for a glass counterface, and $2^{+3.1}_{-2} \mu\text{m}$ for the silicone elastomer. The measured calibration film thickness range was 2-135 μm .
- Experimental film thickness speed sweep results compared well with theoretical calculations.
- Thicker lubricant films are formed in compliant/compliant contacts than compliant/hard contacts, and film thickness increases with speed.
- PEO solutions form thicker films than reference fluids, particularly in compliant/compliant contacts. This indicates that they may be better suited to lubricating the skin/cartridge contact in shaving than the reference fluids studied here for increased protection of skin from the blades.
- PEO film thickness increases with the molecular weight (and viscosity) of the solution.
- $2.6 \times 10^6 \text{ g/mol } M_w$ PEO showed highly unusual and unexpected film thickness results for all repeat tests. This may be because it consists of a combination of $1 \times 10^6 \text{ g/mol } M_w$ PEO and $5 \times 10^6 \text{ g/mol } M_w$ PEO. Further investigation into the rheology of this solution is required to reach a conclusion, however that is outside of the scope of this thesis – the project aim is to understand razor cartridge lubrication, which further analysis of $2.6 \times 10^6 \text{ g/mol } M_w$ PEO does not support at this stage.

6.11. References

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7. LIF FLUID FLOW AND FILM THICKNESS MEASUREMENTS FOR REFERENCE FLUIDS IN A RAZOR CARTRIDGE

Summary

In the previous Chapter laser induced fluorescence was established as a valid technique for observing lubricant flow in a compliant contact. In this Chapter the technique is applied to a shaving cartridge/complaint contact. The experiments were conducted with a Gillette razor cartridge loaded and sliding against a glass disc and a silicone elastomer coated disc, with reference fluids lubricating the contact. The aim was to visualise lubricant flow and measure film thickness in the razor cartridge contact. It was found that the guard and Lubrastrip maintain relatively thick and consistent lubricant films across the speed range, and minimum films are measured at the blade cutting edges. For some lubricants film thickness increases towards the back of the cartridge. Fluid viscosity affected lubrication, with much lower films measured at high speeds for high viscosity (glycerol and xanthan gum) solutions. Film thickness typically decreases with increasing sliding speed, and a compliant (silicone elastomer) counterface allows formation of a thicker lubricant film than a hard (glass) counterface. The presence of the guard improves razor cartridge lubrication by stabilising film thickness across the blade cutting edge interfaces.

7.1. Introduction

Chapter 6 described a LIF technique that was suitable for measuring lubricant films in compliant contacts, with film thickness values of micron magnitude. It was possible to visualise lubricant distribution across the contact profile and measure film thickness.

This Chapter further develops the LIF technique to study lubrication in a razor cartridge contact. Experiments were carried out with reference fluids to examine fluid flow and local film thickness in the

cartridge contact. Calibration methods and experimental conditions remained the same as in Chapter 6, and the effect of a complex line contact (the razor cartridge) on lubrication was observed. This will provide information that can be combined with friction test results to understand lubricant response and how this might affect the razor cartridge user's perception of shaving comfort.

7.2. Experimental conditions

The experiments in this Chapter follow the same methodology as described in Chapter 6, unless otherwise described here. Optical and loading equipment remain unchanged, as does the calibration, image capture and data processing method.

7.2.1. Razor cartridge/disc contact

A Gillette razor cartridge was mounted onto a specially designed support, which replaced the spacer and ball in Chapter 6 (Figures 7.1 and 7.2). The design of the razor cartridge allows it to pivot in the xy axis, self-aligning with the surface that it is loaded against (i.e. facial skin).

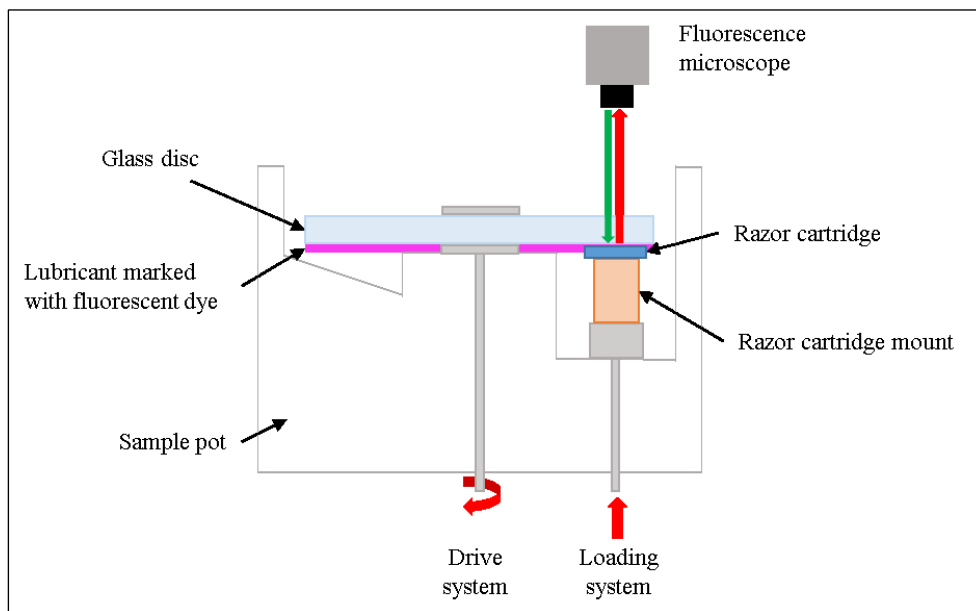


Figure 7.1: LIF setup for razor cartridge/glass disc contact

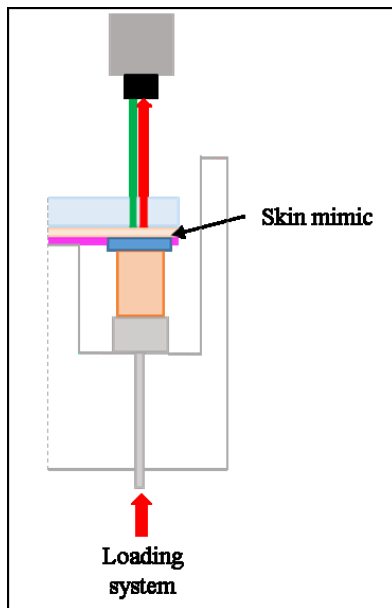


Figure 7.2: Addition of skin mimic coating to the LIF setup for razor cartridge contact setup

The razor cartridge and razor cartridge mount is shown in Figure 7.3, and the location within the LIF rig in Figure 7.4. It was aligned such that the blades were perpendicular to the direction of sliding, as this would best replicate a “real life” shaving contact.



Figure 7.3: Razor cartridge mount for LIF tests

The camera was aligned to capture lubricant distribution through the middle section of the cartridge (Figure 7.4), and the field of view was 3 mm. Due to this relatively small field of view, it was necessary to capture data for the whole cartridge in 5 segments:

1. Guard
2. Back of guard and blade 1
3. Blades 2 and 3
4. Blades 4 and 5

5. Lubrastrip

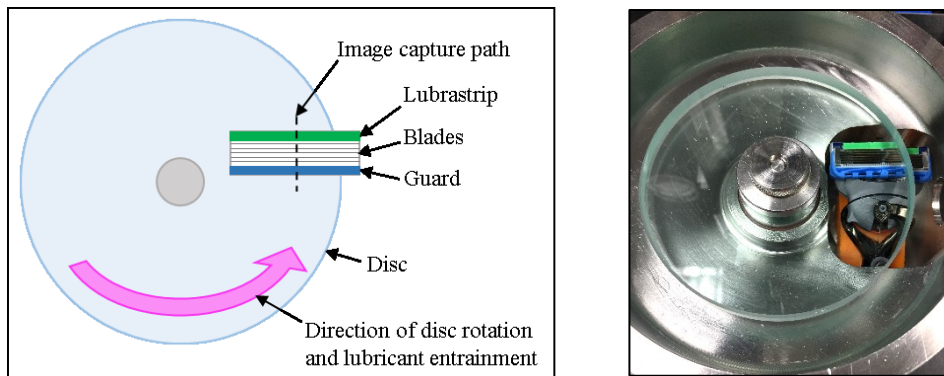


Figure 7.4: Razor cartridge location in LIF rig

The razor cartridge is made up of three components (guard, blades and Lubrastrip), and each of these are made from a different material, creating a complex contact where mechanical properties change as the lubricant progresses through the cartridge. Table 7.1 lists the contact materials for the contact, including the glass disc and silicone elastomer skin mimic.

Table 7.1: Mechanical properties of contact materials

Material	Type	Young's Modulus, Pa
Glass	BK7, PCS Instruments, UK	65×10^9
Silicone Elastomer	MED-6021, Polymer Systems Technology Ltd., U.K.	200×10^3
Guard	PolyOne TPE elastomer	50×10^6 [1]
Blade	Coated stainless steel	205×10^9

One of the effects of changes in contact mechanical properties is that it will affect the contact pressures. Contact pressure changes for the razor cartridge against a glass disc and a silicone elastomer disc are very difficult to calculate due to the complex geometry of the razor cartridge and component material mechanical properties. However values calculated in Chapter 6 for the ball-on-disc contact illustrate the changes in contact pressure with contact surface material. It can therefore be speculated that the highest film thickness will occur at the guard/silicone elastomer interface – a compliant/compliant contact – and the lowest film thicknesses at the blade/glass interface – a hard/hard contact.

7.2.2. Lubricants

Reference fluids are described in Chapter 4. The same application method was used as described in Chapter 6.

5 ml of lubricant was pipetted onto the disc, which provided ample lubrication supply during each test. Due to increased hydrophilicity from plasma cleaning of the discs prior to testing (described in Chapter 4), lubricants did not succumb to gravity and leave the disc surface, despite coating the lower face of the disc. Film thickness was not restricted before the contact interface for two reasons:

1. “Real life” shaving occurs in fully-flooded conditions.
2. The guard will prevent excess fluid from entering the blade contact and self-regulate inlet film thickness.
 - a. Comparison experiments without the guard will be conducted to show its effect on blade lubrication.

7.2.3. Test profile

Table 7.2 shows the test profiles for these experiments. They are designed to replicate “real-life” shaving and correspond with the MTM test profiles. The disc specimens were cleaned according to the standard described in Chapter 4. The razor cartridge was washed prior to each test with isopropanol, followed by detergent and deionised water.

The razor cartridges used in these experiments no-longer contained a supply of PEO in the Lubrastrip, although the polystyrene mesh was still present. This ensured that any PEO that would have been supplied from the razor cartridge did not interfere with test fluid lubrication.

Experimental film thickness values were calculated by averaging data from three separate tests. Within each experiment 25 intensity readings were recorded for every speed range.

Table 7.2: LIF experimental conditions

Load	2.5 N
Temperature	25 °C
SRR	200 %
Sliding speed	50 mm/s
	150 mm/s
Disc material	Glass
	Silicone elastomer

7.3. Results: structure

The results in this Chapter are split into two sections, and four sub-sections:

1. Glass disc: (a) with guard (b) without guard
2. Silicone elastomer disc: (a) with guard (b) without guard

The results from each sub-section will be shown as intensity images (for distilled water and glycerol solution) and film thickness graphs (all lubricants). In the intensity images razor cartridge components are clearly visible, and lubricant location is depicted using an intensity colour-scale whereby red indicates large quantities of lubricant, and blue indicates a lack of lubricant. Film thickness graphs show the cross-section profile of the average film thickness measured from the fluorescence intensity images. Figure 7.5 shows example results, on which the lubricant direction and fluorescence measurement path are annotated. These notes apply to all results in this Chapter.

The images were chosen to show typical LIF intensity through the cartridge (Figure 7.5b) for the different test conditions and fluid types. The graphs plot average film thickness calculated from all test measurements (Figure 7.5c). Overall the repeatability of film thickness distribution and changes due to fluid type, contact condition and speed were good however some anomalies remain and these issues are discussed in more detail in Chapter 9.

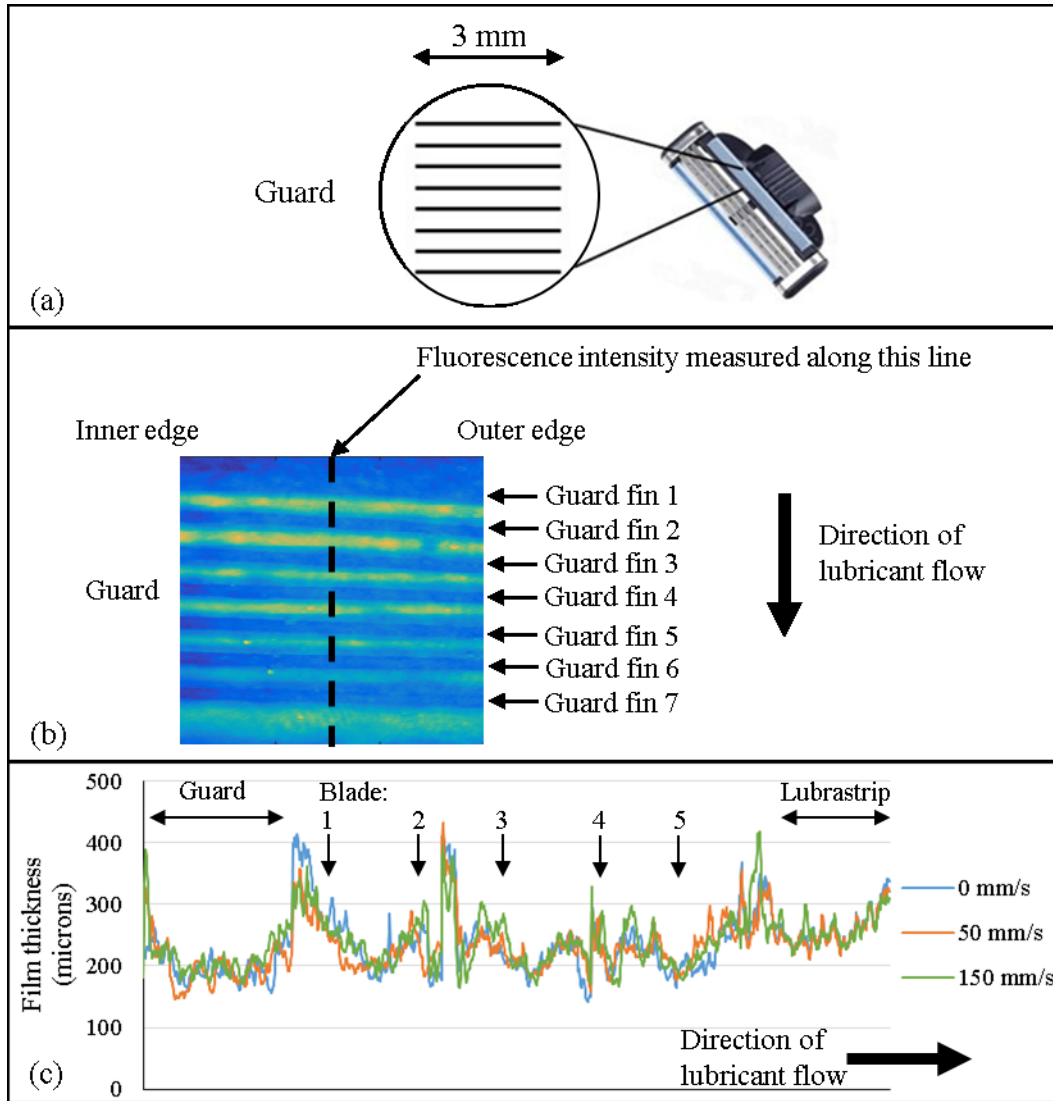


Figure 7.5: (a) Field of view (b) fluorescence intensity measurement path and direction of lubricant flow as shown in LIF image results; (c) direction of lubricant flow as shown in film thickness profile results.

7.4. Results: glass disc

LIF results are shown in Figures 7.6-7.8 for the razor cartridge against glass at sliding speeds of 50 mm/s and 150 mm/s with guard present, and Figures 7.9-7.11 without the guard present.

7.4.1. With guard present

In the LIF images from Figures 7.6 and 7.7 it is possible to see the cartridge components, particularly for the glycerol solution at 150 mm/s (Figure 7.7). Here, the cartridge components cause significant

changes in lubricant film thickness (and therefore fluorescence intensity), which makes them more visible.

For both examples the guard holds lubricant between the fins, allowing a reduced amount of fluid to flow through to the blades (which is possible due to the high flexibility of the material and guard structure). Across the blades there is a lower lubricant film thickness at the front of the blade than at the back, with large amounts of fluid underneath the Lubrastrip.

Comparing film thickness profiles from Figure 7.8, lubricants with higher viscosity produce greater variation in film thickness across the blades. Values for the guard (minimum 100 μm) and Lubrastrip (minimum 150 μm) are high for all lubricants.

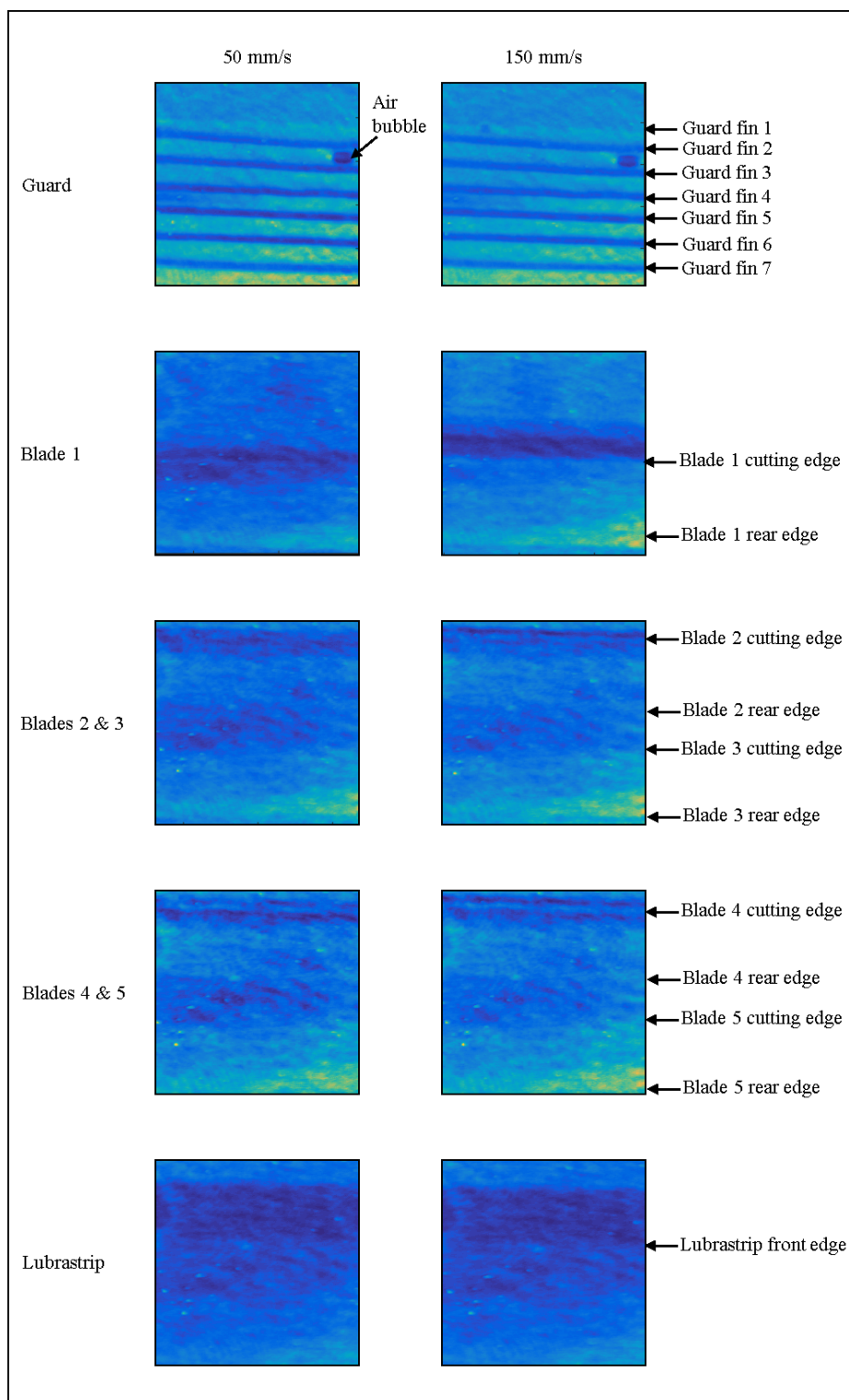


Figure 7.6: LIF images from shaving cartridge against glass disc lubricated by distilled water at 50 mm/s and 150 mm/s

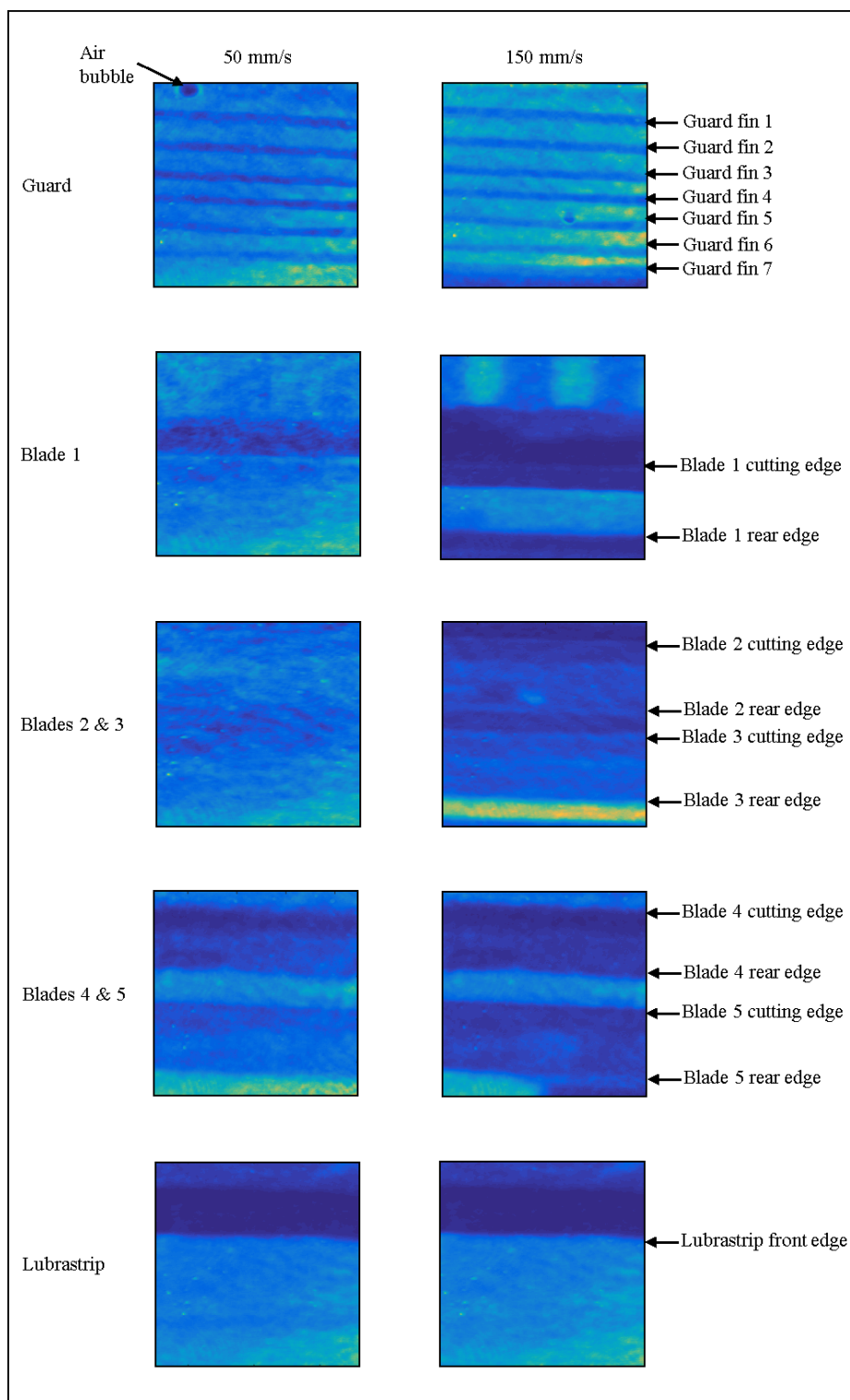


Figure 7.7: LIF images from shaving cartridge against glass disc lubricated by glycerol solution at 50 mm/s and 150 mm/s

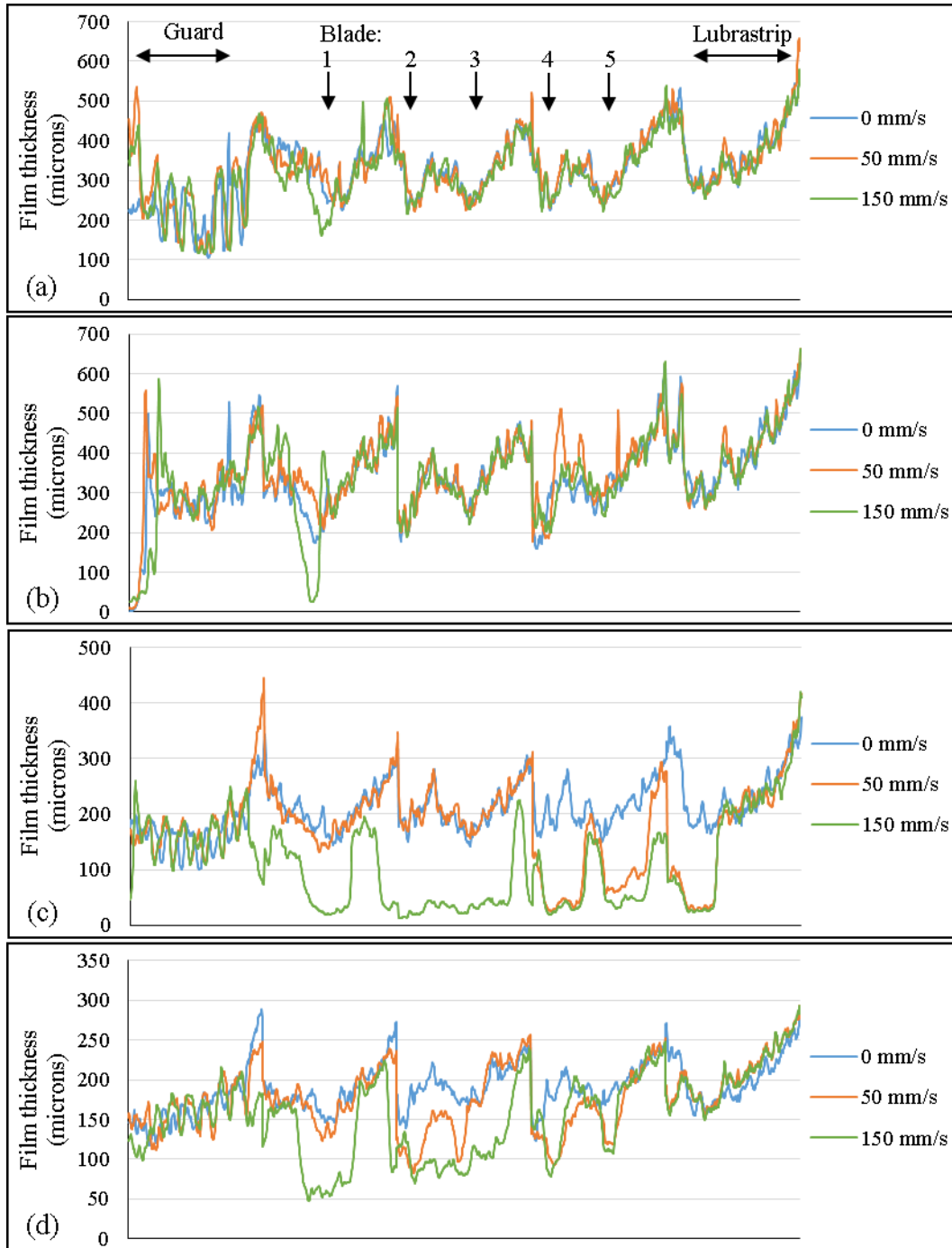


Figure 7.8: Typical film thickness profiles of reference fluids between razor cartridge and glass with the guard present. (a) distilled water (b) Decon 90 (c) glycerol (d) xanthan gum solutions

7.4.2. Without guard present

Figures 7.9-7.11 show LIF image and film thickness profile results for the razor cartridge/glass contact without the guard present. Removing the guard from the razor cartridge reduces film thickness under

the blade cutting edges for all lubricants except for glycerol solution, where the film thickness increases, indicating that the guard restricts glycerol solution flow into the blade contact.

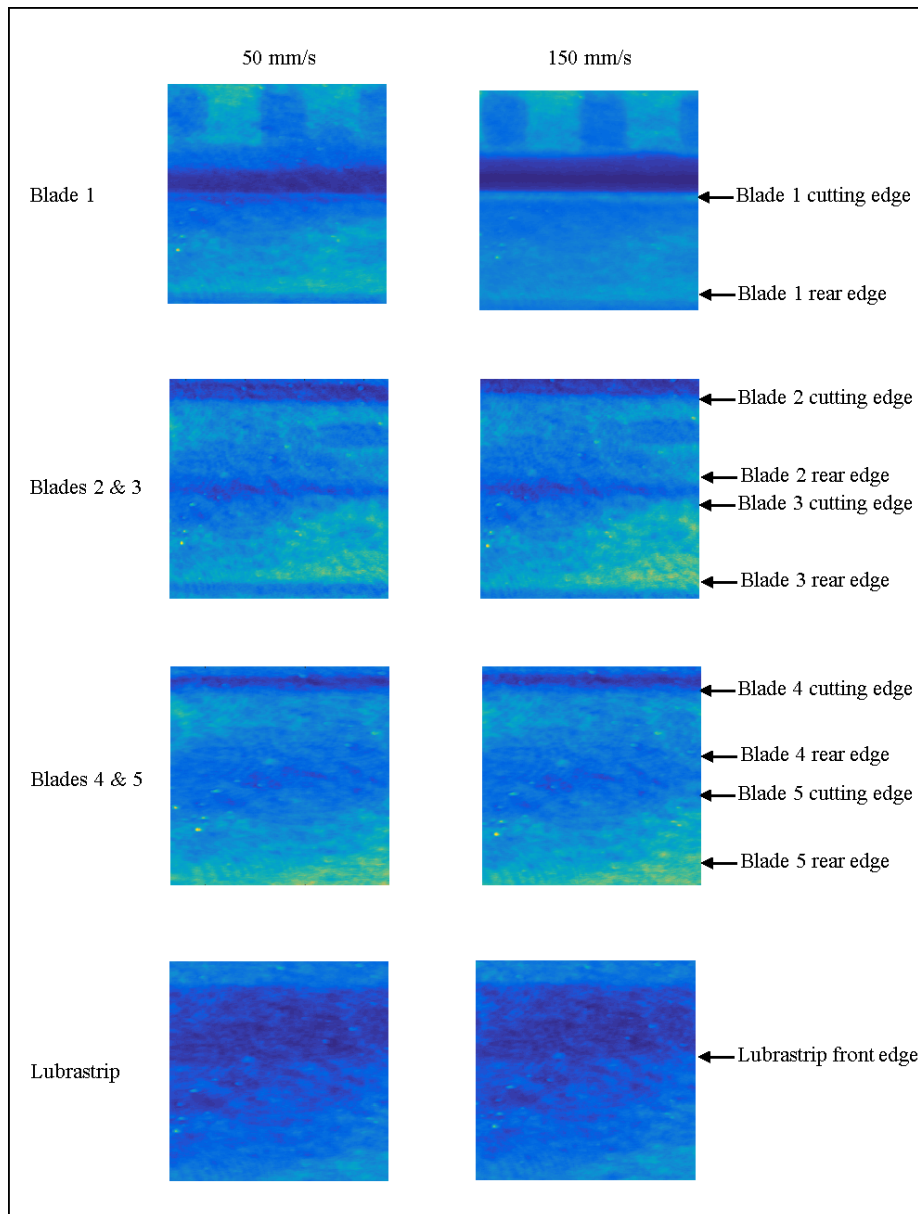


Figure 7.9: LIF images from shaving cartridge (without guard present) against glass disc lubricated by distilled water at 50 mm/s and 150 mm/s

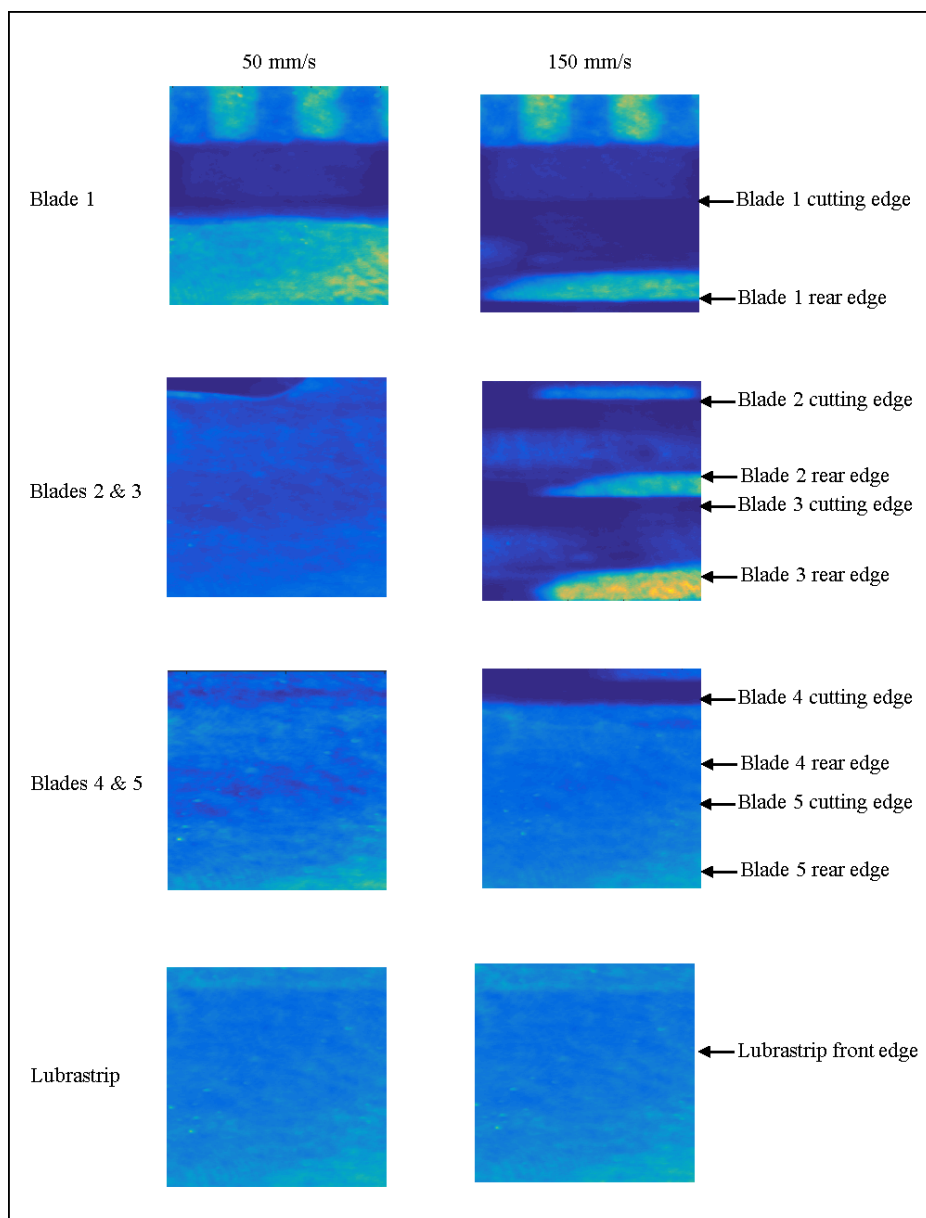


Figure 7.10: LIF images from shaving cartridge (without guard present) against glass disc lubricated by glycerol solution at 50 mm/s and 150 mm/s

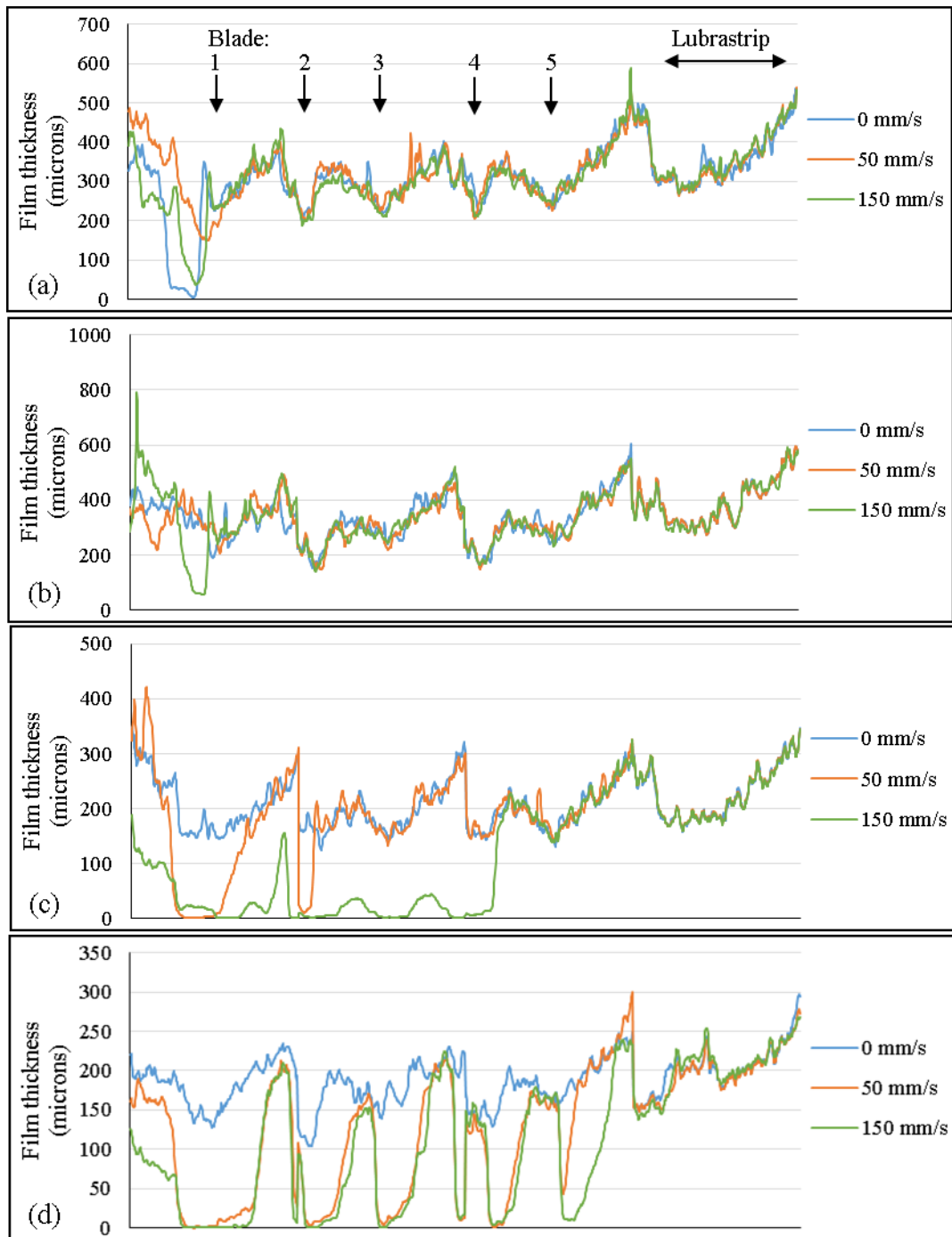


Figure 7.11: Typical film thickness profiles of reference fluids between razor cartridge and glass without the guard present. (a) distilled water (b) Decon 90 (c) glycerol (d) xanthan gum solutions

7.5. Results: silicone elastomer

Film thickness results are shown in Figures 7.12-7.14 for the razor cartridge against silicone elastomer at sliding speeds of 50 mm/s and 150 mm/s with guard present, and Figures 7.15-7.17 without the guard present.

7.5.1. With guard present

There is more lubricant in the contact than for the glass disc, as not only is the location of razor cartridge components less obvious, but in Figures 7.12 and 7.13 the guard is almost entirely separated from the silicone elastomer by the lubricant film.

A more even lubricant film thickness distribution compared to the glass contact is shown in Figure 7.14. Film thickness minimums still occur under blade edges, but unlike for glass there is a measurable lubricant film present.

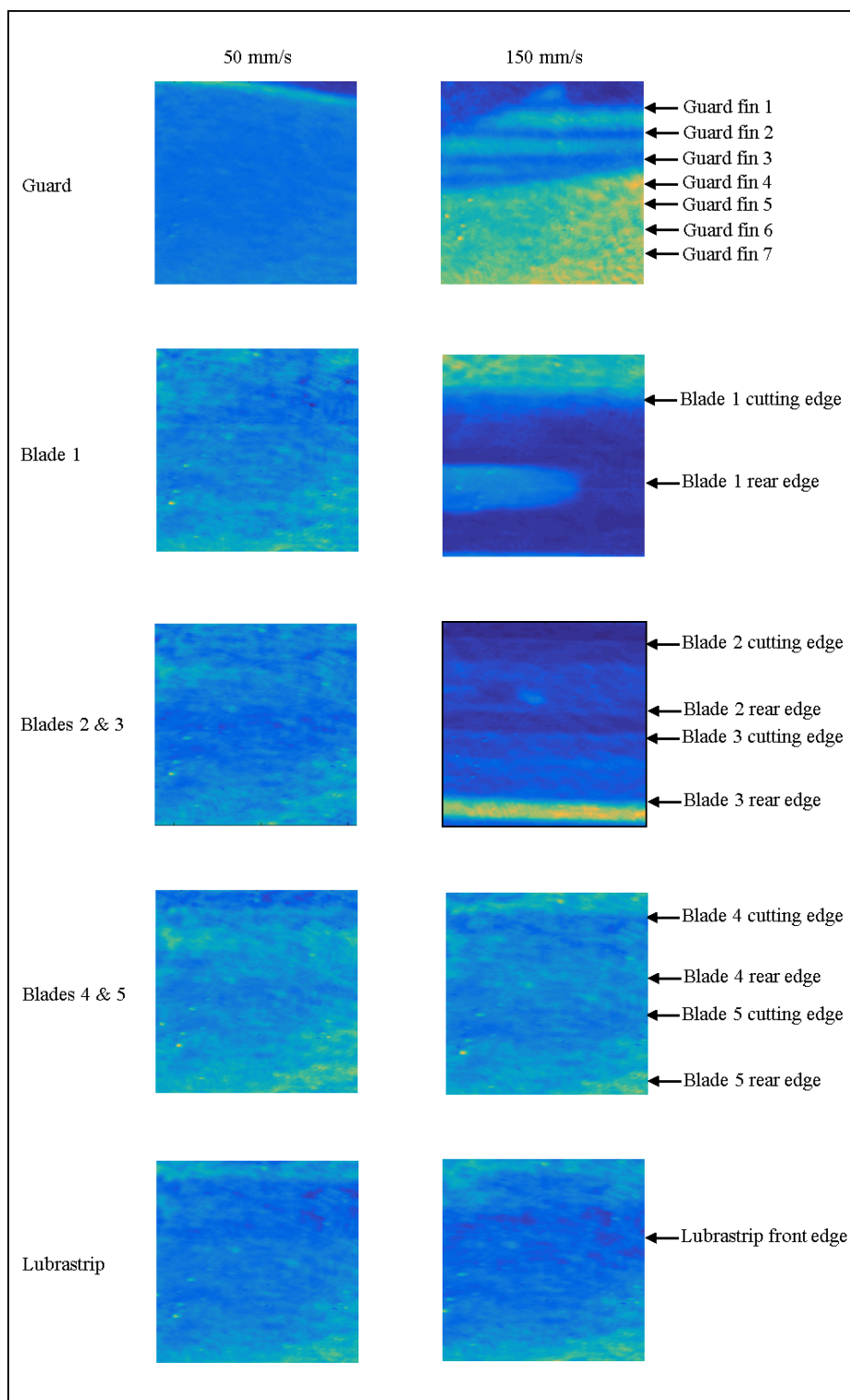


Figure 7.12: LIF images from shaving cartridge against silicone elastomer disc lubricated by distilled water at 50 mm/s and 150 mm/s

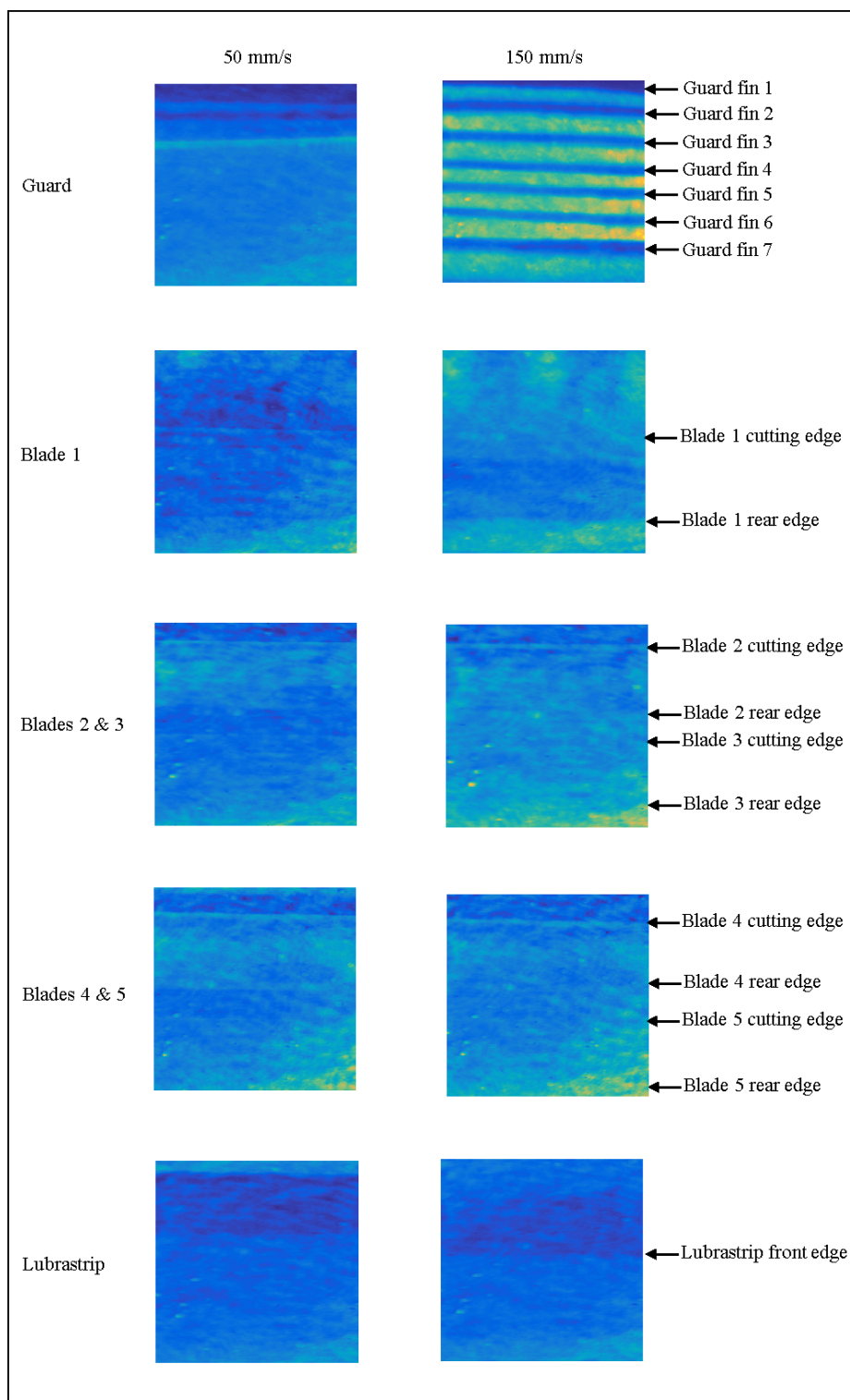


Figure 7.13: LIF images from shaving cartridge against silicone elastomer disc lubricated by glycerol solution at 50 mm/s and 150 mm/s

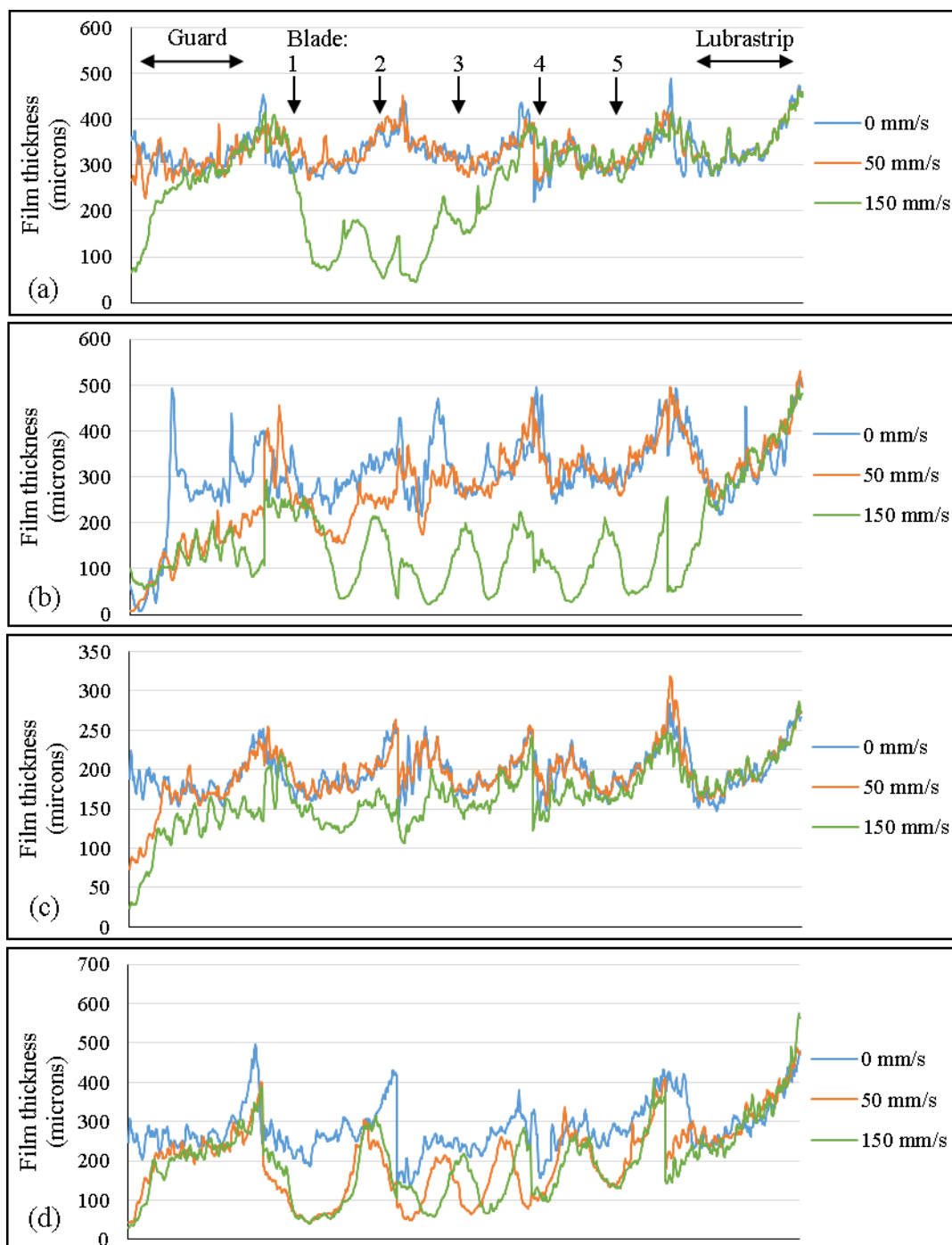


Figure 7.14: Typical film thickness profiles of reference fluids between razor cartridge and silicone elastomer with the guard present. (a) distilled water (b) Decon 90 (c) glycerol (d) xanthan gum solutions

7.5.2. Without guard present

The contrast in fluorescence intensity for presence and absence of lubricant is visible in Figure 7.16, where there is a lack of lubricant under the blade edges 1-3, but a film is formed towards the back of

blades 1-3 and across the remaining half of the razor cartridge. Due to the rotational motion of the disc in the LIF rig, it is possible for lubricant to be drawn into the contact from the outer edge, and travelling transversely into the cartridge.

Film thickness profiles (Figure 7.17) show that removing the guard creates either an increase or more even distribution of lubricant under the razor cartridge, except for the glycerol solution where film thickness is actually reduced, particularly towards the front of the cartridge. For this lubricant the action of the guard in controlling inlet film thickness to the blades appears to improve lubrication. These results are in contrast to the glass contact, where removing the guard decreased film thickness for all lubricants except glycerol solution, where film thickness increased.

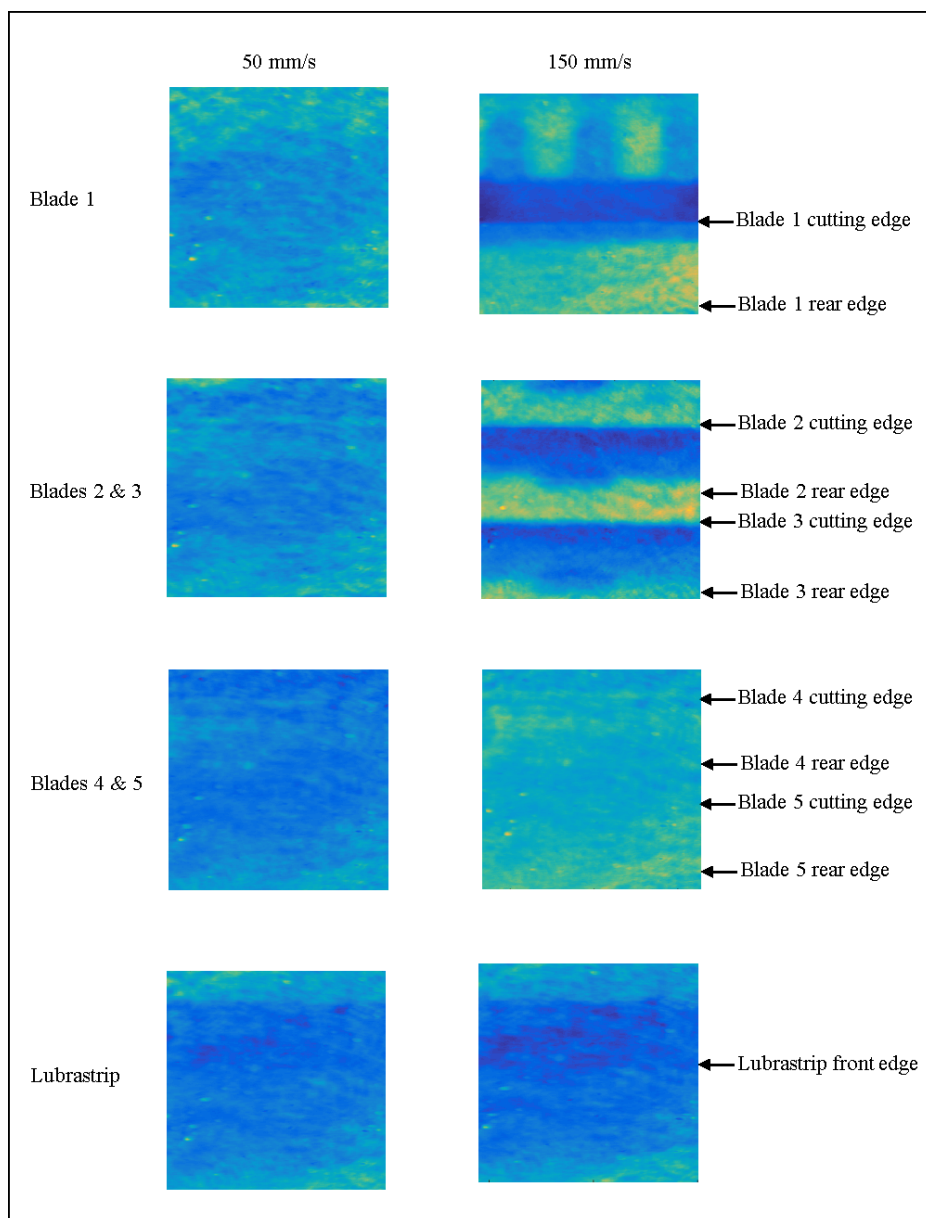


Figure 7.15: LIF images from shaving cartridge (without guard present) against glass disc lubricated by distilled water at 50 mm/s and 150 mm/s

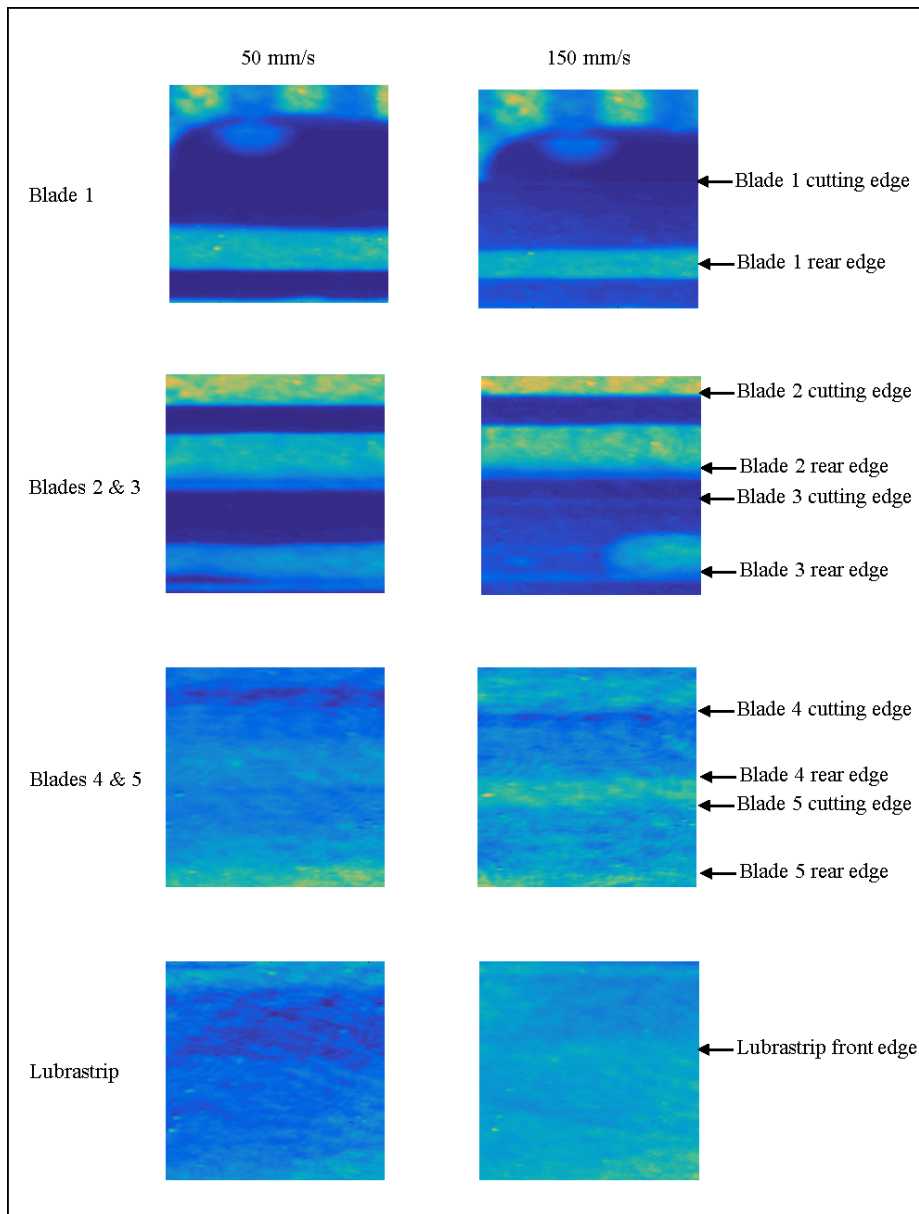


Figure 7.16: LIF images from shaving cartridge (without guard present) against glass disc lubricated by glycerol solution at 50 mm/s and 150 mm/s

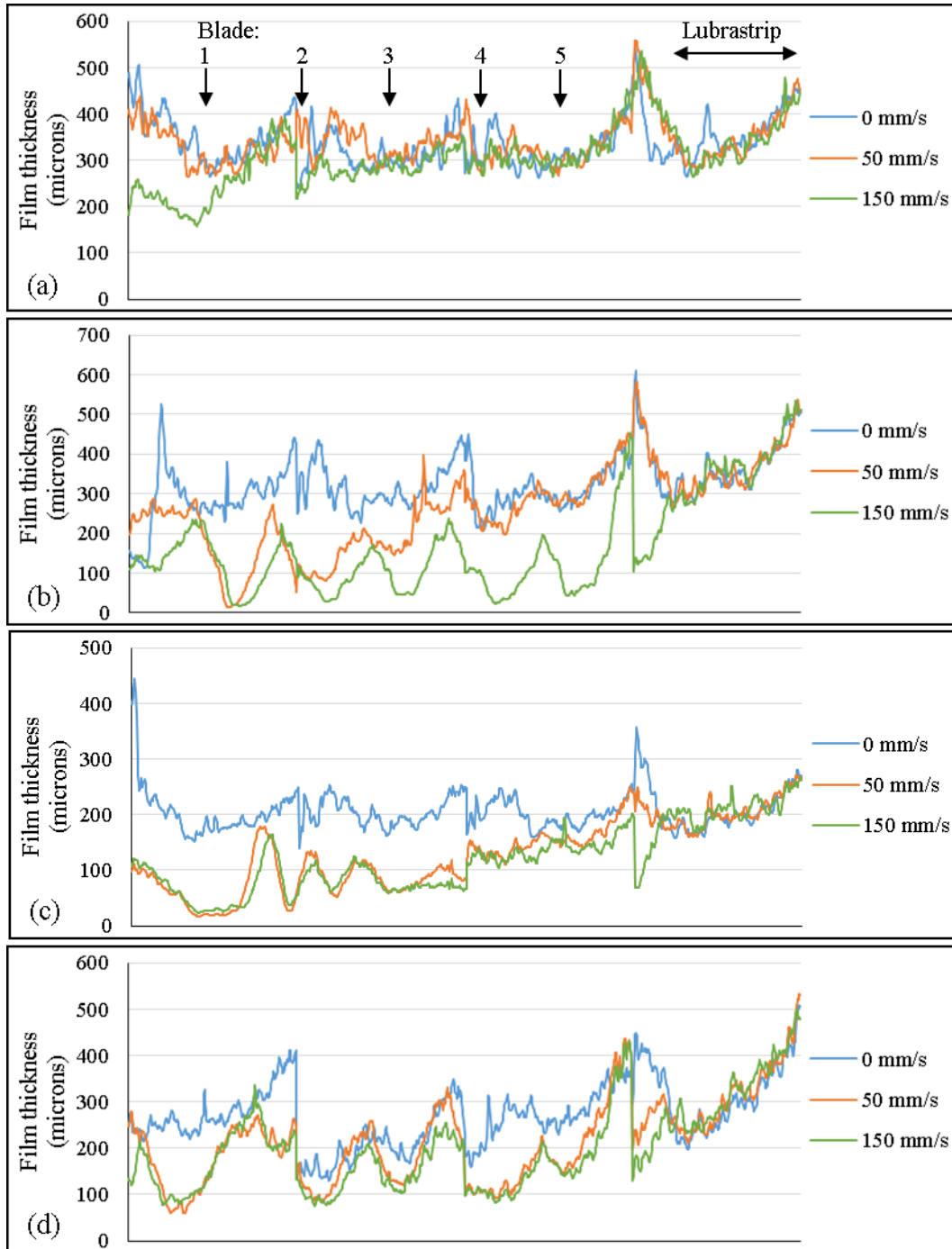


Figure 7.17: Typical film thickness profiles of reference fluids between razor cartridge and silicone elastomer without the guard present. (a) distilled water (b) Decon 90 (c) glycerol (d) xanthan gum solutions

7.6. Discussion

The LIF method has been successfully applied the razor cartridge contact; it allows visualisation of reference lubricant distribution through the cartridge and measurement of film thickness at the contact interfaces. The effects of different counterface material (glass/silicone elastomer), presence of guard

and sliding speed on film distribution are discussed in this section. The effect of reference fluid properties on film thickness is considered in more detail in Chapter 9.

A thick lubricant film (10-300 μm) is formed for all solutions underneath the cartridge. The typical lubricant distribution is as follows:

- Guard: the guard traps lubricant between the fins, which can be clearly seen for some conditions. It has not yet been shown whether or not the guard acts as a distribution reservoir for lubricating the successive blades. Film thickness is in the range 100-350 μm for glass and silicone elastomer counterfaces.
- Blades: minimum lubricant film thickness occurs at the blade cutting edges, particularly for the high viscosity fluids as the speed increases. Films down to 15 μm were measured for glycerol solution in a glass contact.
- Lubrastrip: after the blades film thickness recovers to 150-600 μm for glass and 150-500 μm for silicone elastomer counterfaces.

The effect of reference fluid properties on film thickness will be discussed in Chapter 9.

7.6.1. Hard or compliant counterface

The effect of a hard (glass) or compliant (silicone elastomer) counterface on film formation are summarised in Figure 7.18 for the guard, blade 1, blade 5 and Lubrastrip components, with a sliding speed of 50 mm/s.

Changing the counterface from a hard to a compliant material does not necessarily produce an increase in film thickness (due to reduced contact pressure). For example, Decon 90 solution produces a consistently lower film thickness for the silicone elastomer contact from the guard to blade 5. The effect of the compliant counterface appears to be dependent on lubricant properties; a compliant counterface in the glycerol solution lubricated system promotes a consistent film thickness from the Lubrastrip to blade 5, but xanthan gum solution produces a consistent film thickness for the glass surface rather than the silicone elastomer.

At the guard interface, film thickness is higher in the silicone contact for all lubricants except for Decon 90 solution, where the film thickness reduces by over half. At blade 1 film thickness remains higher in the silicone elastomer contact for distilled water and glycerol solution, but for Decon 90 and xanthan gum solution the film thickness is higher in the glass contact. At blade 5 xanthan gum solution film thickness recovers, and film thickness is now higher than for the silicone counterface.

At the Lubrastrip contact film thickness is consistently higher in the silicone elastomer contact compared to glass.

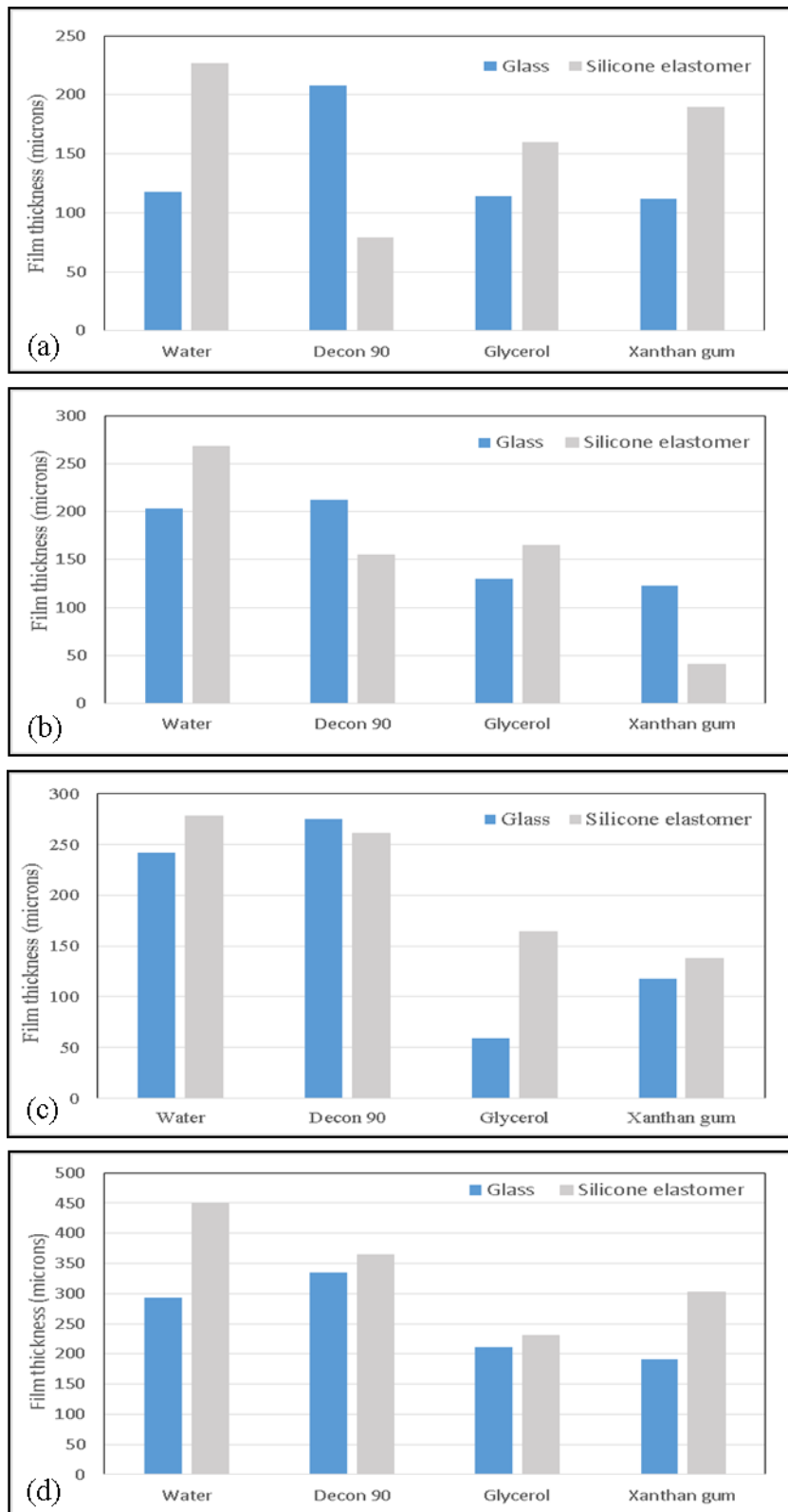


Figure 7.18: Effect of silicone elastomer layer on film thickness for (a) guard (b) blade 1 (c) blade 5 (d) Lubrastrip

7.6.2. Guard presence: glass disc

Figures 7.19 and 7.20 show average film thickness results between the razor cartridge and glass disc at 50 mm/s and 150 mm/s, with the guard present (Figure 7.19) and without the guard present (Figure 7.20). When the guard is present, film thickness underneath the blade cutting edge is more consistent through the razor cartridge, and all lubricants form a thick film.

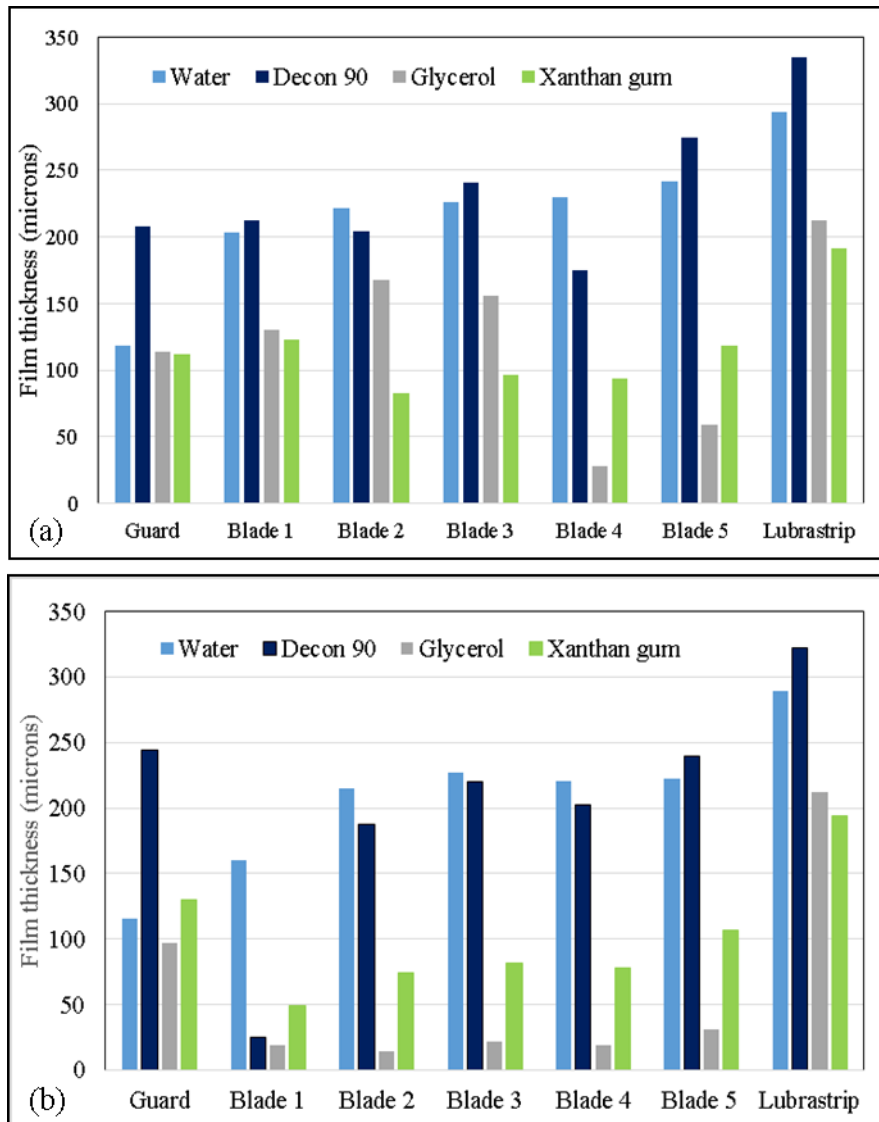


Figure 7.19: Average film thickness results for reference fluids between razor cartridge and glass with guard present (a) 50 mm/s (b) 150 mm/s

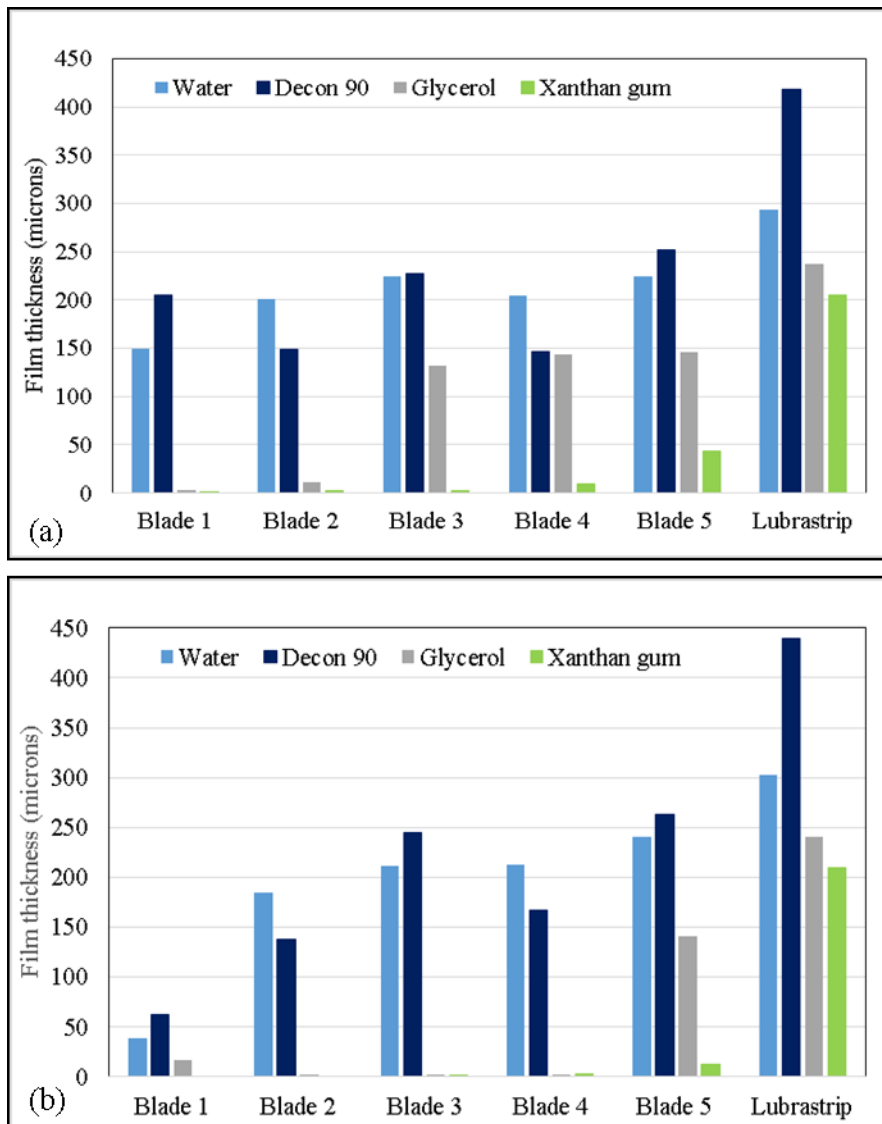


Figure 7.20: Average film thickness results for reference fluids between razor cartridge and glass without guard present (a) 50 mm/s (b) 150 mm/s

The effect of removing the guard is shown more clearly when analysing results from blade 1 and blade 5 only (Figure 7.21 and 7.22). Removing the guard does not necessarily produce an increase in film thickness, and for some lubricants it reduces to zero (or close to) under blade 1 (Figure 7.21). The lubrication at the front of the razor cartridge is improved by the presence of the guard, particularly at the lower speed of 50 mm/s. At the back of the razor cartridge (blade 5, Figure 7.22) removing the guard decreases the effect of reducing film thickness with increasing sliding speed for all fluids except xanthan gum solution, where film thickness is higher when the guard is present. Xanthan gum solution has a high viscosity, but also shear thins under shear forces.

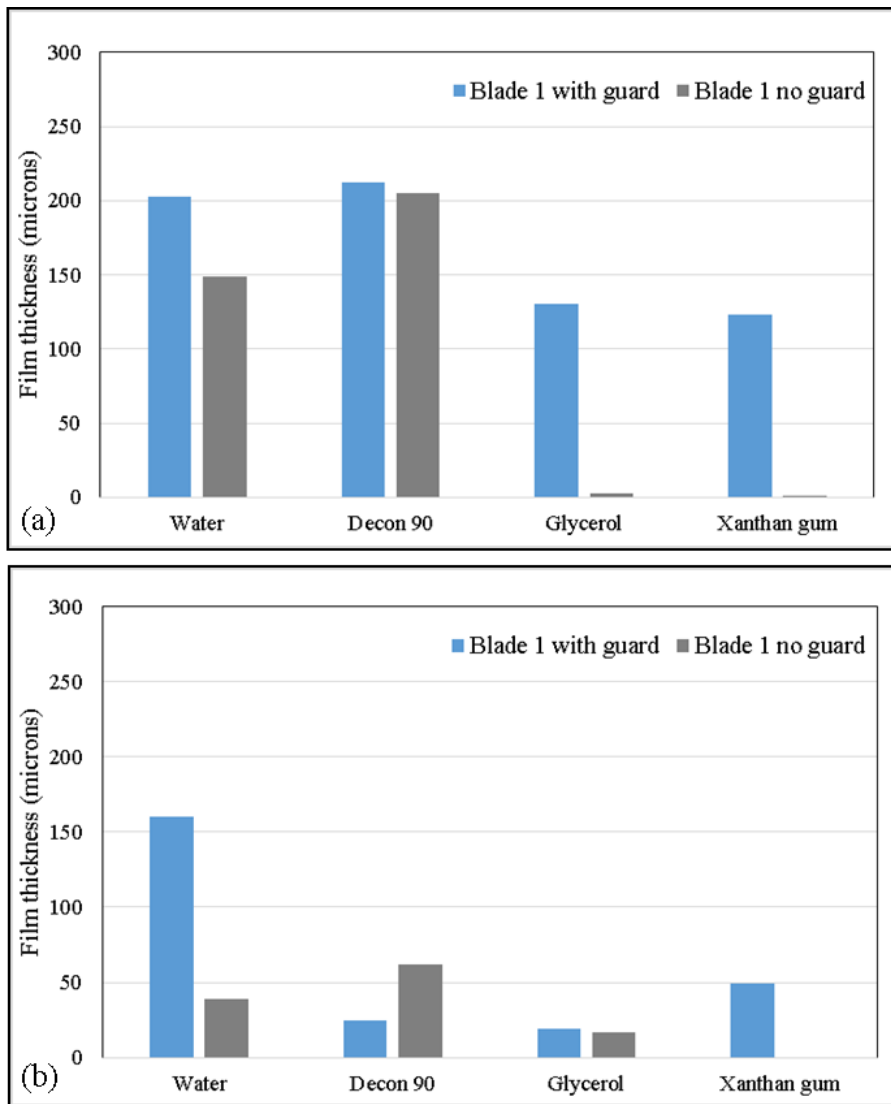


Figure 7.21: Effect of guard on film thickness: Blade 1. For reference fluids between razor cartridge and glass (a) 50 mm/s (b) 150 mm/s

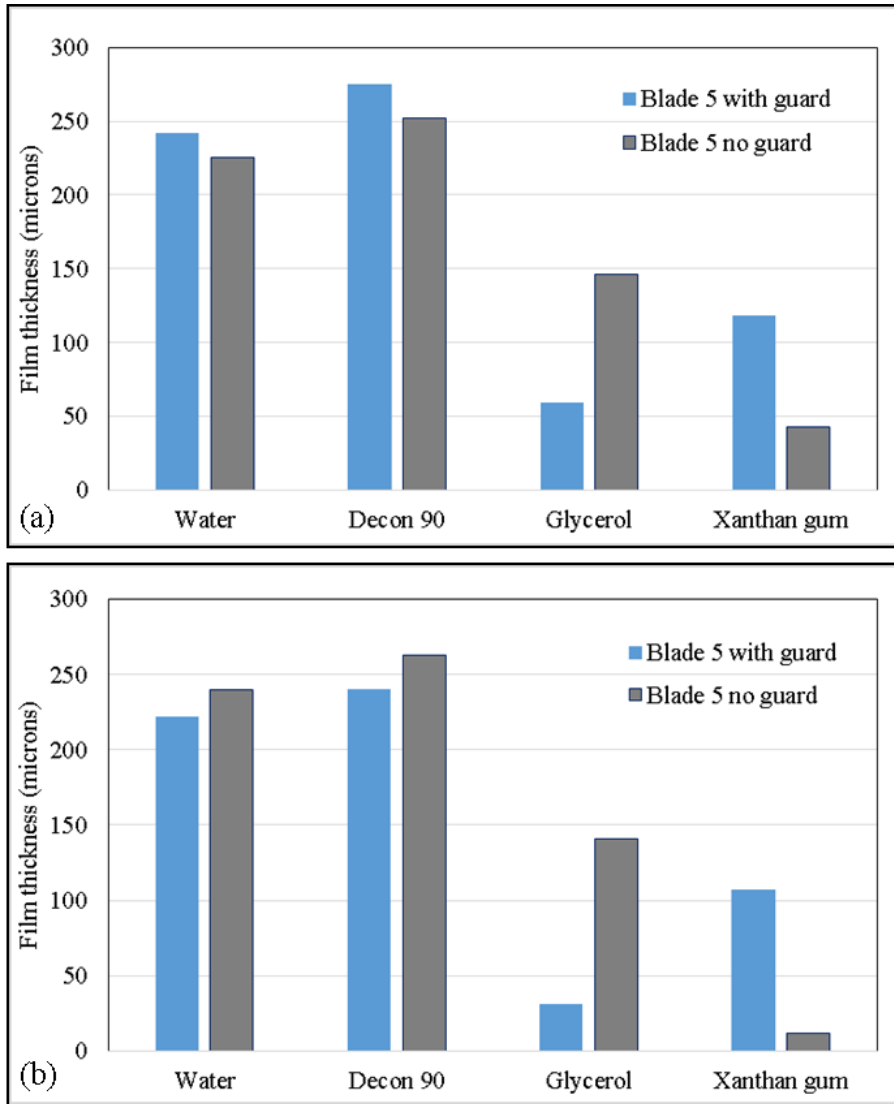


Figure 7.22: Effect of guard on film thickness: Blade 5. For reference fluids between razor cartridge and glass (a) 50 mm/s (b) 150 mm/s

7.6.3. Guard presence: silicone elastomer disc

Figures 7.23 and 7.24 show average film thickness results between the razor cartridge and silicone elastomer disc at 50 mm/s and 150 mm/s, with the guard present (Figure 7.23) and without the guard present (Figure 7.24). For both conditions, film thickness typically increases towards the back of the cartridge, with the thickest film under the Lubrastrip.

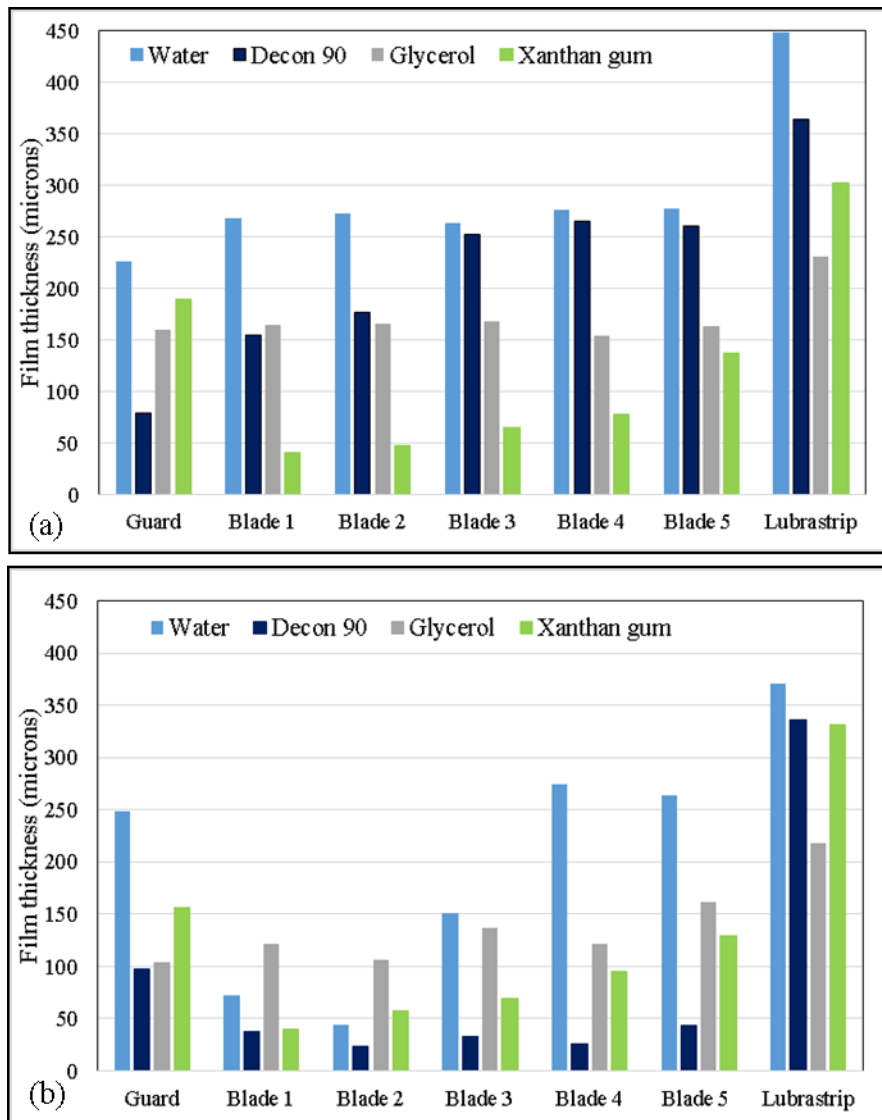


Figure 7.23: Average film thickness results for reference fluids between razor cartridge and silicone elastomer with guard present (a) 50 mm/s (b) 150 mm/s

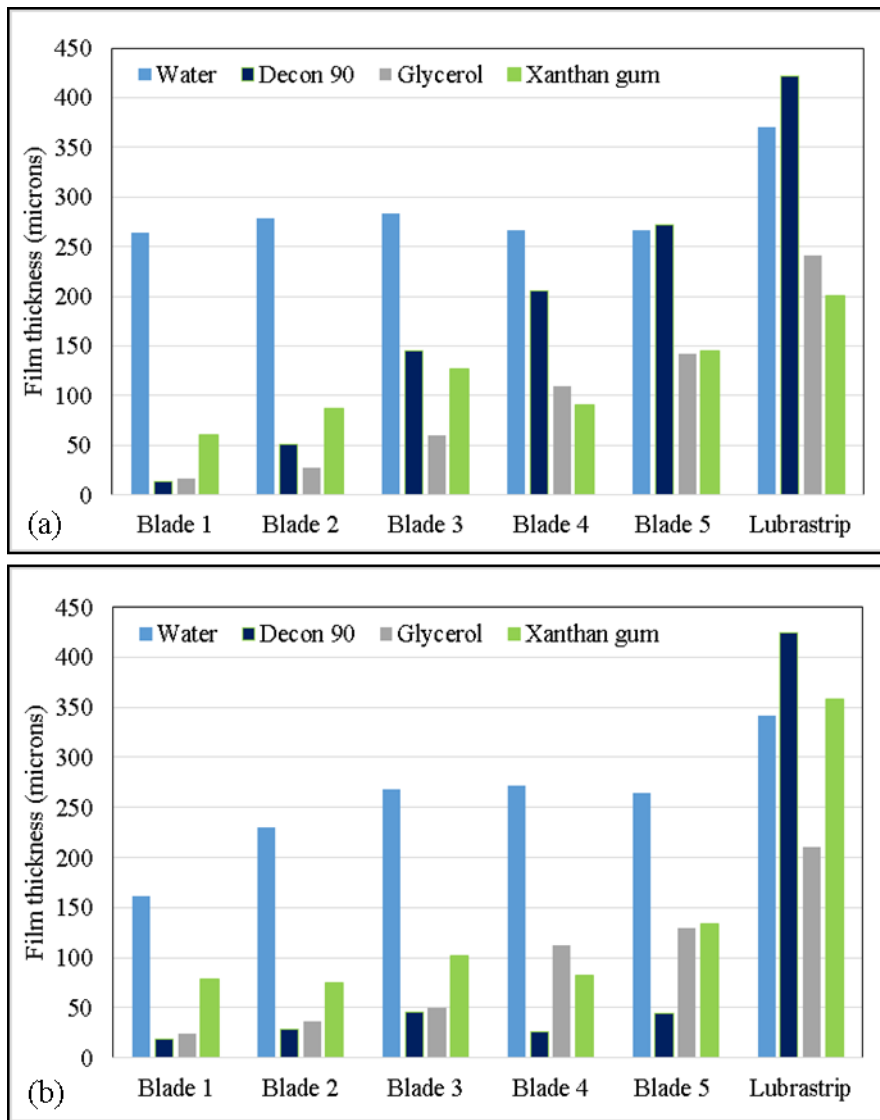


Figure 7.24: Average film thickness results for reference fluids between razor cartridge and silicone elastomer without guard present (a) 50 mm/s (b) 150 mm/s

Once again, comparing blades 1 and 5 (Figures 7.25 and 7.26) shows the effect of the guard more clearly. For blade 1 (Figure 7.25), removing the guard reduces the effect of sliding speed on film thickness (when the guard is present film thickness is significantly higher at 50 mm/s than 150 mm/s). However there is little effect on guard presence for blade 5 (Figure 7.26).

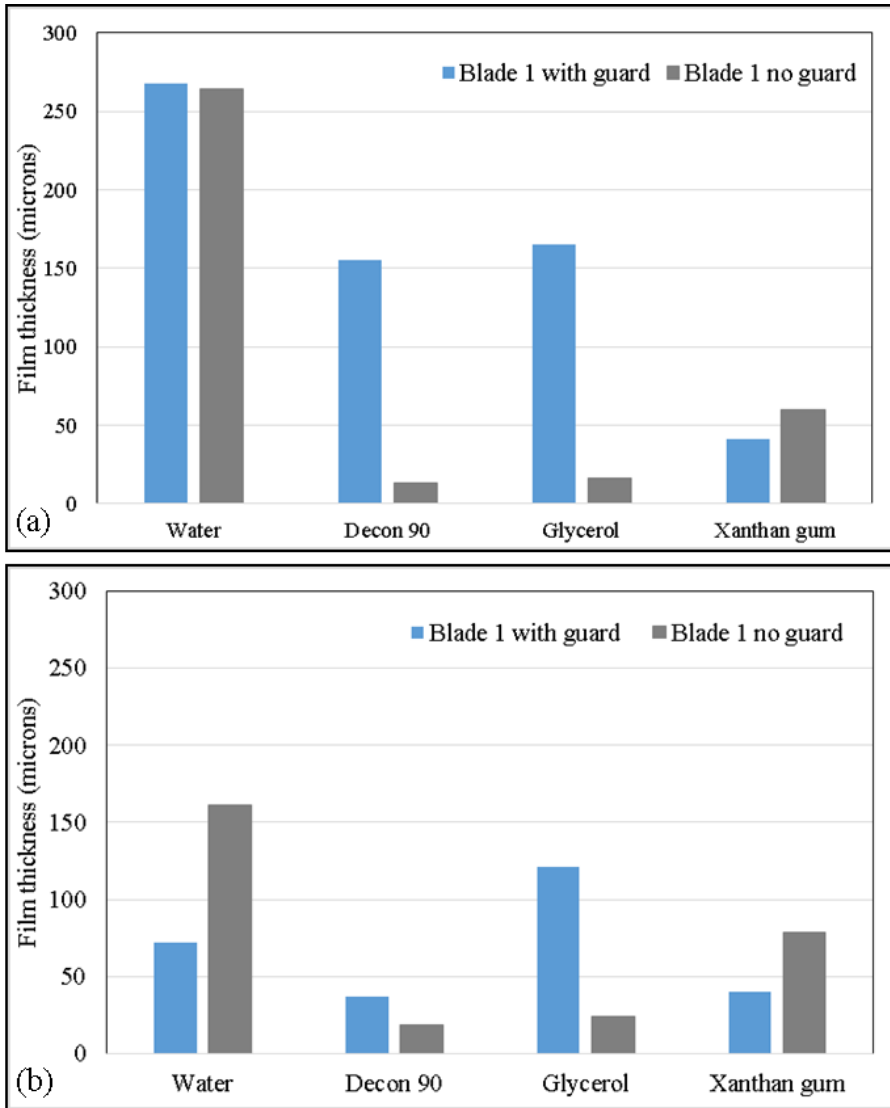


Figure 7.25: Effect of guard on film thickness: Blade 1. For reference fluids between razor cartridge and silicone elastomer (a) 50 mm/s (b) 150 mm/s

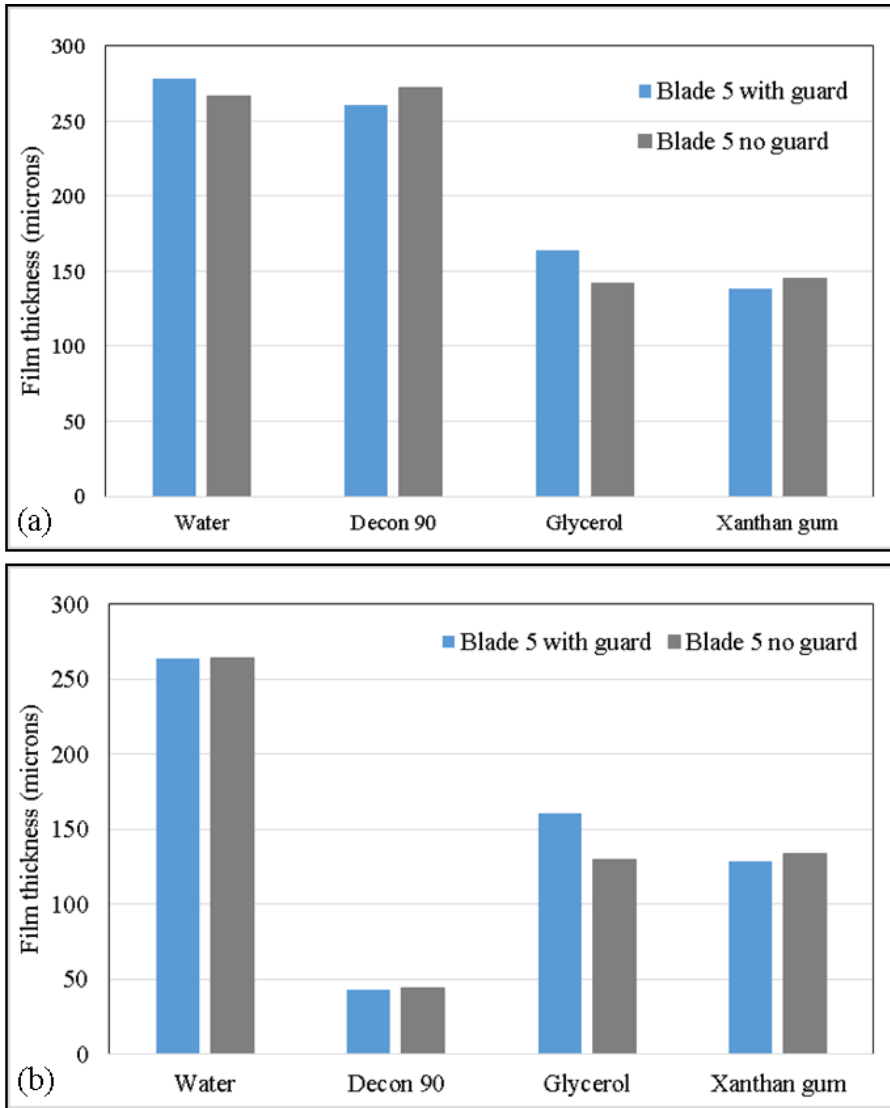


Figure 7.26: Effect of guard on film thickness: Blade 5. For reference fluids between razor cartridge and silicone elastomer (a) 50 mm/s (b) 150 mm/s

7.7. Conclusions

The LIF method has been successfully applied the razor cartridge contact and allows visualisation of lubricant flow through the cartridge and measurement of film thickness at both hard and compliant contact interfaces. The results are further discussed in Chapter 9, but at this stage the reference fluids have shown that:

- The guard and Lubrastrip maintain relatively thick and consistent lubricant films across the speed range.

- Minimum films are measured at the blade cutting edges, although for some lubricants the film increases towards the back of the cartridge.
- Fluid viscosity has a significant effect on lubrication through the razor cartridge, with much lower films measured at high speeds for the high viscosity (glycerol and xanthan gum) solutions.
- Film thickness typically decreases with increasing sliding speed.
- A compliant (silicone elastomer) counterface allows formation of a thicker lubricant film than for a hard (glass) counterface.
- The presence of the guard improves razor cartridge lubrication by stabilising film thickness across the blade cutting edge interfaces.

7.8. References

- [1] Ocallaghan, D. Procter & Gamble. Email sent to: Suzanna Whitehouse. 2nd December 2014.

8. LIF FLUID FLOW AND FILM THICKNESS MEASUREMENTS FOR PEO FLUIDS IN A RAZOR CARTRIDGE

Summary

In the previous Chapter laser induced fluorescence (LIF) was successfully applied as a technique for imaging fluid distribution and measuring film thickness in a razor cartridge contact for the reference fluids. In this Chapter the LIF technique is applied to the razor cartridge contact lubricated by PEO fluids. The experiments were conducted with a Gillette razor cartridge loaded and sliding against a glass disc and a silicone elastomer coated disc, with PEO solutions lubricating the contact. The aim was to visualise lubricant flow and measure film thickness in the razor cartridge contact. Typical lubrication patterns were observed for each cartridge component as well as the effect of lubricant properties on films formed through the razor cartridge – higher molecular weight PEO solutions produced visible channels of lubricant, stretching across the cartridge contact. Presence of the guard was shown to improve razor cartridge lubrication for a compliant counterface. The compliant (silicone elastomer) countersurface produced thicker lubricant films across the razor cartridge compared to the hard (glass) countersurface.

8.1. Introduction

This Chapter uses the developed LIF technique from Chapter 7 to study the flow behaviour of PEO in the razor cartridge contact. The experiments in this Chapter follow the same methodology as described in Chapter 6 – optical and loading equipment remain unchanged, as does the calibration, image capture and data processing method. Razor cartridge mounting within the LIF rig and image capture remains as described in Chapter 7.

8.2. Experimental conditions

8.2.1. PEO Lubricants

The PEO fluids are described in Chapter 4 and the same application method was used as described in Chapters 6 and 7.

8.2.2. Test profile

Table 8.1 shows the test profiles for these experiments. They are designed to replicate “real-life” shaving and correspond with the MTM test profiles. The disc specimens were cleaned according to the standard described in Chapter 4. The razor cartridge was washed prior to each test with isopropanol, followed by detergent and pure water.

The razor cartridges used in these experiments no-longer contained a supply of PEO in the Lubrastrip, although the polystyrene mesh was still present. This ensured that any PEO that would have been supplied from the razor cartridge did not interfere with test fluid lubrication.

Table 8.1: LIF experimental conditions

Load	2.5 N
Temperature	25 °C
SRR	200 %
Sliding speed	50 mm/s
	150 mm/s
Disc material	Glass
	Silicone elastomer

Experimental film thickness values were calculated by averaging data from three separate tests. Within each experiment 25 intensity readings were recorded for every speed range.

8.3. Results: structure

The results in this Chapter are split into two sections, and four sub-sections:

1. Glass disc: (a) With guard (b) Without guard
2. Silicone elastomer disc: (a) With guard (b) Without guard

The results from each sub-section will be shown as intensity images (for 1×10^6 g/mol M_w PEO and 2.6×10^6 g/mol M_w PEO solutions) and average film thickness graphs (for all lubricants). In the intensity images razor cartridge components are clearly visible, and lubricant location is depicted using an intensity colour-scale whereby red indicates large quantities of lubricant, and blue indicates a lack of lubricant. Film thickness graphs show the cross-section profile of the average film thickness measured from the fluorescence intensity images.

The images were chosen to show typical LIF intensity through the cartridge for the different test conditions and fluid types. The graphs plot average film thickness calculated from all test measurements. Overall the repeatability of film thickness distribution and changes due to fluid type, contact condition and speed were good, however some anomalies remain and these issues are discussed in more detail in Chapter 9.

8.4. Results: glass disc

Film thickness results are shown in Figures 8.1-8.3 for the razor cartridge against glass at sliding speeds of 50 mm/s and 150 mm/s with guard present, and Figures 8.4-8.6 without the guard present.

8.4.1. With guard present

As has been shown in Chapter 7 with the reference fluids, it is possible to visualise cartridge components using LIF. Figures 8.1 and 8.2 show the lubricant LIF intensity through the razor cartridge against glass contact, at 50 mm/s and 150 mm/s, for 1×10^6 g/mol M_w PEO and 2.6×10^6 g/mol M_w PEO solutions. As with the reference fluids, lubricant is captured between the guard fins, with a restricted quantity passing underneath the guard to the blades. However, at 50 mm/s for 1×10^6 g/mol M_w PEO (Figure 8.2) there is a bubble of lubricant separating the guard from the glass, which is repeatable. In Chapter 7 this was only observed for the silicone elastomer countersurface. The PEO solutions also show viscoelastic behaviour whereby a lubricant film appears to stretch across the multiple blades contact.

These are visible as diagonal “bands” in the figures, as annotated by the words “lubricant film” in Figure 8.1. In Figure 8.2 droplets of lubricant have been deposited onto the razor cartridge, particularly across blades 2 and 3, away from the cutting edge contact.

When comparing film thickness profiles across the PEO solution range (Figure 8.3), molecular weight solutions below 1×10^6 g/mol provide a consistent lubricant film of 150-250 μm across the razor cartridge, of similar values between the different cartridge components. As molecular weight increases from 1×10^6 g/mol, film thickness decreases at higher speeds - initially in the blade contact to less than 20 μm . This followed by the guard film thickness which drops from ~ 200 μm to < 50 μm for the 2.6×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO solutions. Lubrastrip film thickness values are similar (~ 200 μm) for all PEO solutions.

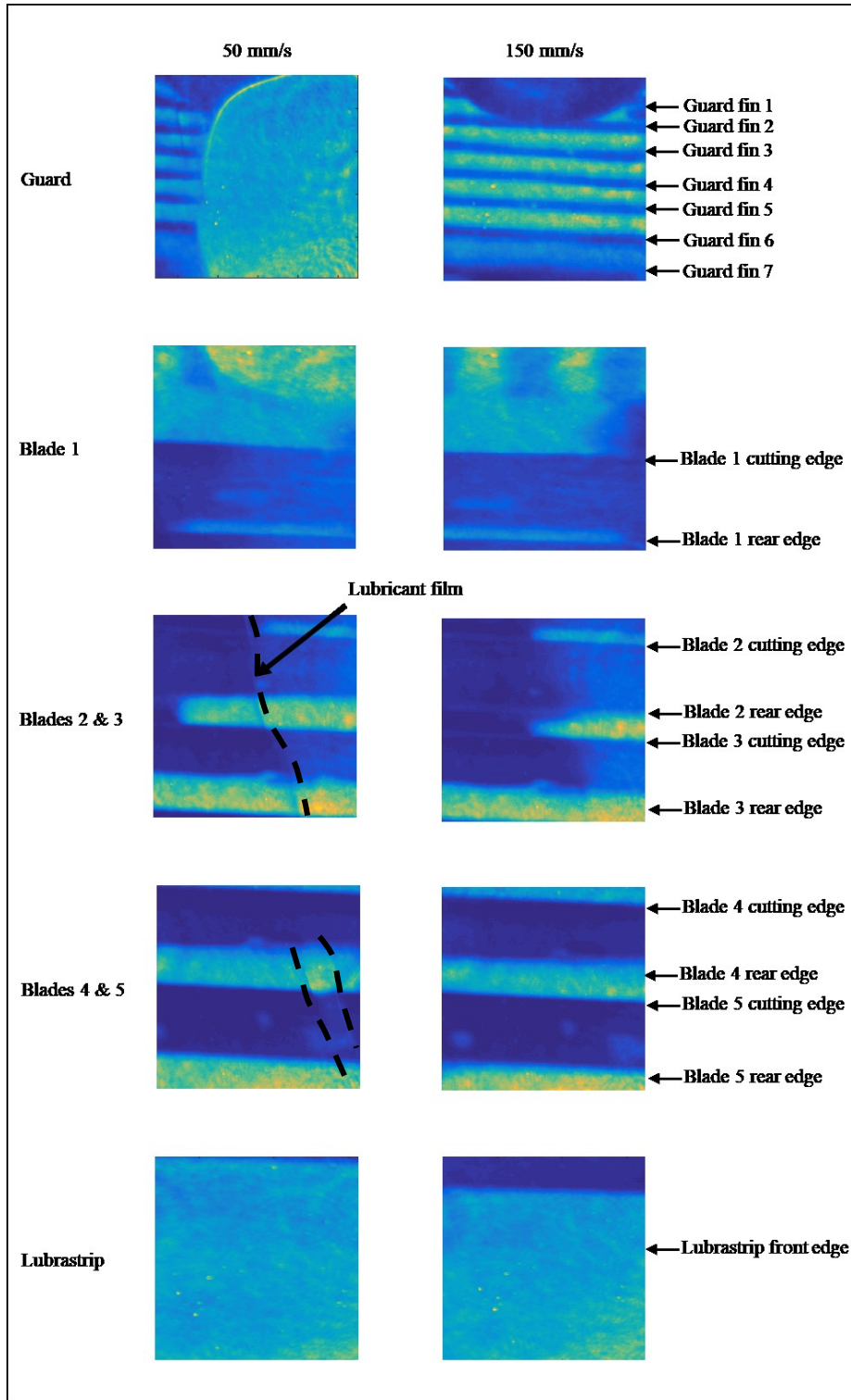


Figure 8.1: LIF images from shaving cartridge against glass disc lubricated by $1 \times 10^6 M_w$ PEO solution at 50 mm/s and 150 mm/s

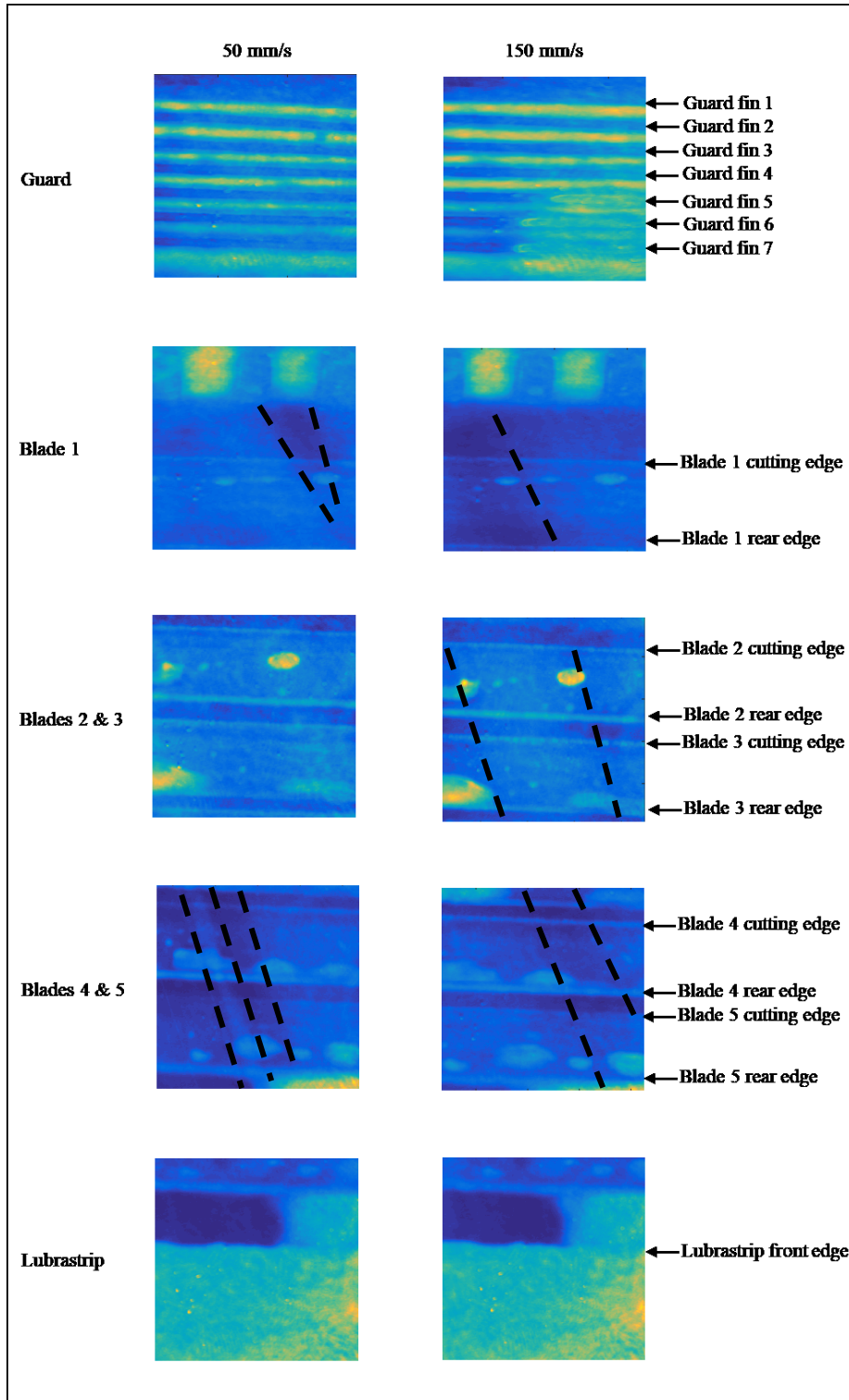


Figure 8.2: LIF images from shaving cartridge against glass disc lubricated by $2.6 \times 10^6 M_w$ PEO solution at 50 mm/s and 150 mm/s

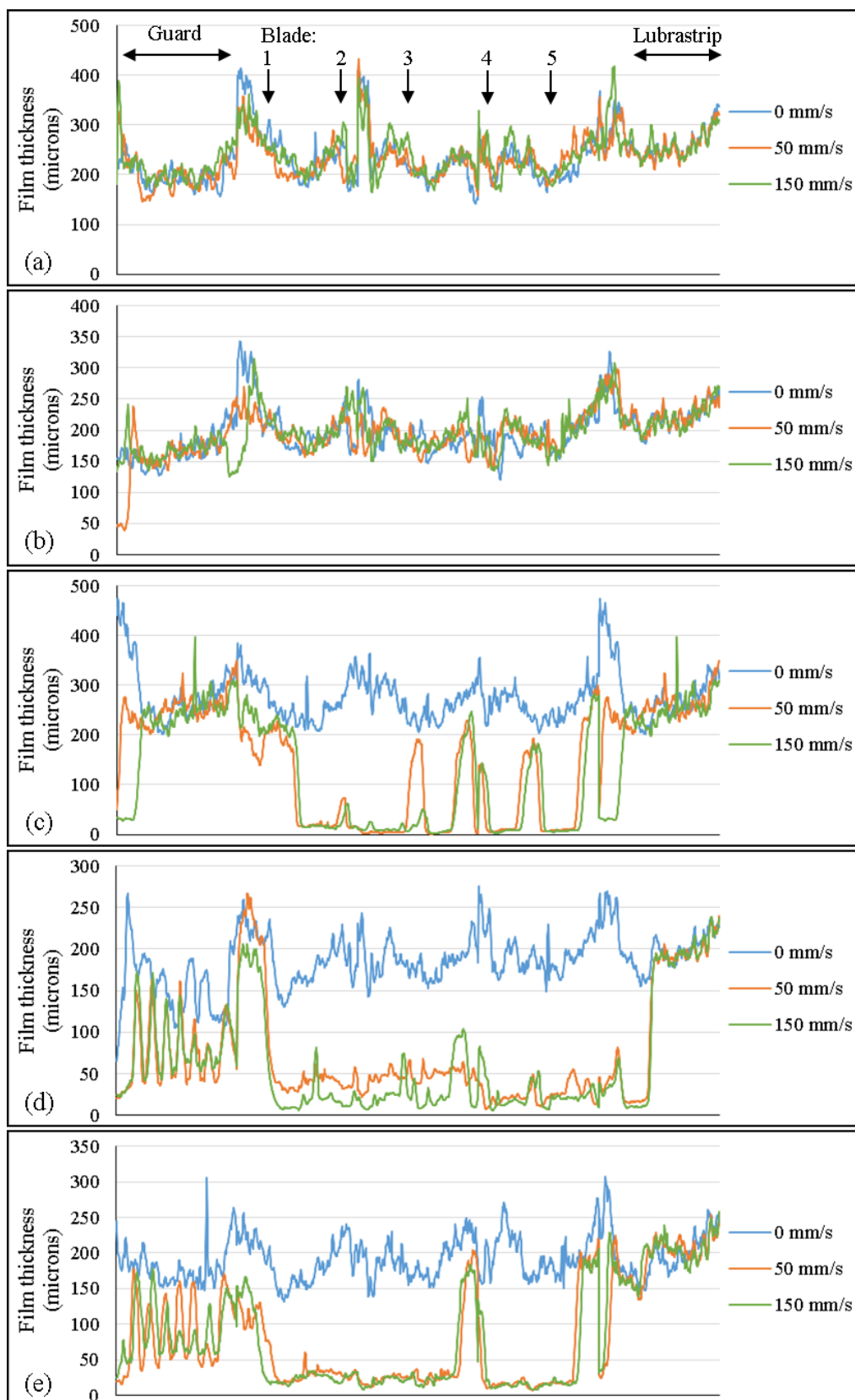


Figure 8.3: Typical film thickness profiles of PEO solutions between razor cartridge and glass with the guard present. (a) 200×10^3 g/mol M_w (b) 400×10^3 g/mol M_w (c) 1×10^6 g/mol M_w (d) 2.6×10^6 g/mol M_w (e) 5×10^6 g/mol M_w

8.4.2. Without guard present

Figures 8.4-8.6 show LIF image and film thickness profile results for the razor cartridge/glass contact without the guard present. Removing the guard with 1×10^6 g/mol M_w PEO (Figure 8.4) causes the lubricant to flood the razor cartridge contact at 50 mm/s obscuring the individual cartridge components. In Figure 8.5, for 50 mm/s PEO solutions can be seen to flow through the cartridge's in-built lubricant channels ahead of blade 1.

When comparing film thickness profiles (Figure 8.6), removing the guard causes disruption to the lubricant film for PEO solutions below 1×10^6 g/mol M_w PEO solution, although from blade 3 the film thickness is comparable to when the guard is present. For 1×10^6 g/mol M_w PEO solution, removing the guard increases film thickness across the razor cartridge contact at 50 mm/s when compared to Figure 8.3 (with the guard present). Once speed increases the film thickness across the contact is similar to when the guard is present. For PEO solutions above 1×10^6 g/mol M_w , removing the guard does not cause a significant change in film thickness. Under these conditions film thickness drops to ~ 20 μm through the blades, although much thicker films are recorded between the blades recovering to ~ 150 μm . The presence of the guard clearly moderates flow at the front of the cartridge but has little influence on flow and film thickness towards the rear.

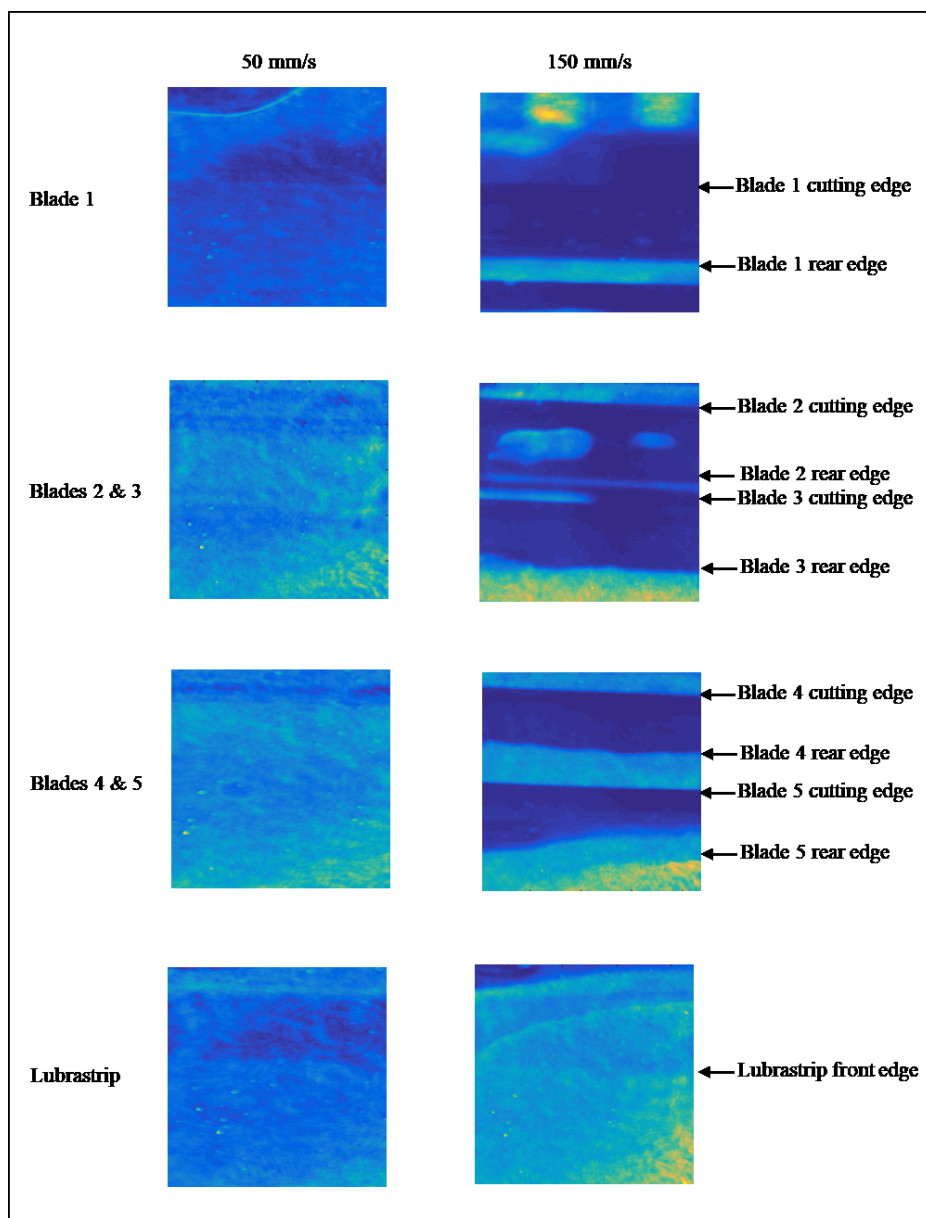


Figure 8.4: LIF images from shaving cartridge (without guard present) against glass disc lubricated by $1 \times 10^6 M_w$ PEO solution at 50 mm/s and 150 mm/s

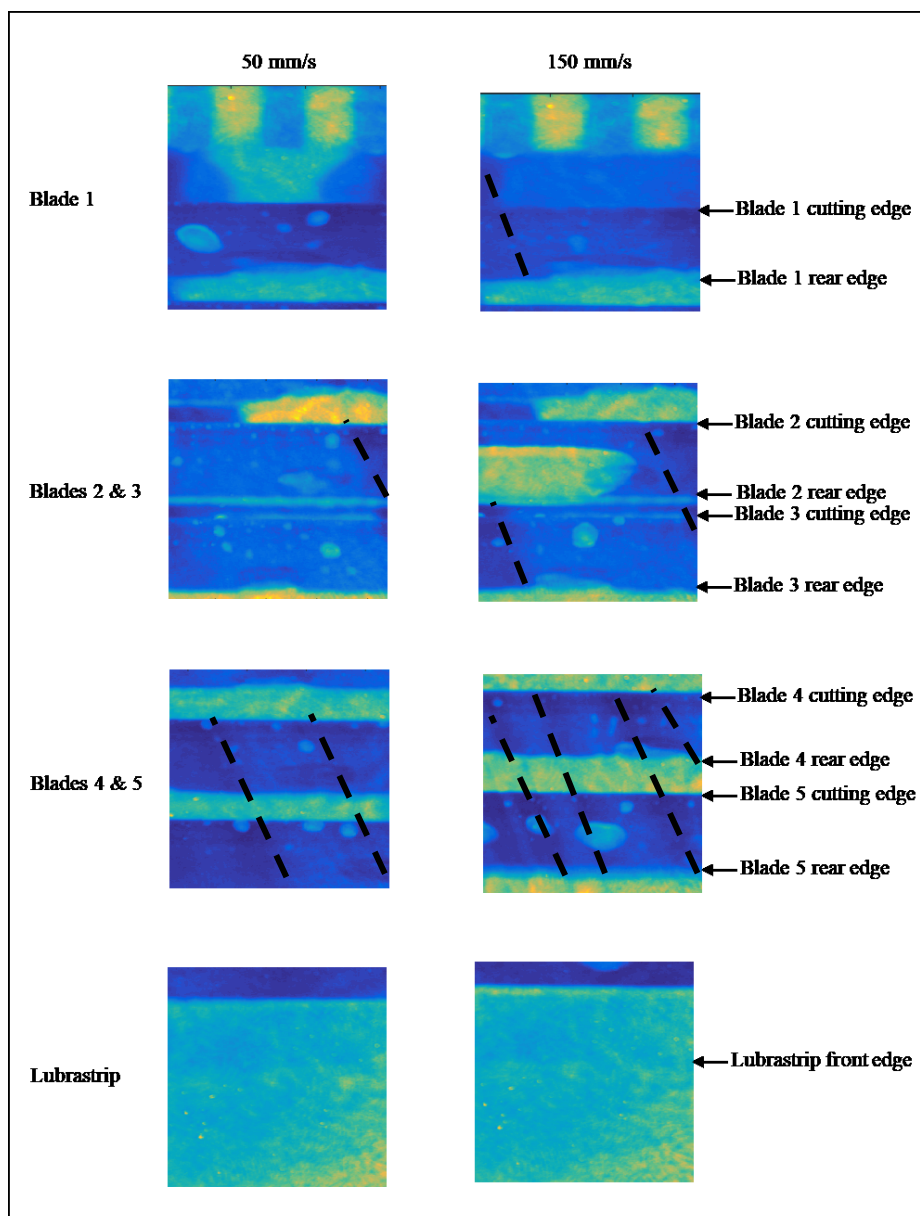


Figure 8.5: LIF images from shaving cartridge (without guard present) against glass disc lubricated by $2.6 \times 10^6 M_w$ PEO solution at 50 mm/s and 150 mm/s

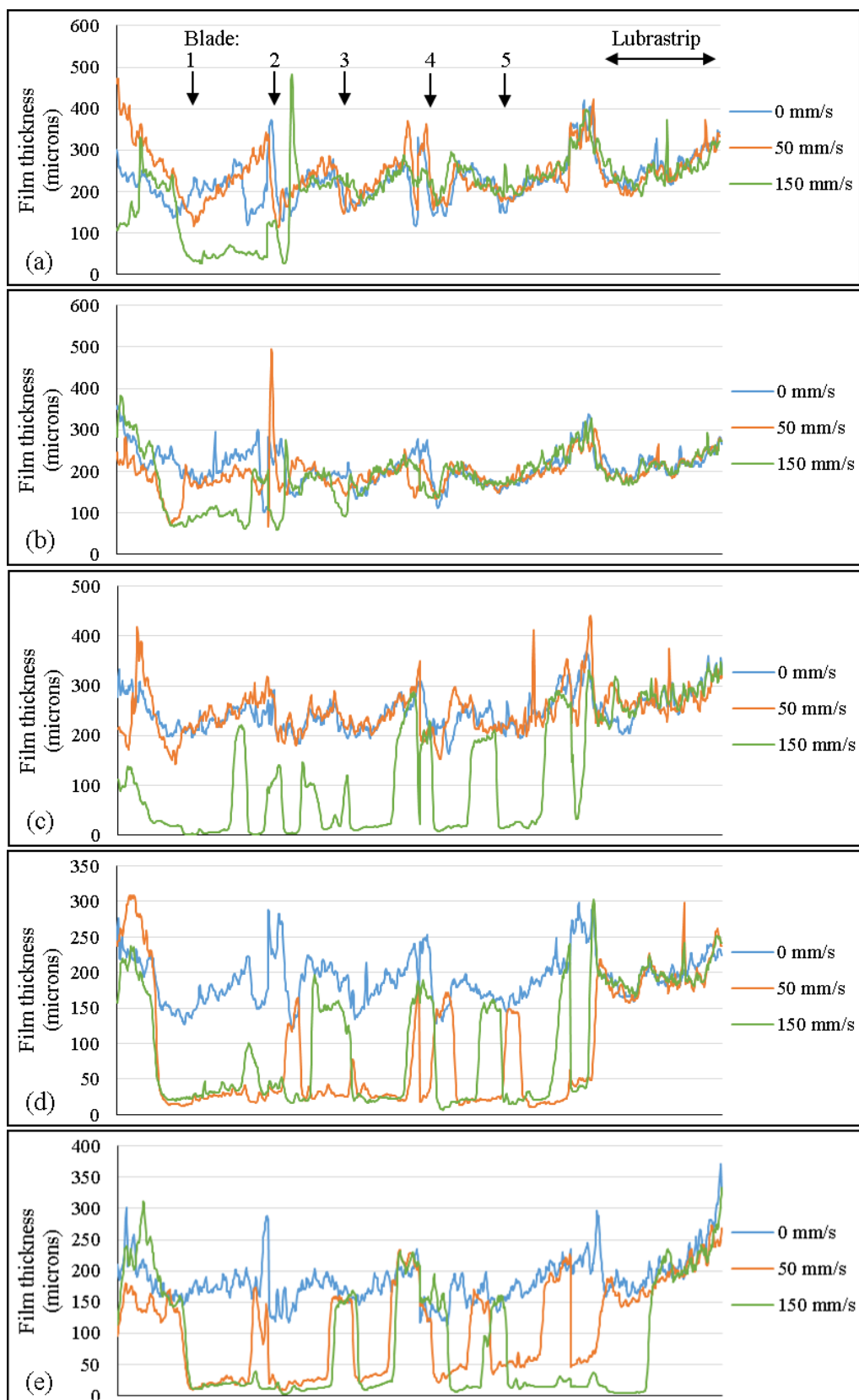


Figure 8.6: Typical film thickness profiles of PEO solutions between razor cartridge and glass without the guard present. (a) 200×10^3 g/mol M_w (b) 400×10^3 g/mol M_w (c) 1×10^6 g/mol M_w (d) 2.6×10^6 g/mol M_w (e) 5×10^6 g/mol M_w

8.5. Results: silicone elastomer

Film thickness results are shown in Figures 8.7-8.9 for the razor cartridge against silicone elastomer at sliding speeds of 50 mm/s and 150 mm/s with guard present, and Figures 8.10-8.12 without the guard present.

8.5.1. With guard present

As shown in Chapter 7, when the silicone elastomer countersurface is used there is more lubricant in the razor cartridge contact. In Figure 8.7 with 1×10^6 g/mol M_w PEO solution at a sliding speed of 50 mm/s, the guard is completely separated from the silicone elastomer by the lubricant film. This results in an excess of lubricant at the back of the guard, which escapes the cartridge contact before reaching blade 1. Figure 8.8 shows LIF images for 2.6×10^6 g/mol M_w PEO solution, and here channels of lubricant stretching across the whole razor cartridge contact are visible. These have been marked with dashed lines on Figure 8.8.

The intensity image colouring of Figure 8.8 appears to show significantly more lubricant present than seen previously. However the intensity images are not directly comparable between different fluids for film thickness and should only be used to visualise lubricant distribution.

In the film thickness profiles shown in Figure 8.9, PEO solutions below 1×10^6 g/mol M_w lubricating films are negatively impacted by the compliant countersurface. The film thickness decreases as speed increases, and there is a variable distribution of film thickness across the razor cartridge, although Lubrastrip values remain relatively unchanged. For PEO solutions above 1×10^6 g/mol M_w , minimum film thickness remains relatively unchanged. However, the film thickness data is taken from the centre of the image, which does not necessarily represent the entire contact lubrication. For example, Figure 8.8 shows lubricant channels through the contact, but these do not pass through the measured path.

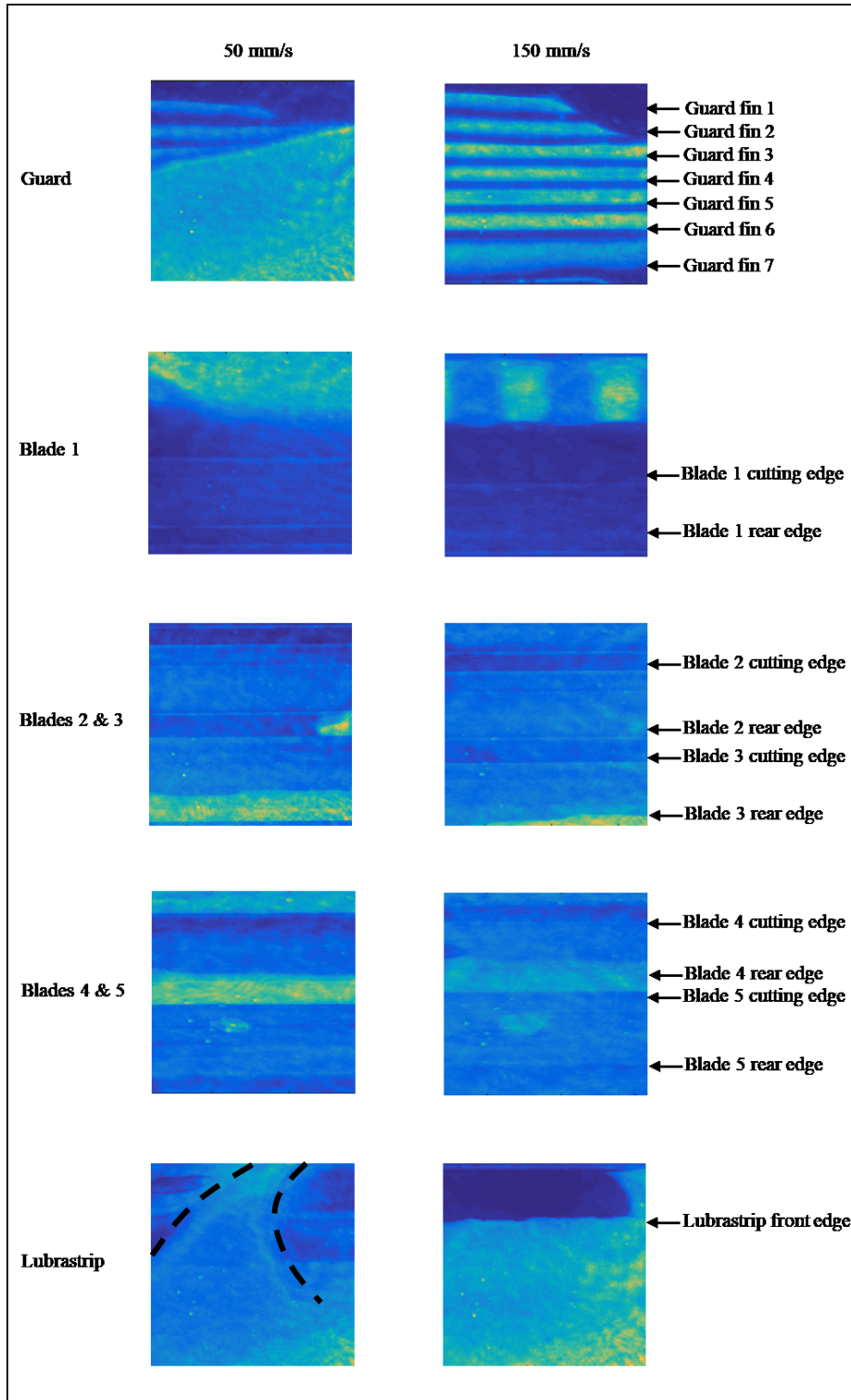


Figure 8.7: LIF images from shaving cartridge against silicone elastomer disc lubricated by $1 \times 10^{-6} M_w$ PEO solution at 50 mm/s and 150 mm/s

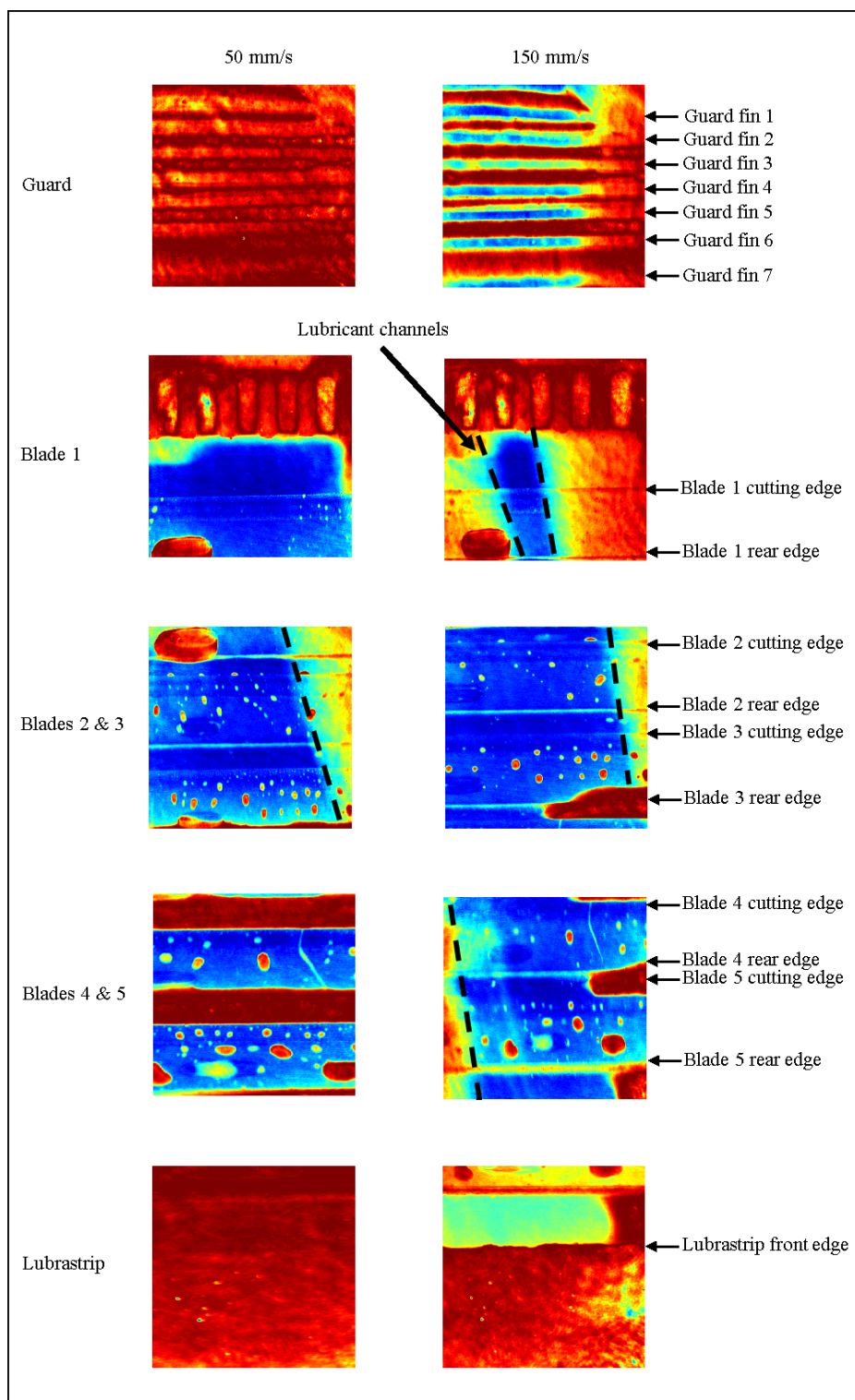


Figure 8.8: LIF images from shaving cartridge against silicone elastomer disc lubricated by 2.6×10^6 M_w PEO solution at 50 mm/s and 150 mm/s

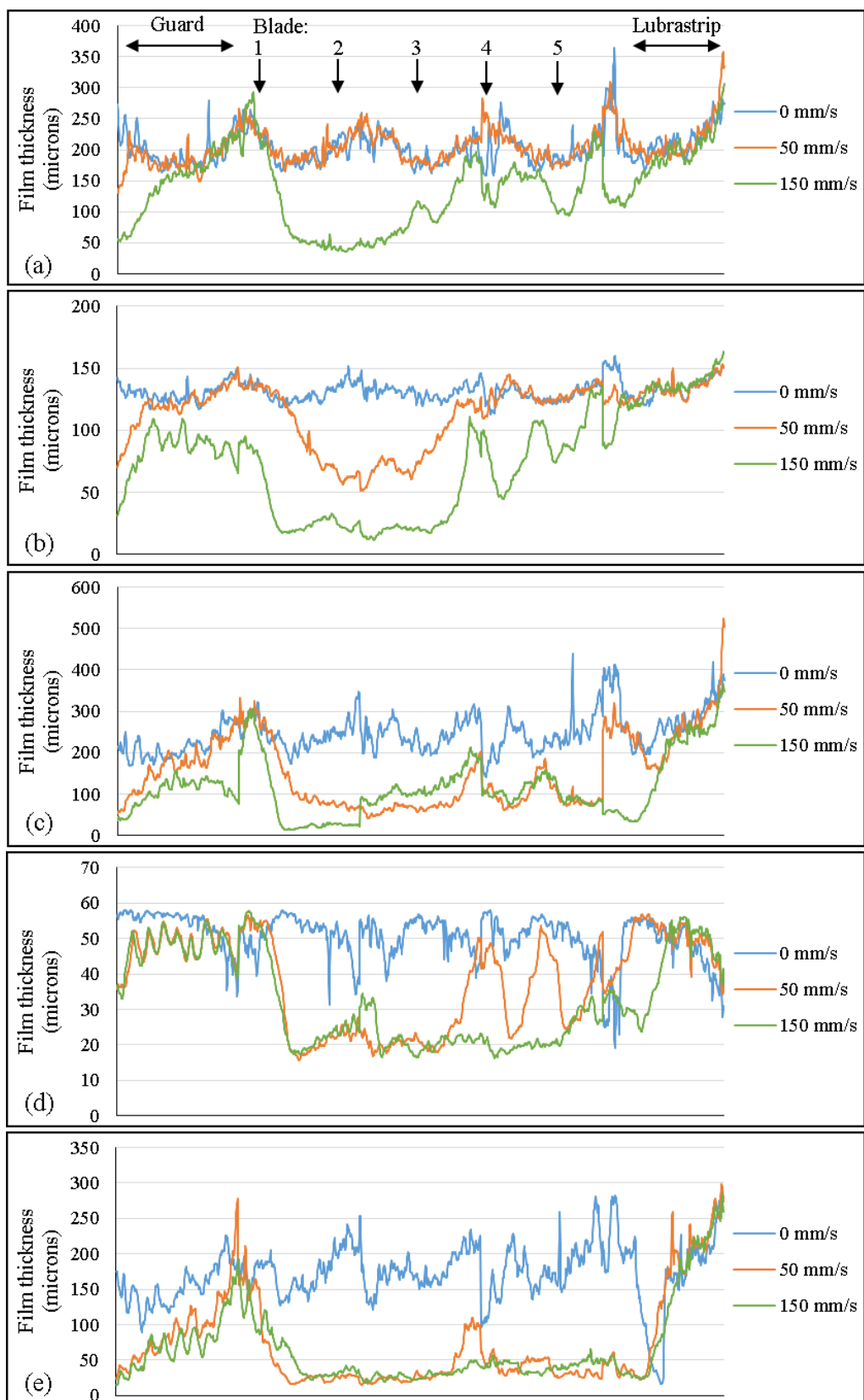


Figure 8.9: Typical film thickness profiles of PEO solutions between razor cartridge and silicone elastomer with the guard present. (a) 200×10^3 g/mol M_w (b) 400×10^3 g/mol M_w (c) 1×10^6 g/mol M_w (d) 2.6×10^6 g/mol M_w (e) 5×10^6 g/mol M_w

8.5.2. Without guard present

Removing the guard produces an increase in film thickness, particularly towards the back of the razor cartridge (Figure 8.10 and Figure 8.11, 50 mm/s). Channels of lubricant are visible under blades 4 and 5 and the Lubrastrip of Figure 8.10 at 150 mm/s and under blade 1 and blades 2 and 3 of Figure 8.11 at 50 mm/s. Figure 8.11 shows 2.6×10^6 g/mol M_w PEO solution collecting around the cartridge in-built lubricant channels (combe), but unlike for glass it does not appear to flow through to blade 1.

Film thickness profiles in Figure 8.12 show that removing the guard does not necessarily increase film thickness under the blades, but the lubricating film becomes more consistent through the contact for each condition. However, the blade film thickness profile for 5×10^6 g/mol M_w PEO solution at 150 mm/s decreases to $< 20 \mu\text{m}$ towards the back of the razor cartridge, although film recovery ($\sim 100\text{-}150 \mu\text{m}$) is observed between the blades.

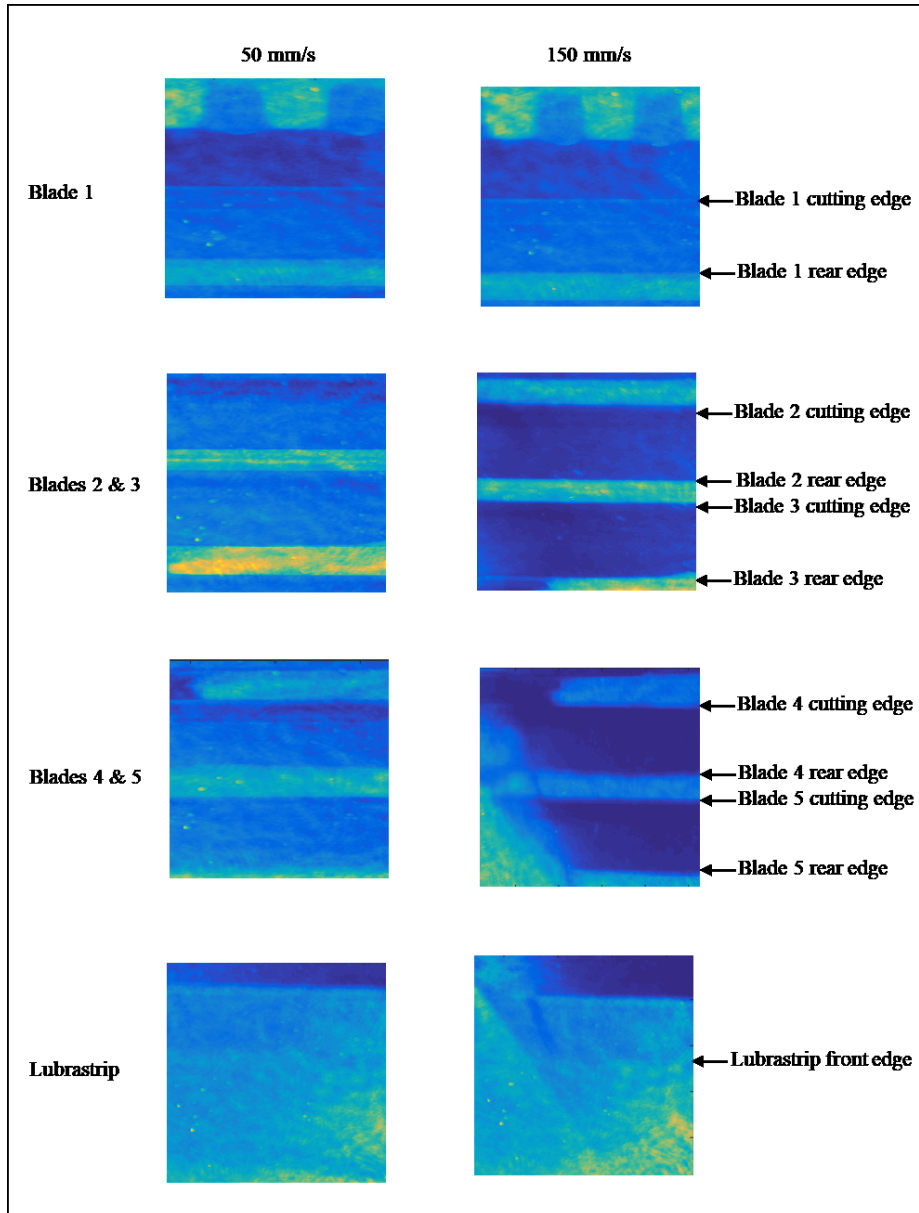


Figure 8.10: LIF images from shaving cartridge (without guard present) against silicone elastomer disc lubricated by $1 \times 10^6 M_w$ PEO solution at 50 mm/s and 150 mm/s

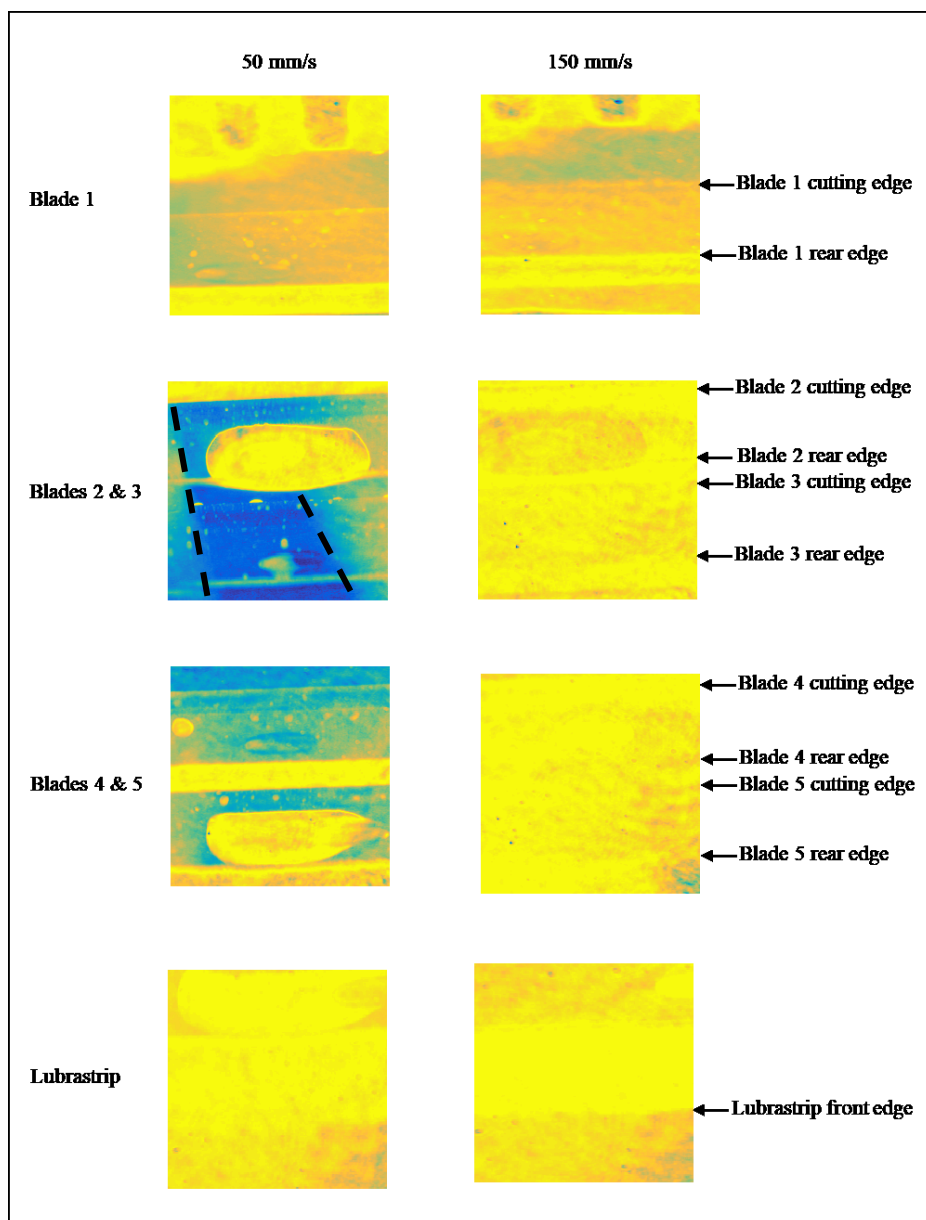


Figure 8.11: LIF images from shaving cartridge (without guard present) against silicone elastomer disc lubricated by $2.6 \times 10^6 M_w$ PEO solution at 50 mm/s and 150 mm/s

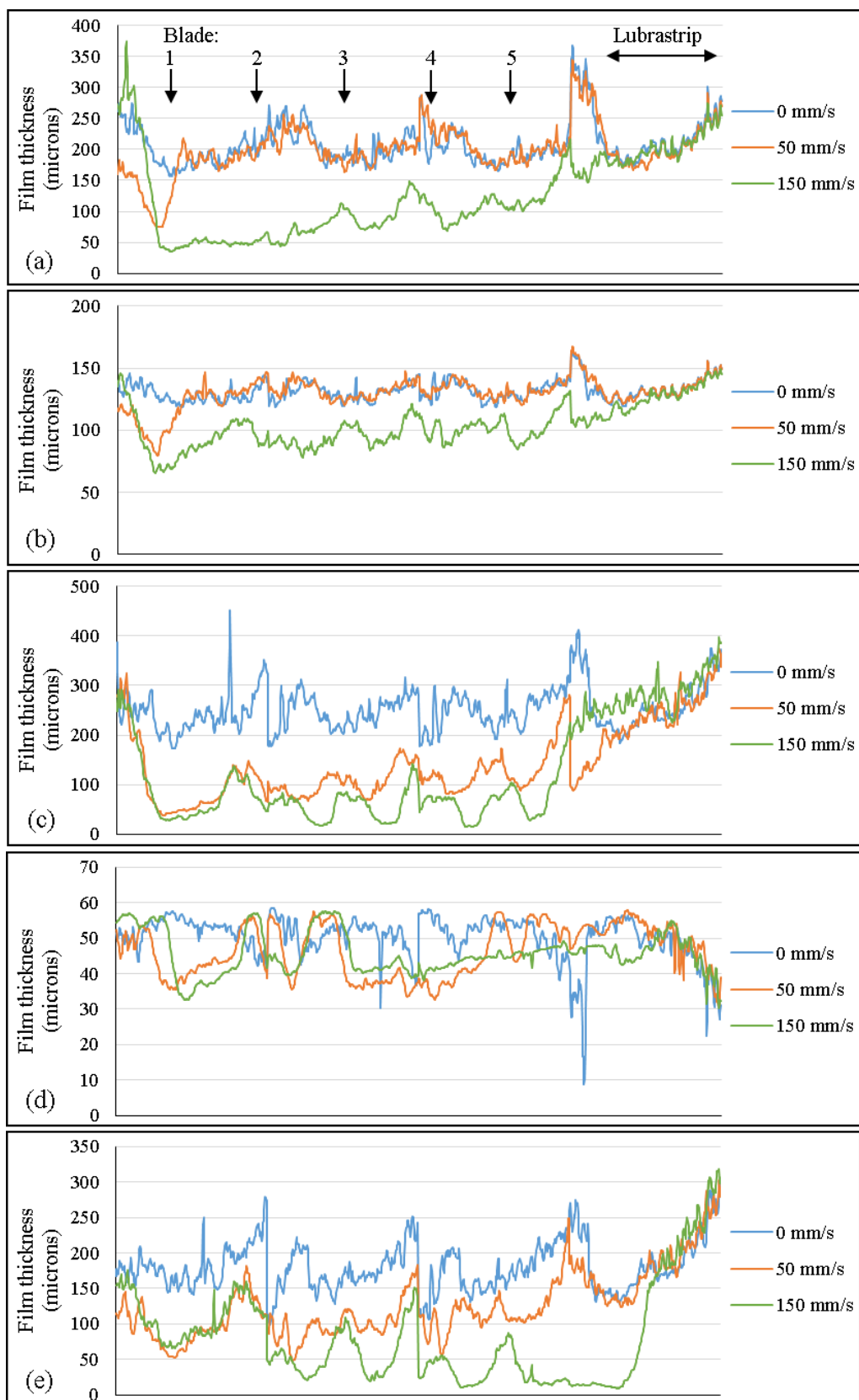


Figure 8.12: Typical film thickness profiles of PEO solutions between razor cartridge and silicone elastomer without the guard present. (a) 200×10^3 g/mol M_w (b) 400×10^3 g/mol M_w (c) 1×10^6 g/mol M_w (d) 2.6×10^6 g/mol M_w (e) 5×10^6 g/mol M_w

8.6. Discussion

LIF allows visualisation of PEO lubricant flow through the cartridge and measurement of film thickness at the contact interfaces. LIF images and film thickness results have been presented in this Chapter for the PEO solutions. The effects of counterface material (glass/silicone elastomer), presence of guard and sliding speed on film distribution are discussed in this section. The effect of PEO type on film thickness and comparison with reference fluids is considered in more detail in Chapter 9.

A thick lubricant film (10-300 μm) is formed for all solutions underneath the cartridge, particularly for the silicone elastomer disc setup. The typical lubricant distribution is as follows:

- Guard: the guard traps lubricant between the fins which are clearly seen for some conditions. It has not yet been shown whether or not this acts as a distribution reservoir for lubricating the successive blades. Film thickness is in the range 150-200 μm for glass and silicone counterfaces although this decreases to $< 80 \mu\text{m}$ for the high ($2.6 \times 10^6 \text{ g/mol}$ and $5 \times 10^6 \text{ g/mol}$) molecular weight PEO solutions as the speed increases.
- Blades: minimum lubricant film thickness occurs at the blade cutting edges, particularly for the high molecular weight fluids as the speed increases. Films down to 20 μm were measured for the $2.6 \times 10^6 \text{ g/mol } M_w$ PEO and $5 \times 10^6 \text{ g/mol } M_w$ PEO solutions for both glass and silicone elastomer counterfaces.
- Lubrastrip: after the blades the film thickness recovers to 200-300 μm for glass and 50-300 μm for silicone elastomer counterfaces depending on PEO molecular weight.

The effect of fluid properties (reference and PEO) on film thickness will be discussed in Chapter 9.

8.6.1. Hard or compliant counterface

The effect of a hard (glass) or compliant (silicone elastomer) counterface on film formation are summarised in Figure 8.13 for the guard, blade 1, blade 5 and Lubrastrip components, with a sliding speed of 50 mm/s.

Changing the counterface from a hard to a compliant material does not necessarily produce an increase in film thickness (due to reduced contact pressure). 400×10^3 g/mol M_w PEO solution in particular shows a decrease in film thickness across the cartridge for the silicone elastomer contact, and the effect of the compliant counterface appears to be dependent on the viscoelastic properties of the PEO solution.

At the guard interface, film thickness values remain at similar levels for both contact materials, except PEO solutions 400×10^3 g/mol M_w and 1×10^3 g/mol M_w , where the film thickness reduces significantly for the silicone elastomer contact.

However, across blades 1 and 5 PEO solution 1×10^3 g/mol M_w has a higher film thickness for the compliant contact, despite the reduction under the guard. This is the only solution of the range tested to show a consistent and significant film thickness increase for both blades with the compliant material. The remaining solutions typically have reduced film thickness at blade 1 for the silicone elastomer contact, which increases at blade 5. For the blades 1 and 5 contact, PEO solutions of molecular weight below 1×10^3 g/mol form thicker, more consistent films for a hard counterface material.

At the Lubrastrip contact the effect of countersurface material varies between solutions without any obvious pattern. However, the largest film thickness occurs for 1×10^3 g/mol M_w PEO solution against a compliant counterface, which may be because the Lubrastrip is designed to hold 1×10^3 g/mol M_w PEO as the on board lubricant, and deposit it onto a compliant counterface (skin).

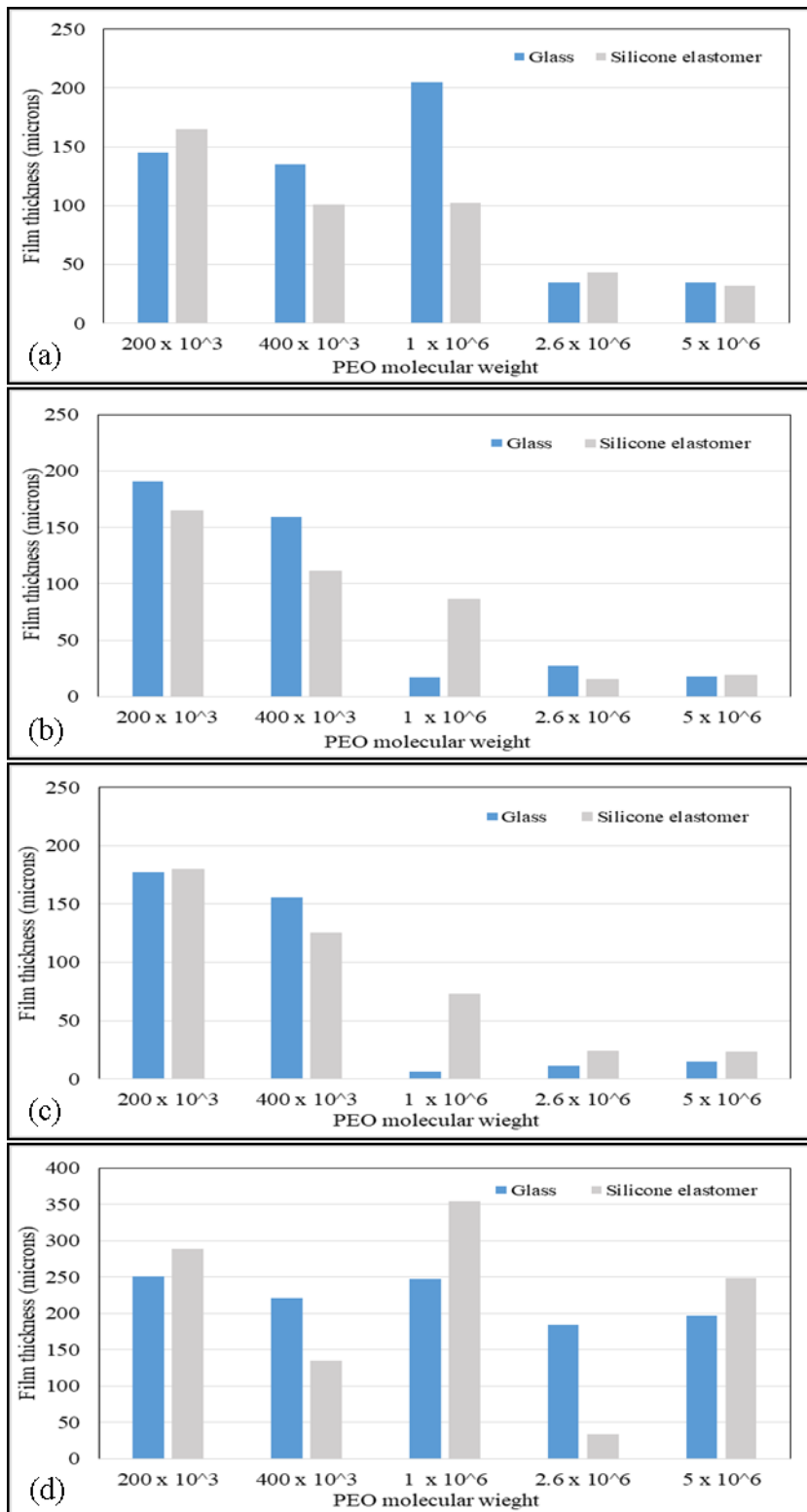


Figure 8.13: Effect of silicone elastomer layer on film thickness for (a) guard (b) blade 1 (c) blade 5 (d) Lubrastrip

8.6.2. Guard presence: glass disc

Average film thickness results between the razor cartridge and glass disc at 50 mm/s and 150 mm/s are shown with the guard present (Figure 8.14) and without the guard present (Figure 8.15). When the guard is present, film thickness underneath the blade cutting edge is more consistent through the razor cartridge and less affected by sliding speed.

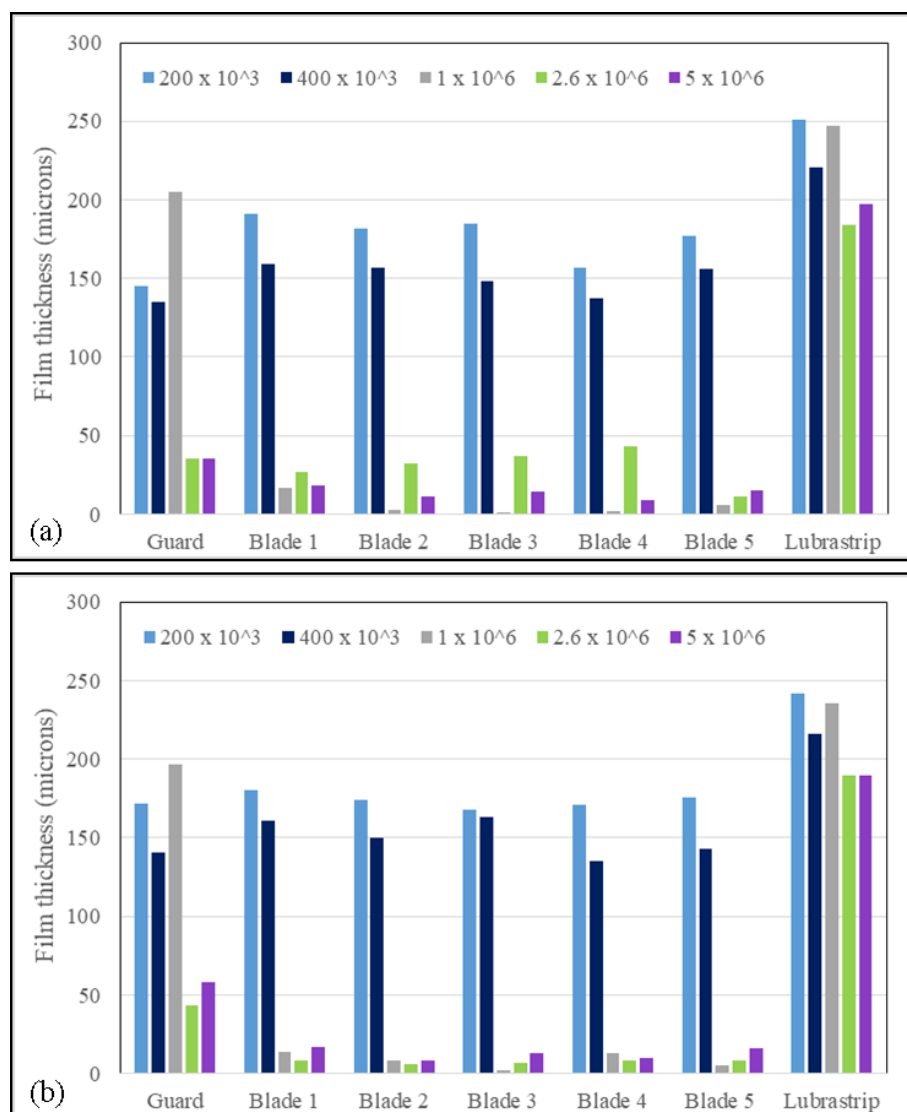


Figure 8.14: Average film thickness results for PEO solutions of varying molecular weight between razor cartridge and glass with guard present (a) 50 mm/s (b) 150 mm/s

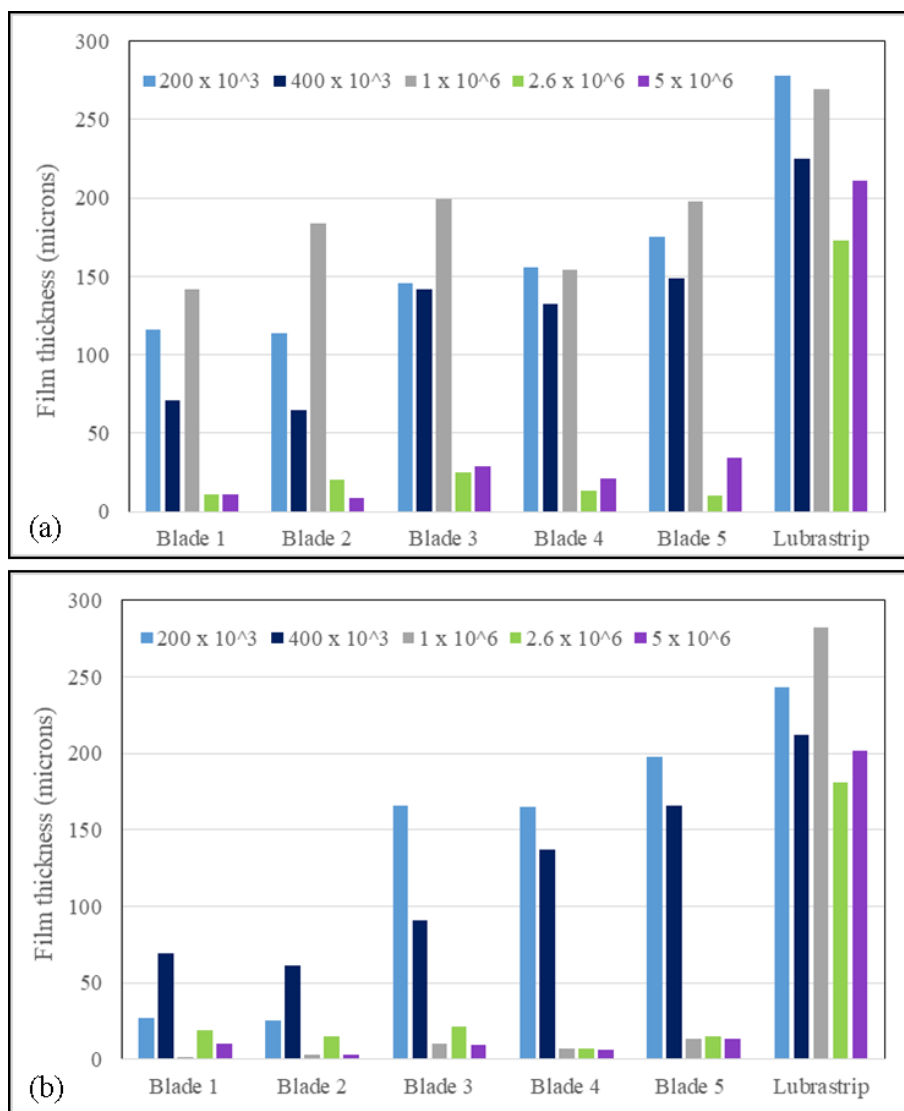


Figure 8.15: Average film thickness results for PEO solutions of varying molecular weight between razor cartridge and glass without guard present (a) 50 mm/s (b) 150 mm/s

The effect of removing the guard is shown more clearly when analysing results from blade 1 and blade 5 only (Figure 8.16 and 8.17). Removing the guard does not necessarily produce an increase in film thickness, and for some lubricants it reduces to zero (or close to) under blade 1 (Figure 8.16). For most PEO solutions film thickness at the front of the razor cartridge is improved by the presence of the guard, particularly at the lower speed of 50 mm/s. 1 x 10⁶ g/mol M_w PEO and 2.6 x 10⁶ g/mol M_w PEO solutions display different behaviour to the other fluids with a film thickness increase once the guard is removed at 50 mm/s and 150 mm/s respectively.

At the back of the razor cartridge (blade 5, Figure 8.17) removing the guard typically creates less of a change in film thickness than for blade 1 (Figure 8.16). For all solutions at a sliding speed of 50 mm/s

film thickness values remain similar to those when the guard is present, except for 1×10^6 M_w PEO and 5×10^6 g/mol M_w PEO solutions where an increase in film thickness is seen (although for 1×10^6 M_w PEO this was also seen for blade 1). At the higher speed of 150 mm/s, removing the guard increases film thickness to levels equal to or higher than when the guard is present.

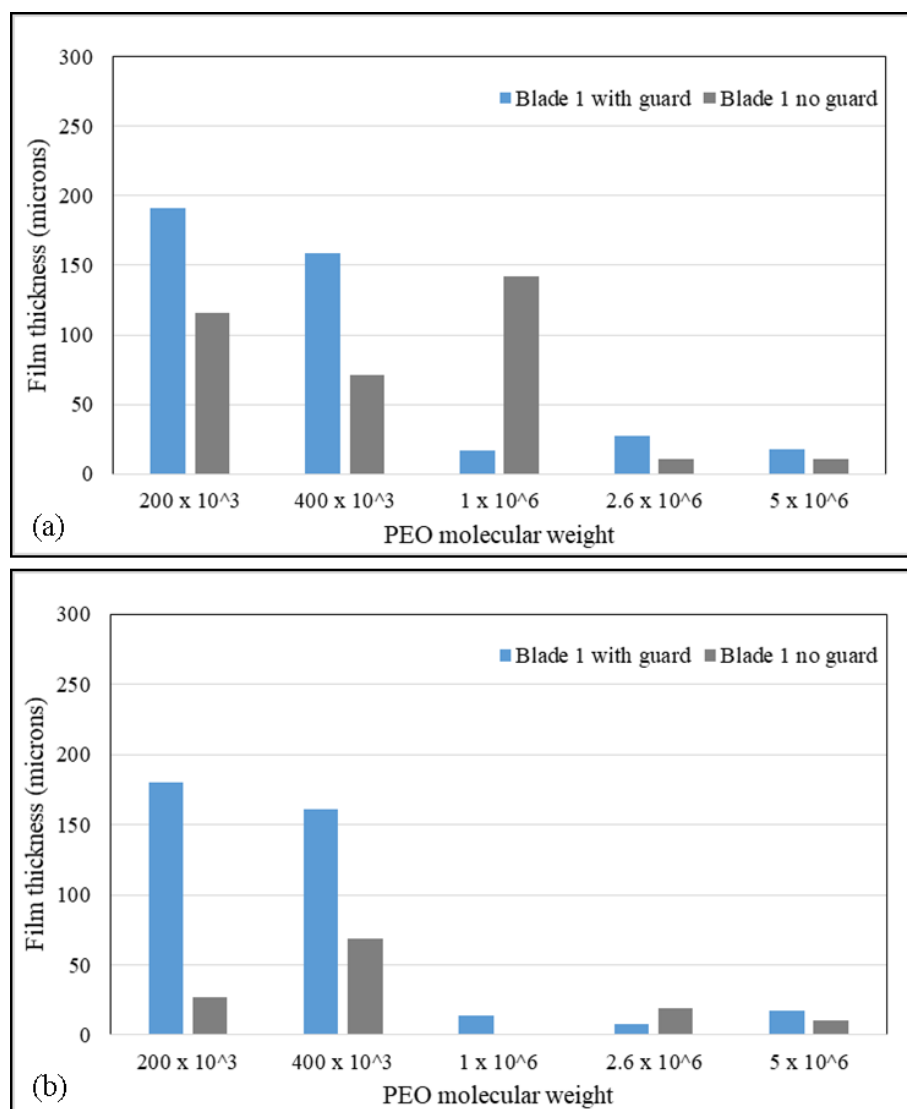


Figure 8.16: Effect of guard on film thickness: Blade 1. For PEO solutions between razor cartridge and glass (a) 50 mm/s (b) 150 mm/s

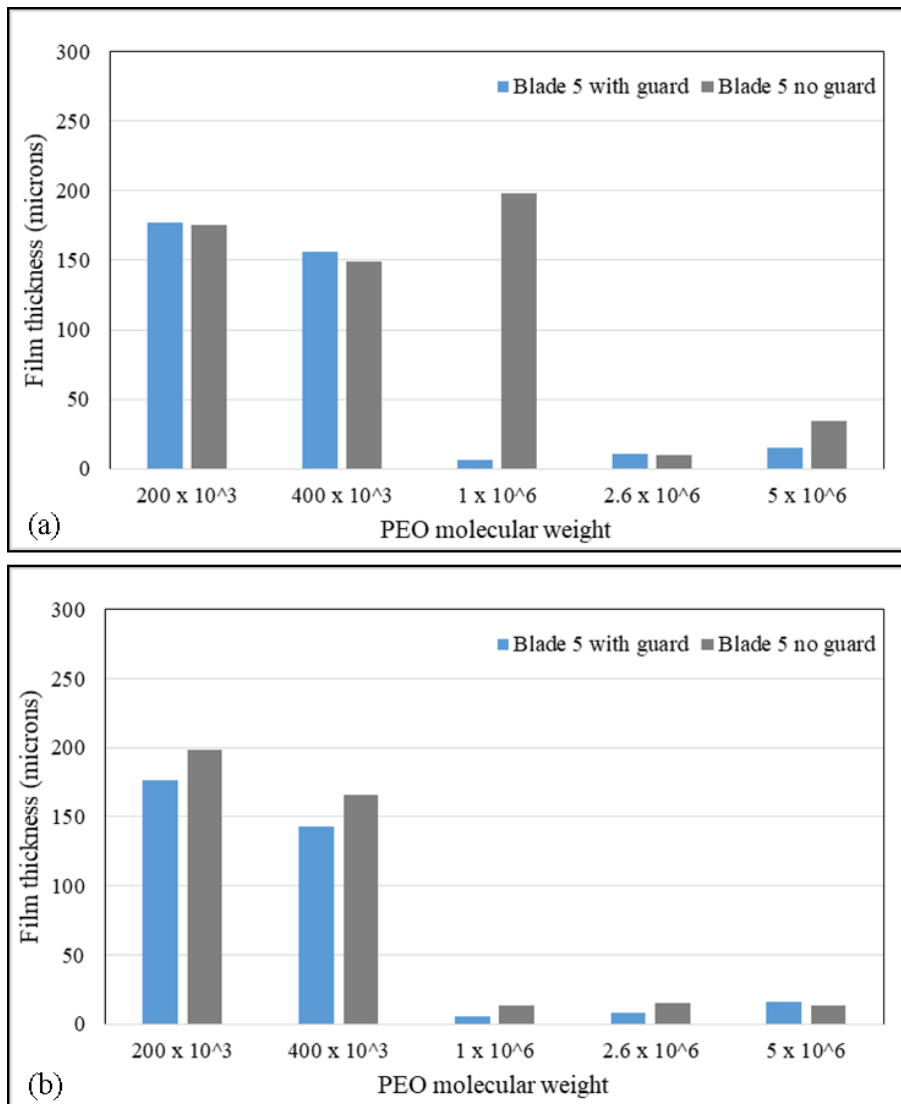


Figure 8.17: Effect of guard on film thickness: Blade 5. For PEO solutions between razor cartridge and glass (a) 50 mm/s (b) 150 mm/s

8.6.3. Guard presence: silicone elastomer disc

Average film thickness results between the razor cartridge and silicone elastomer disc at 50 mm/s and 150 mm/s are shown with the guard present (Figure 8.18) and without the guard present (Figure 8.19). Removing the guard causes film thickness to increase across the razor cartridge contact, although significant decreases are seen with increased sliding speed.

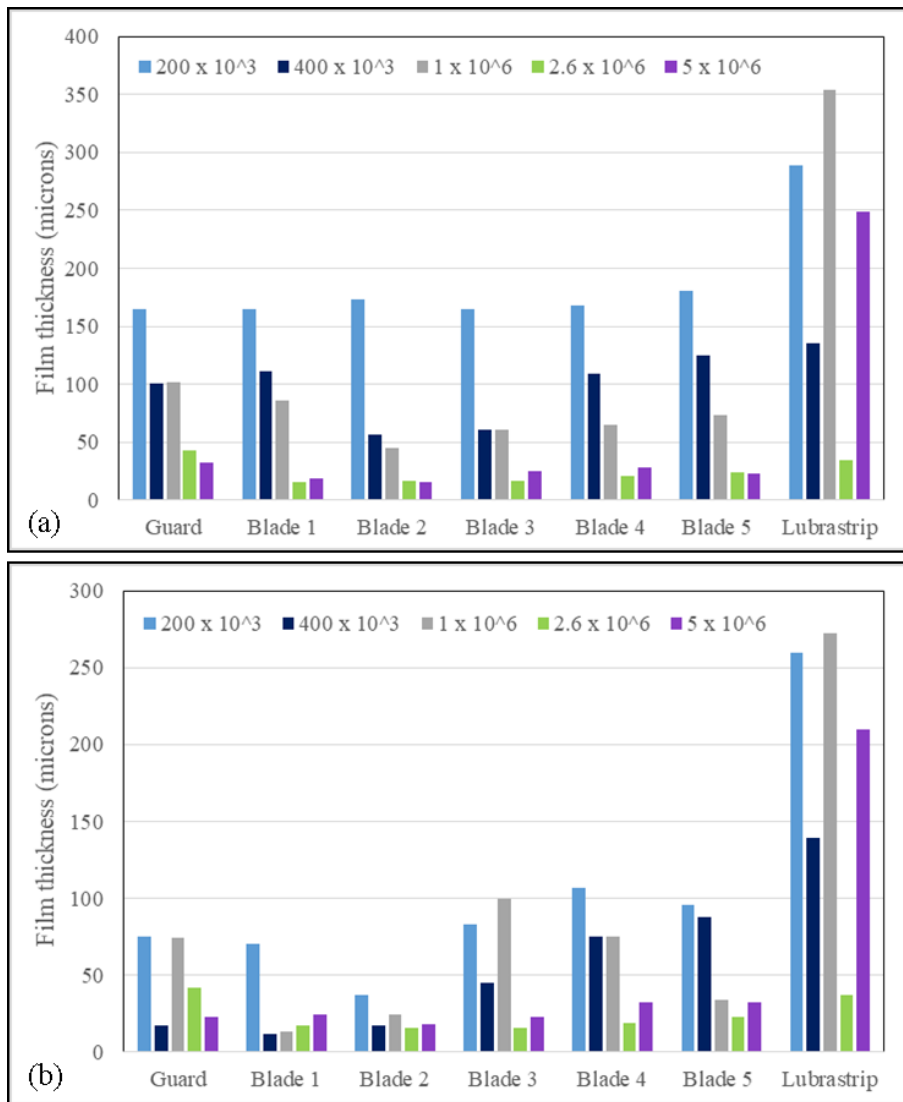


Figure 8.18: Average film thickness results for PEO solutions of varying molecular weight between razor cartridge and silicone elastomer with guard present (a) 50 mm/s (b) 150 mm/s

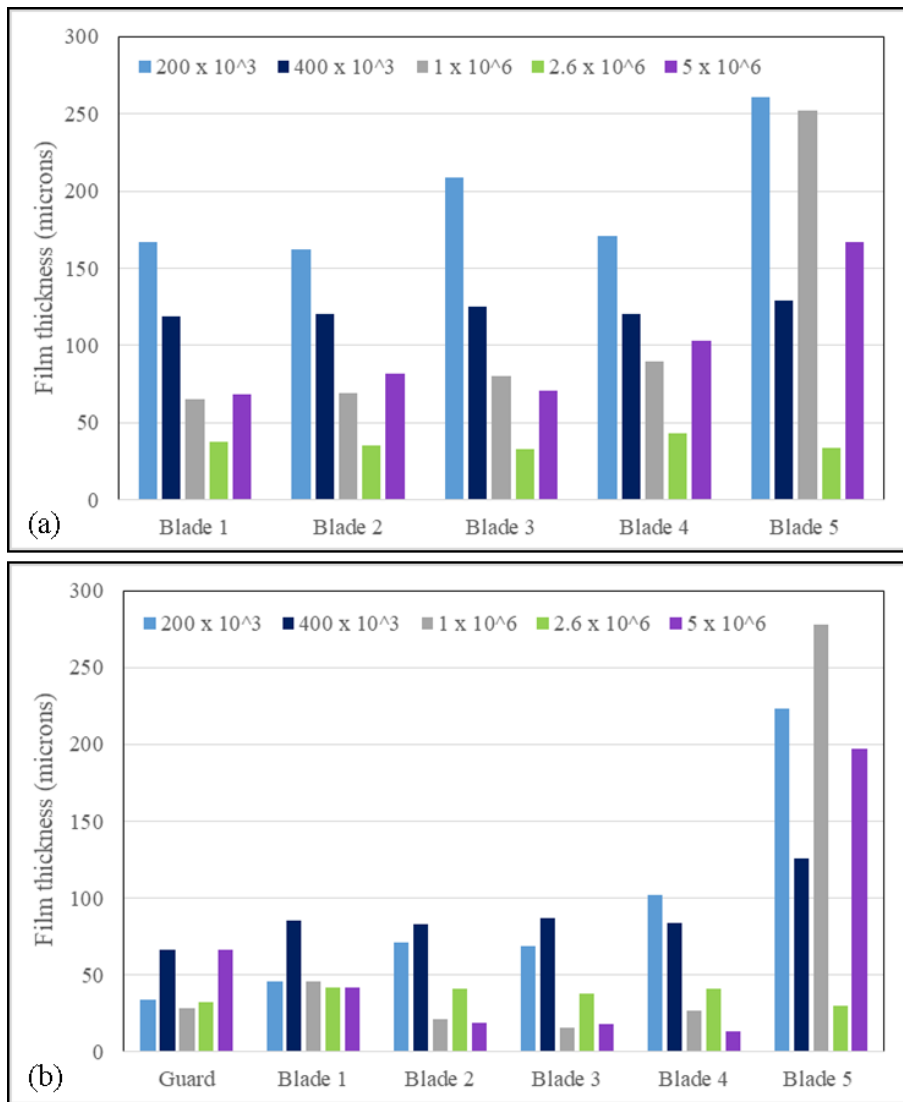


Figure 8.19: Average film thickness results for PEO solutions of varying molecular weight between razor cartridge and silicone elastomer without guard present (a) 50 mm/s (b) 150 mm/s

Once again, comparing blades 1 and 5 shows the effect of the guard more clearly. For blade 1 (Figure 8.20), removing the guard reduces the effect of sliding speed on film thickness (when the guard is present film thickness is significantly higher at 50 mm/s than 150 mm/s). However, removing the guard produces results for blade 5 (Figure 8.21) where film thickness reduces significantly with sliding speed.

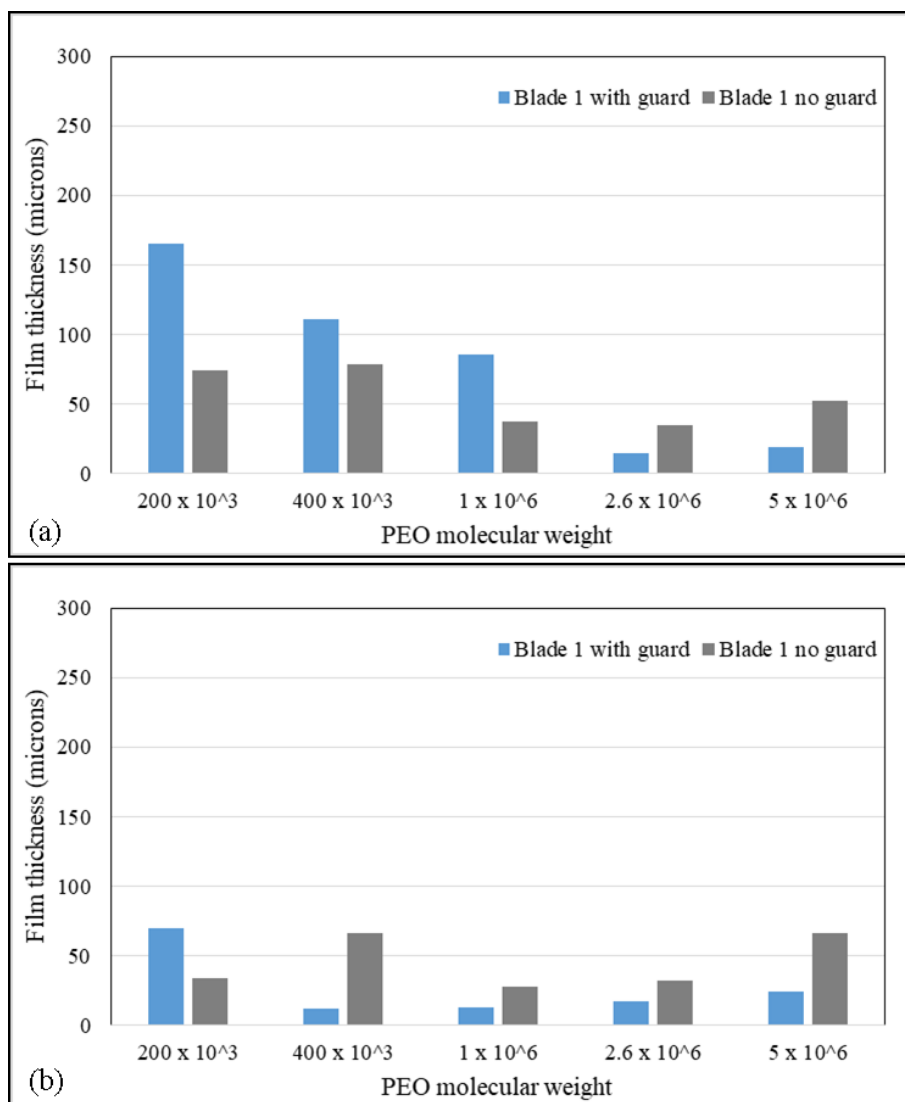


Figure 8.20: Effect of guard on film thickness: Blade 1. For PEO solutions between razor cartridge and silicone elastomer (a) 50 mm/s (b) 150 mm/s

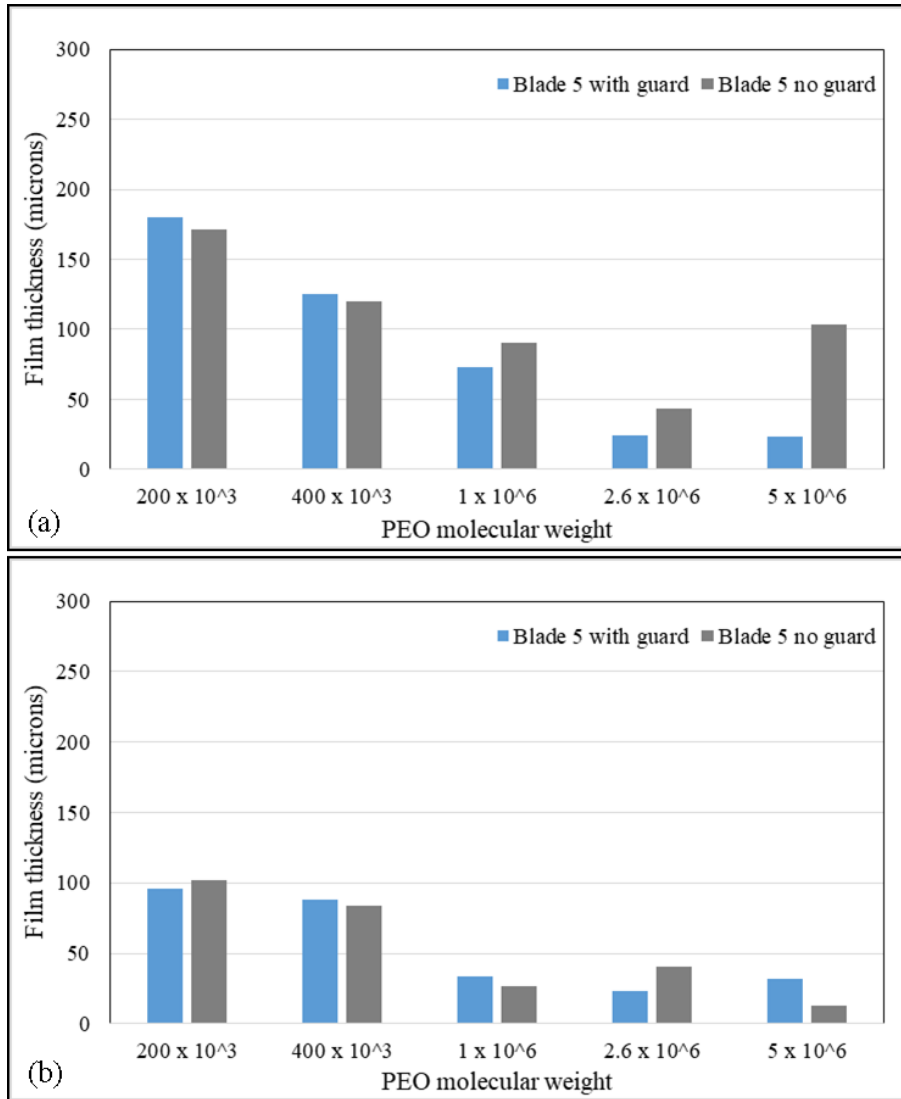


Figure 8.21: Effect of guard on film thickness: Blade 5. For PEO solutions between razor cartridge and silicone elastomer (a) 50 mm/s (b) 150 mm/s

8.7. Conclusion

The LIF method has been successfully applied the razor cartridge contact and allows visualisation of PEO solution lubricant flow through the cartridge and measurement of film thickness at both hard and compliant contact interfaces. The results are further discussed in Chapter 9, but at this stage the PEO fluids have shown that:

The guard and Lubrastrip maintain relatively thick and consistent lubricant films across the speed range.

- The minimum films are measured at the blade cutting edges, although for some results the film increases towards the back of the cartridge.

- The PEO molecular weight has a significant effect on film thickness, with much lower films measured at high speeds for the high molecular weight (1×10^6 g/mol, 2.6×10^6 g/mol and 5×10^6 g/mol) solutions
- Higher molecular weight PEO solutions produced visible channels of lubricant, which stretch across the cartridge contact.
- Film thickness typically decreases with increasing sliding speed.
- A compliant (silicone elastomer) counterface allows formation of a thicker lubricant film with the high molecular weight PEOs than for a hard (glass) counterface.
- The presence of the guard improves razor cartridge lubrication for a compliant counterface.

8.8. References

- [1] Ocallaghan, D. Procter & Gamble. Email sent to: Suzanna Whitehouse. 2nd December 2014.

9. COMPARISON OF EXPERIMENTAL METHODS AND RAZOR CARTRIDGE LUBRICATION MECHANISMS

Summary

The thesis has reported a range of experimental techniques to characterise friction and film thickness under simple and complex contact geometries for reference and PEO fluids. In some cases problems with repeatability of results were experienced and these are discussed in this Chapter. Laser induced fluorescence (LIF) was successfully applied as a technique for measuring film thickness and imaging fluid distribution in a razor cartridge contact for the test solutions. In this Chapter the results from the LIF technique are discussed with respect to razor cartridge design and lubricant behaviour. Starvation and reflow mechanisms within the cartridge/skin contact are also discussed. Relationships between molecular weight, viscoelasticity and film thickness were established.

9.1. Introduction

The LIF results reported in Chapters 7 and 8 have shown clearly that cartridge components and associated lubricating film formation can be observed during simulated shaving. Film thickness and distribution has been shown to change in a complex manner depending on the nature of the contact (hard or compliant), the presence of a guard, sliding speed and fluid properties. In this chapter the effects of fluid properties and contact conditions on film formation are examined in more detail. In addition the origins of experimental errors and variability in film thickness and friction results are discussed for the different techniques used.

9.2. Comparison of experimental methods

A range of experimental methods have been reported in the thesis characterising friction and film thickness in hard and compliant contacts for different geometries. Chapter 5 reported standard MTM tests to measure friction under different sliding and slide/roll conditions. The LIF technique was used in Chapter 6 to measure film thickness for a simple ball/flat geometry. Finally, Chapters 7 and 8 reported LIF images and film thickness results for the lubricated razor cartridge. Throughout the project problems were experienced with the repeatability of test results and these are discussed in more detail in this section.

9.2.1. MTM tests

The MTM device is currently used by Gillette as a screening test for shaving prep fluids as it measures friction under a range of slide/roll and speed conditions. In the current work the possibility of using more complex test profiles, for example Stribeck-type curves and restricted lubricant supply, was tested. Currently Gillette use two simple, pure sliding profiles with excess fluid at room temperature: a speed sweep (10-500 mm/s) and a single speed/time test (150 mm/s).

Pure sliding (SRR 200%) and 100% SRR tests were run over a range of speeds (10-200 mm/s), which included the two critical sliding speeds identified for shaving of 50 mm/s (the tricky bits!) and 150 mm/s (standard shaving speed). Overall more consistent results were obtained with the 100% SRR tests, and using this profile Stribeck-type curves were obtained for both reference and PEO fluids. Reducing the amount of fluid present to simulate what happens during shaving tended to reduce friction coefficients for the PEO fluids but problems were encountered with repeatability of these results. However using a scraper height that reduced film thickness to $\sim 100\ \mu\text{m}$ was a reasonable mimic of film thicknesses found in the cartridge lubricant supply regions (guard, blade troughs etc.) from the LIF study.

One of the problems encountered throughout the study was with the use of PDMS as a skin mimic. Although the specimens were rigorously washed with detergent, water and isopropanol, with a final plasma clean to render the surfaces hydrophilic, there still appeared to be surface wetting issues –

particularly for some of the higher viscosity fluids. In the MTM this was seen as erratic friction measurements for the simple sliding condition suggesting variability in fluid entrainment. Although this could also have been exacerbated by using the MTM in pin-on-disc mode where the friction is measured in one direction only. Thus the pure sliding and scraper results had greater variability. The friction results were significantly improved using the SRR mode (where friction is averaged for different relative rotation conditions of the ball/disc).

Glycerol appeared to suffer from surface wetting problems in both the MTM and razor cartridge tests. Hydrophilic effects from plasma cleaning last for approximately 30 minutes [1], which was sufficient for each test (lasting 10 minutes). Therefore this is unlikely to be a contributing factor. The difference in low sliding speed friction measurements for glycerol under pure sliding and SRR conditions is shown in Figure 9.1. Good agreement is seen at high speeds but there are significant differences at low speeds – similar results are also reported by Myant et al. [2]. The origins of this are unclear and should be addressed in future work.

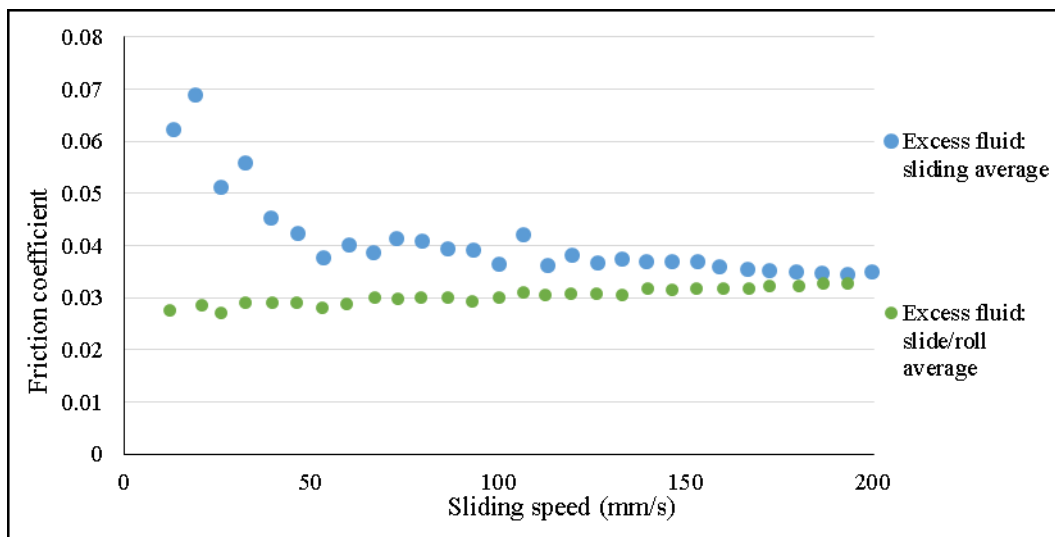


Figure 9.1: Fully flooded friction curves for glycerol under pure sliding and SRR conditions

9.2.2. LIF imaging and film thickness measurements

The LIF techniques rely on intensity measurements which by their nature (due to fluctuations of the pulsed laser) can show significant variation from test to test. To overcome this variability a calibration procedure was carried out before each test. Overall good repeatability was established for ball/disc film

measurements (see Figure 9.2), the lower film thickness detection limit was $0.25 \pm 0.36 \mu\text{m}$ for a glass contact, and $1.22^{+3.09}_{-1.22} \mu\text{m}$ for a silicone elastomer contact. The overall film measurement range was approximately $0.5\text{-}600 \mu\text{m}$, which compares to a minimum film thickness of $0.2 \mu\text{m}$ [3] and $0.3 \mu\text{m}$ [4], and a film thickness range of $50\text{-}100 \mu\text{m}$ [5] reported by other studies.

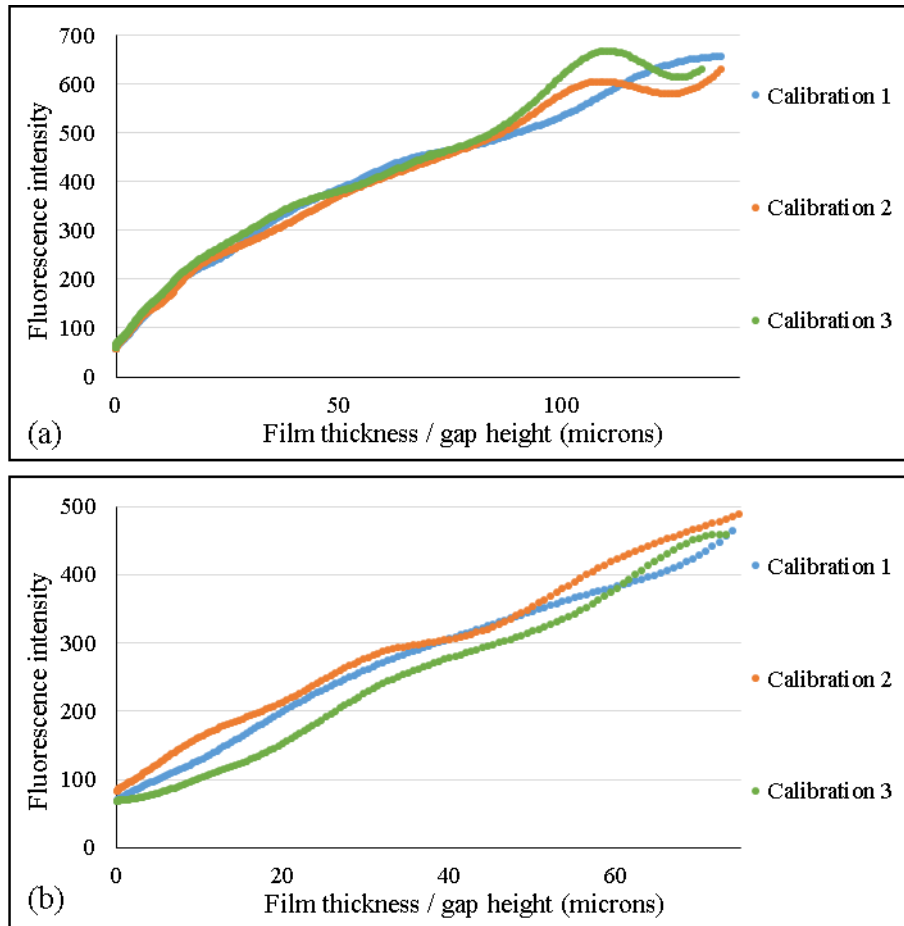


Figure 9.2: LIF calibration and film thickness measurements for ball-disc geometry (a) glass (b) silicone elastomer

The LIF method applied to the razor cartridge contact provided clear images of the different components and the fluid distribution within the contact regions. The clarity of the images was excellent, particularly for the glass counterface. See example shown later in Figure 9.6 for the guard fin region.

Because of the changes in intensity level between tests the starting point for all the LIF cartridge measurements was a series of profiles taken of the stationary disc loaded against the razor cartridge, which was flooded with fluid. Under these conditions you would expect to see very similar film thickness profiles; however it must be remembered the gap heights are a combination of the razor

geometry and clips which hold the cartridge away from the skin surface. For each fluid good repeatability was seen from different tests; this is seen in Figure 9.3, which plots example profiles for water against a glass disc. On the left hand side of the plot a series of sharp variations is often observed (very clearly in the profiles below), which correspond to the guard fins.

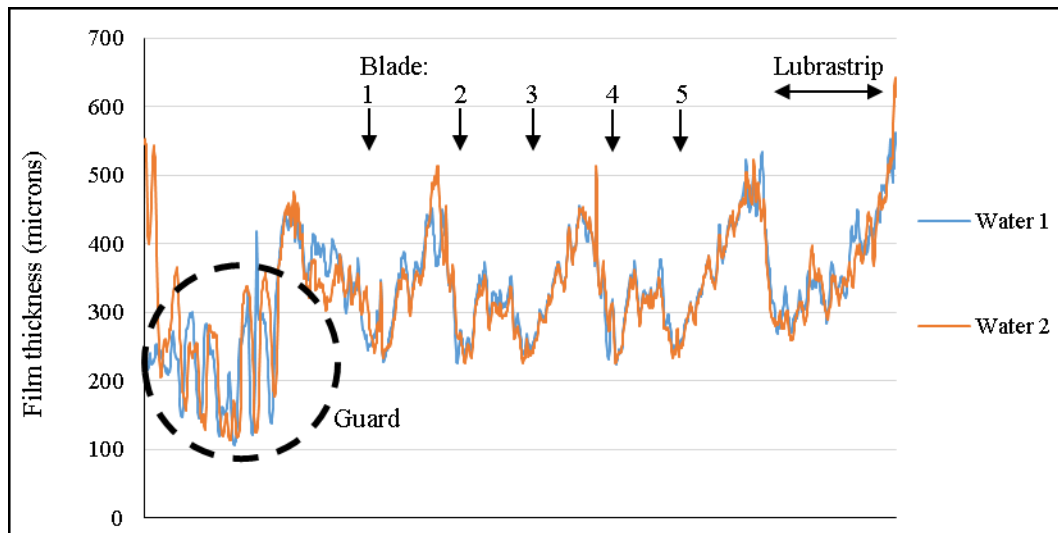


Figure 9.3: Example stationary film profiles for razor cartridge against glass disc for tests with distilled water

However there was variation in the overall film heights between the different fluids and this appeared to be related to viscosity. Thinner films were measured for the higher viscosities and this can be seen in Figure 9.4.

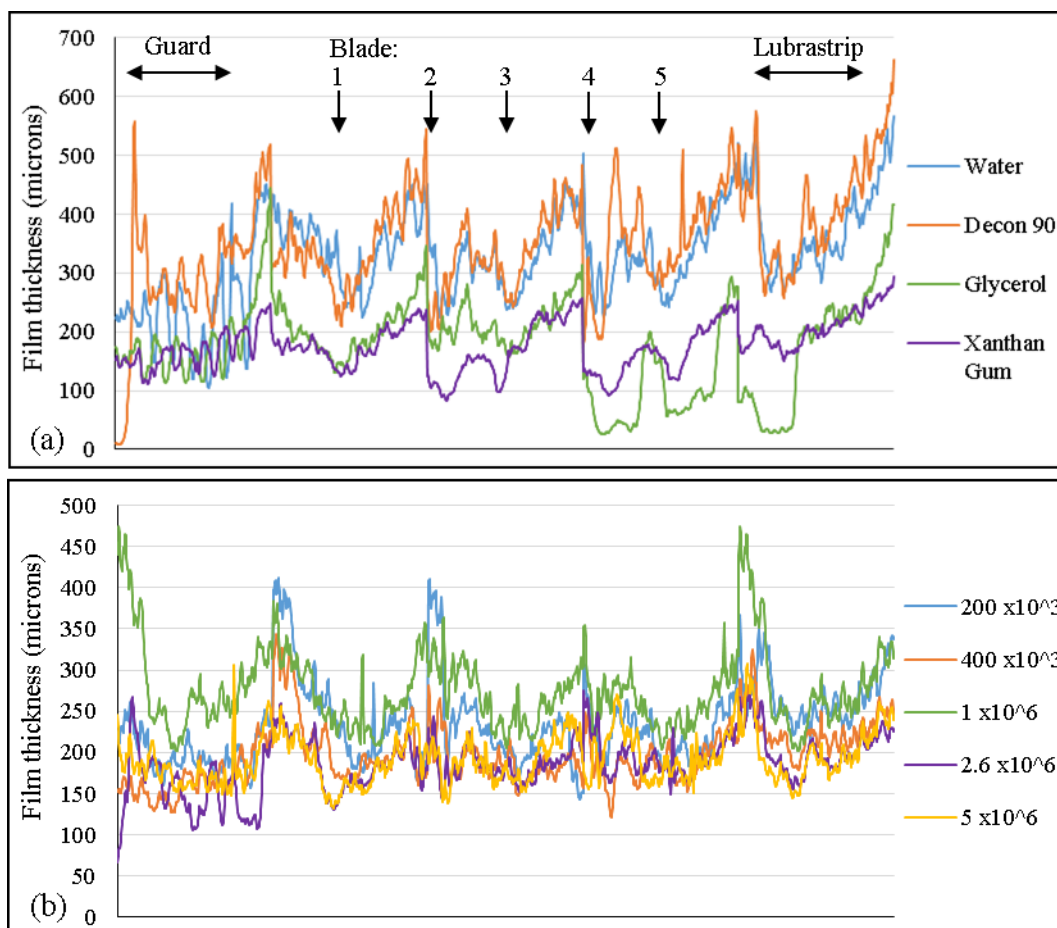


Figure 9.4: Average film profiles for razor cartridge stationary contact against glass (a) reference (b) PEO fluids

The film profiles were further modified by the counterface material. Loading the razor against a soft counterface moderated the film profile for the low viscosity fluids (Figure 9.5a) but had little effect on the higher viscosity fluids (Figure 9.5b). Averaged results are compared for glass and silicone counterfaces in Figure 9.5 for (a) water and (b) 1×10^6 M_w PEO. In this case the fins are clearly seen for the water-glass contact but definition is lost for the silicone elastomer and high viscosity fluid, which might indicate deformation of the elastomer around the contact region. Examples of LIF images from the guard fins for glass and silicone elastomer counterfaces are shown in Figure 9.6.

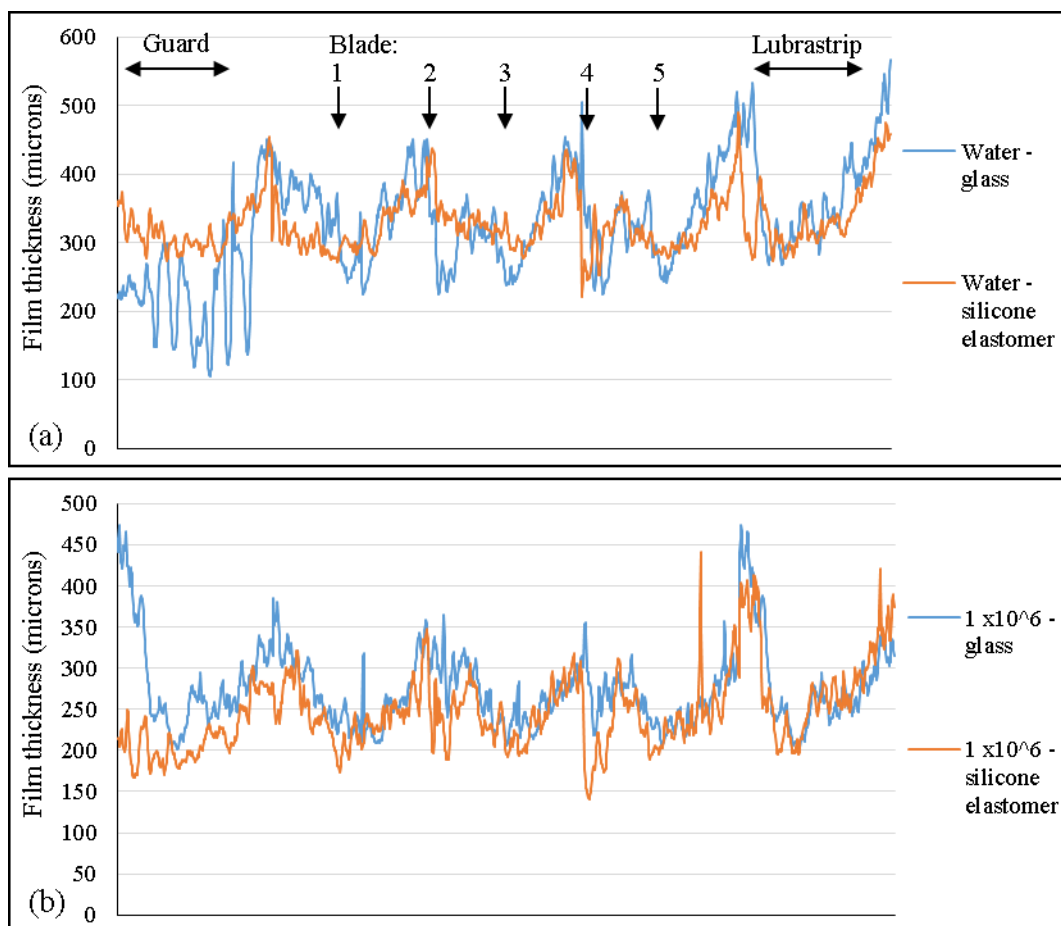


Figure 9.5: Effect of silicone elastomer counterface on static razor cartridge film profiles (a) water, (b) 1×10^6 g/mol M_w PEO solution

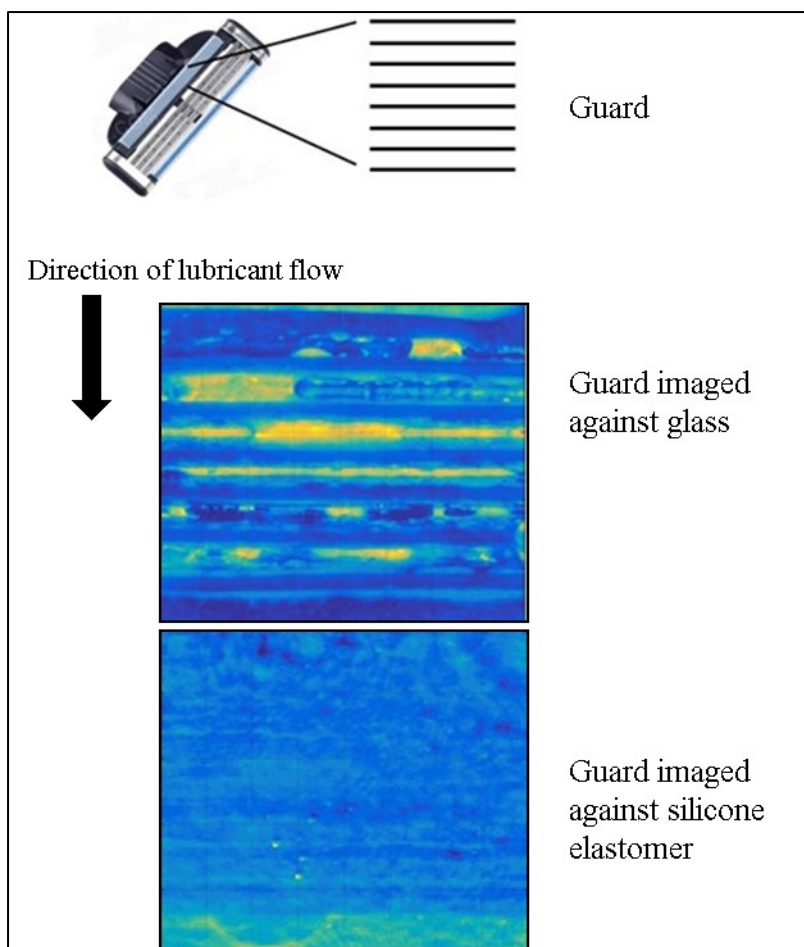


Figure 9.6: LIF image of guard fin region for glass and elastomer counterfaces.

The reduced films for the high viscosity/viscoelastic fluids are again thought to be due to poor surface wetting so that fluid either did not completely fill the cavities or was lost under loading. Attempts were made to reduce these effects by pipetting additional fluid into the contact. Further study is needed to understand the effect of surface wetting both to improve measurement repeatability and to understand starvation and replenishment mechanisms. This is discussed in more detail later in this Chapter. Razor cartridge film results under sliding must therefore be interpreted with care and in relation to the film measured at zero speed. However trends in the effects of speed and fluid type on film distribution can still be inferred. Deformation of the silicone surfaces will also modify the contact local film thickness. It appears that when lightly loaded a fluid film is maintained of 100-300 μm under the blades for all fluids with the cartridge clips in place. However once sliding commences the fluid film profile changes significantly.

The following discussion will only consider results taken with the guard in place. Removal of the guard alters the film distribution but it is not representative of the shaving condition and will not be discussed in detail here

9.3. Effect of fluid properties on razor cartridge film profiles

Once sliding commenced film thickness distribution changed and examples are shown below for a low (distilled water) and high viscosity (1×10^6 g/mol M_w PEO) fluid against glass (Figure 9.7) and silicone elastomer (Figure 9.8). For the water/glass system film thickness distribution was similar for all speeds (Figure 9.7a). The film under the guard was typically 100-300 μm , immediately behind the guard this increased to 400 μm . The blades maintained films of ~ 250 μm , increasing to 400-500 μm in the troughs between the blades.

The distribution for the high viscosity fluid (Figure 9.7b) was very different and clearly showed a reduction in film thickness under the blades to less than 10 μm at higher speeds. However the PEO film between the blades appears to recover to ~ 200 μm , particularly towards the rear of the cartridge, so there is plenty of fluid present to form and maintain a film under the rear blades.

For the cartridge/silicone elastomer contact the 1×10^6 g/mol M_w PEO solution maintained a much thicker film through the blades (~ 50 -100 μm), again increasing towards the rear of the cartridge.

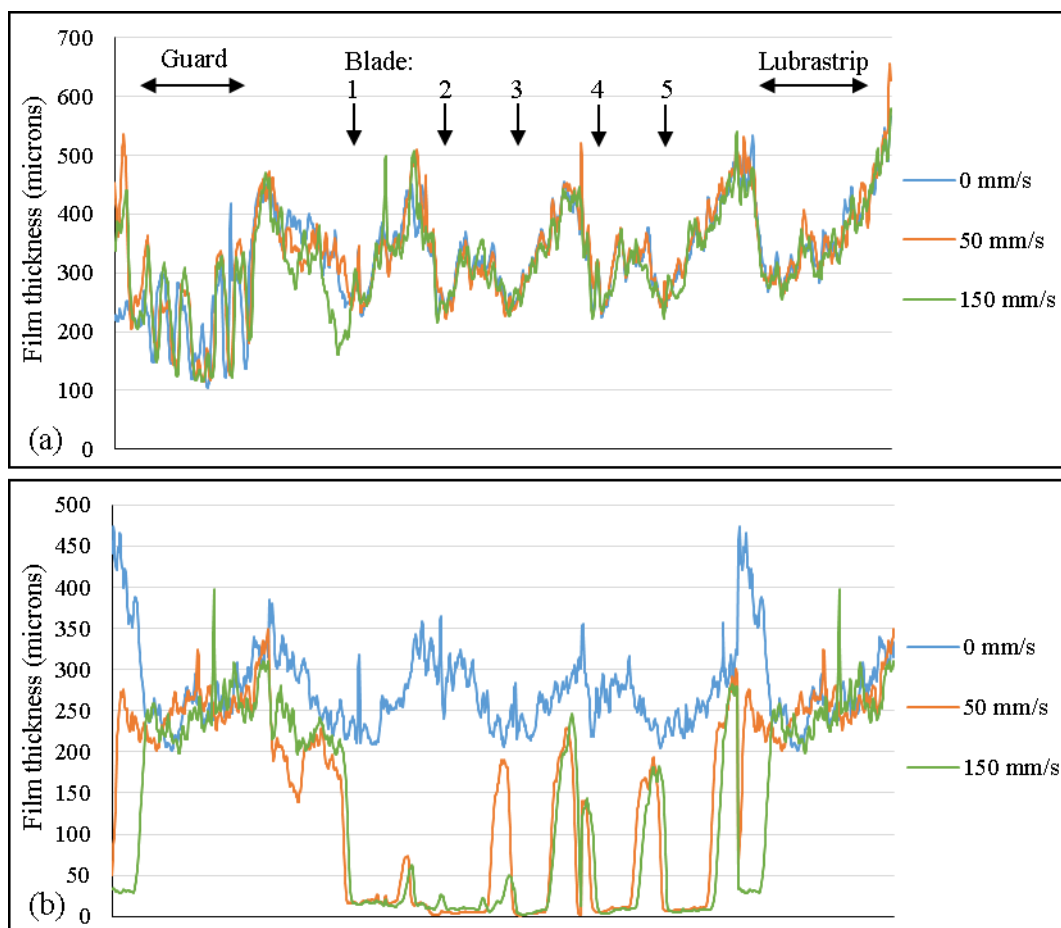


Figure 9.7: Average razor film profile changes for (a) water and (b) $1 \times 10^6 M_w$ PEO during sliding against glass

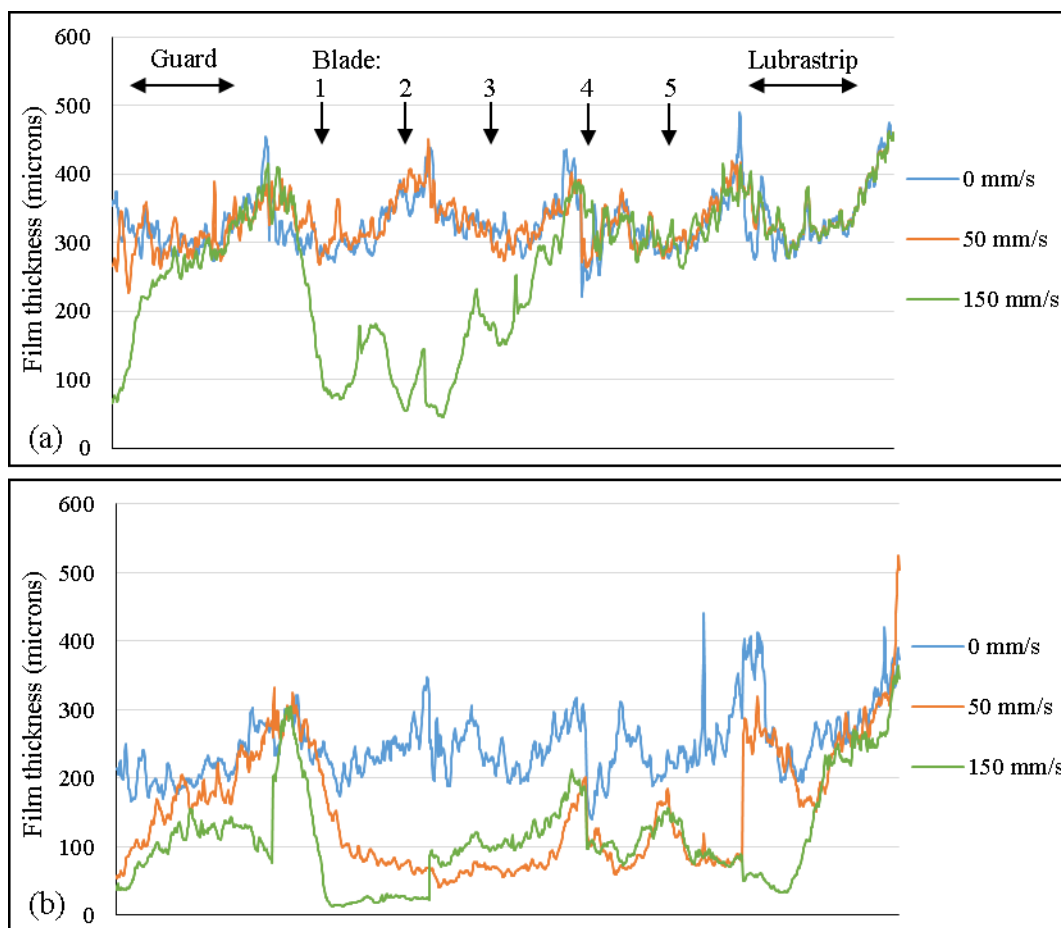


Figure 9.8: Average razor film profile changes for (a) water and (b) 1×10^6 g/mol M_w PEO during sliding against silicone elastomer

The effect of fluid type on film thickness for guard, blade 1 and blade 5 regions is summarised in Figure 9.9 for glass and Figure 9.10 for silicone elastomer counterfaces. For the glass contact in Figure 9.9, film thickness across the razor cartridge contact decreases as viscosity (and molecular weight) increases. This is also seen for reference fluids, although 1×10^6 g/mol M_w PEO and xanthan gum solutions (which have similar viscosities) produce different film thickness profiles with increasing sliding speed: 1×10^6 g/mol M_w PEO film thickness at blade 1 is greater than blade 5 for both speeds, but film thickness at blade 1 for xanthan gum more than halves when sliding speed increases from 50-150 mm/s. This difference in blade 1 film thickness as speed increases is seen for all PEO and high viscosity (glycerol and xanthan gum) reference fluids.

Increasing sliding speed reduces film thickness for all reference fluids at the blade interface – the effect at the guard is more variable. The same effect is not necessarily seen for PEO solutions, and at high

viscosities especially (2.6×10^6 g/mol M_w and 5×10^6 g/mol M_w), film thickness across the blades is similar at the higher sliding speed of 150 mm/s. Film thickness at the guard is lower than at the blades for low viscosity PEO solutions (200×10^3 g/mol M_w and 400×10^3 g/mol M_w), although the difference is reduced at higher speeds. For higher viscosity PEO solutions (1×10^6 g/mol M_w and above), film thickness at the guard is much higher than across the blades. 1×10^6 g/mol M_w produces an especially high film thickness at the guard contact – more than 10x larger than at blade 1.

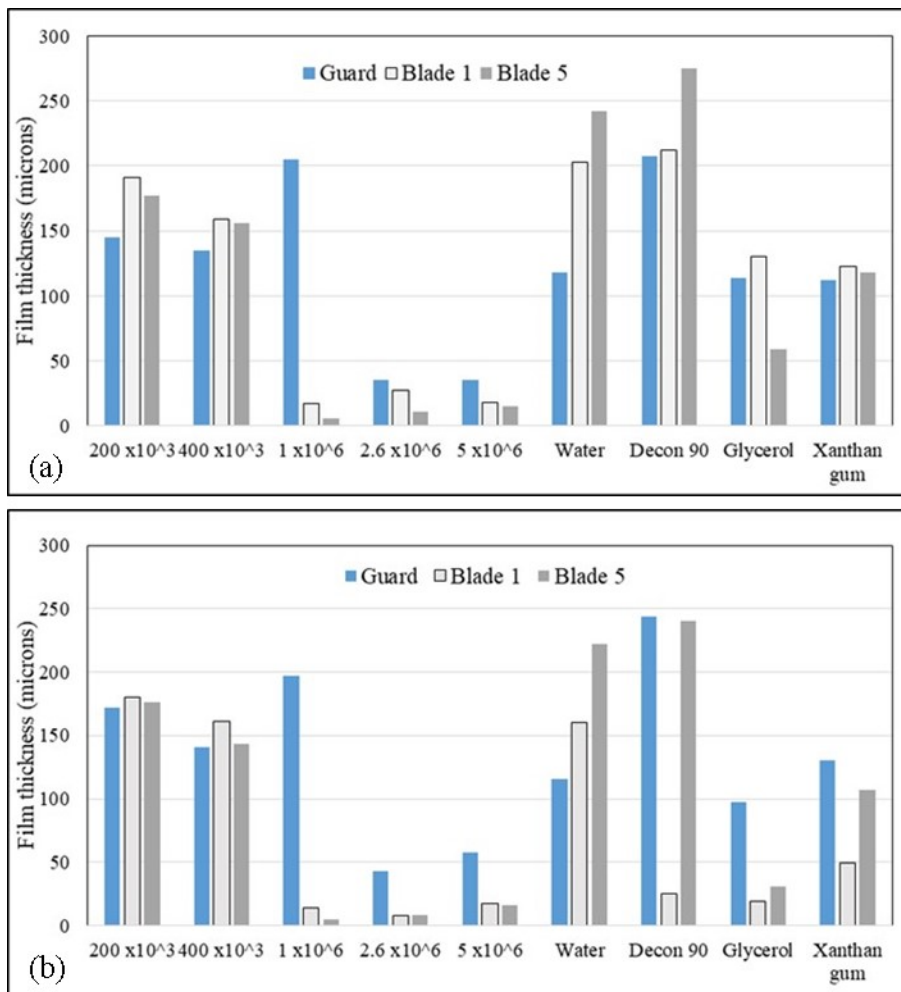


Figure 9.9: Film thickness results for test fluids in a razor cartridge/glass contact with sliding speed (a) 50 mm/s, (b) 150 mm/s

Introducing a compliant counterface produces a much clearer trend between PEO molecular weight and film thickness across the razor cartridge. At 50 mm/s sliding speed (Figure 9.10a), film thickness clearly decreases with increasing molecular weight (and viscosity). Blade 1 film thickness is typically higher

than at blade 5 (excluding 1×10^6 g/mol M_w PEO solution), and the guard film thickness is similar to that for a glass counterface.

At 150 mm/s (Figure 9.10b), film thickness for low viscosity PEO solutions (200×10^3 g/mol M_w and 400×10^3 g/mol M_w), is lower than for the glass counterface. But for 1×10^6 g/mol M_w PEO solution and above, film thickness is slightly higher. Film thickness at Blade 5 is consistently higher for PEO solutions in the silicone elastomer contact at sliding speed 150 mm/s.

Results for reference fluids did not produce such an obvious trend for the compliant counterface. Although glycerol solution has a much higher film thickness for the silicone elastomer counterface, but this may be due to improved surface wetting aiding replenishment (this is explored further in the following discussions).

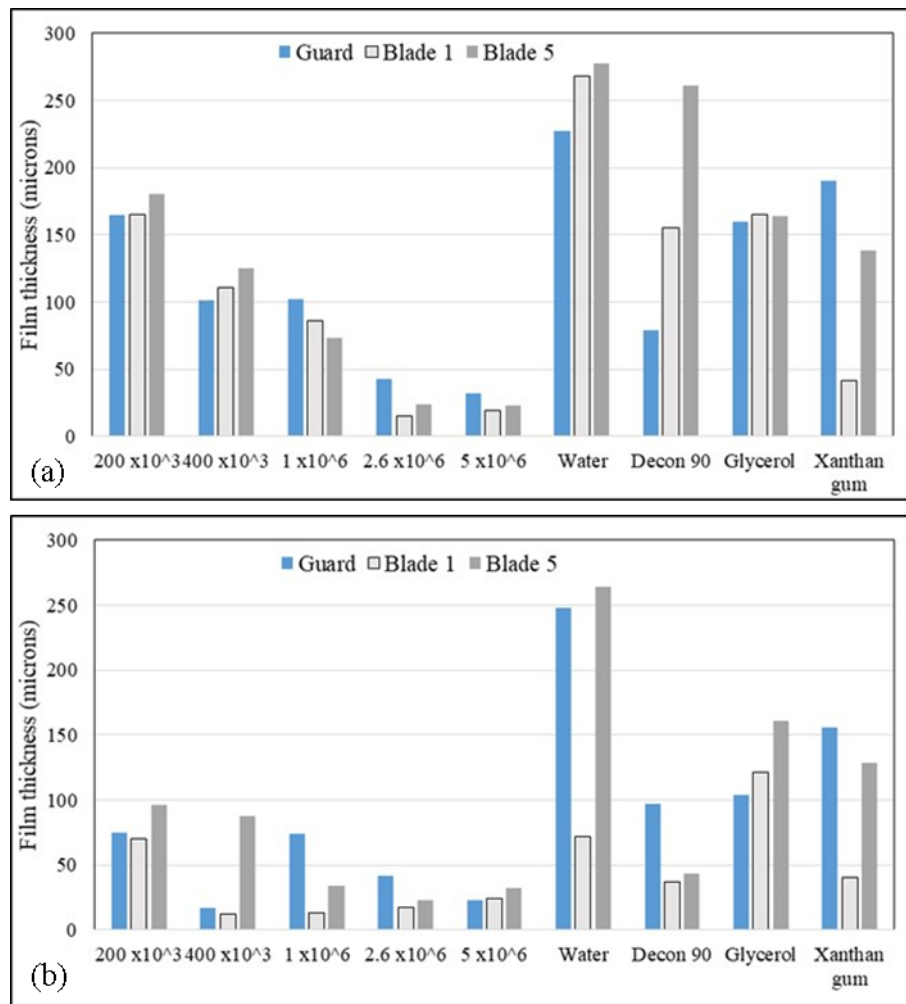


Figure 9.10: Film thickness results for test fluids in a razor cartridge/silicone elastomer contact with sliding speed (a) 50 mm/s, (b) 150 mm/s

It has been shown that changes in lubricant (chemistry and viscosity), counterface material (hard or compliant) and sliding speed have an effect on the film thickness profiles across the razor cartridge. Successful lubrication is defined by the relationship between lubricant replenishment and starvation within the contact [6, 7], and contact conditions (lubricant, contact material, speed etc.) will affect user perception due to friction.

The reduction in film thickness under sliding and the observation that the film often decreased further at higher speeds indicated lubricant starvation of the contact region. Starvation occurs when there is insufficient fluid in the inlet region to form full film in the contact area [8] and it is typically seen in machine elements where there are repeated contacts (bearings), line contacts (bearings), and a high viscosity, or reduced amount of mobile lubricant (grease) or at high speeds (bearings/gears) [9, 10]. In the razor system there are multiple contacts through the cartridge and the lubricant supply is determined by the guard at front.

For starved contacts the film thickness is typically much lower than the calculated film thickness, and for some systems, depending on severity, this can contribute to higher friction [11]. However if the fluid film is normally large then starvation might contribute to *reduced* friction which could be an advantage in razor lubrication. Severity of starvation in the contact is determined by lubricant viscosity [11], quantity [13] and distribution [10, 14], as well as time between subsequent contacts [13, 15, 16] and contact geometry [8]. Models have also related starvation directly to film thickness in the inlet [10, 14]. These factors are strongly linked to lubricant flow, which is influenced by the surface tension of the lubricant [17].

Lubricant supply mechanisms are surface tension driven, controlled by local, capillary-driven flow around the contact [18, 19]. Reflow is influenced by surface spreading properties of the lubricant, and the ability of a fluid to spread spontaneously on a smooth surface is characterised by the surface energy balance [20]. The equilibrium contact angle, θ , is given by Young's equation (Equation 9.1):

$$\gamma_{sv} - \gamma_{sl} = \gamma_{lv} \cos \theta \quad (9.1)$$

where γ_{sv} , γ_{sl} and γ_{lv} are the surface tension at the solid-vapour, solid-liquid and liquid-vapour interface respectively. In a starved lubrication regime, the ability of the lubricant to replenish the contact is determined by the rate of reflow, depending on lubricant viscosity, surface tension and contact angle [21, 22], which are linked to surface wetting [23, 24]. This is particularly relevant in the simulation of a skin contact because the presence of sebum on the skin's surface promotes amphiphilic wettability [25], which may reduce starvation. Additionally, the polarity and surface energy of skin will influence lubricant surface wetting [26].

In studies of grease lubrication it has been observed in a rolling point contact [20] that at very low speeds lubricant collects at the contact interface and travels with the rolling contact, held in place by surface tension forces. This is also seen with emulsion, except it is the released oil phase which collects around the contact [26]. Because of this surface tension, a separating film can be formed and retained at the contact interface [17], with the contact maintaining its own local reservoir, where retention depends on contact geometry, speed and lubricant properties [20, 22]. However a balance is required, as seen in oil lubricated systems where the ability of the lubricant to wet the surface and creep is relied upon to carry the lubricant to otherwise inaccessible surfaces [27].

It can therefore be assumed that while surface tension promotes film formation and replenishment, poor surface wetting properties reduce replenishment, and an example of this is the glycerol solution used throughout this project. Glycerol solution has a high surface tension, strongly resisting spreading [28], and although its high viscosity (3.45 mPa.s) should produce a thick film thickness [29] (Figure 9.11a), both MTM results (9.11b) and LIF cartridge lubrication results (Figure 9.11c) showed poor lubrication with this fluid.

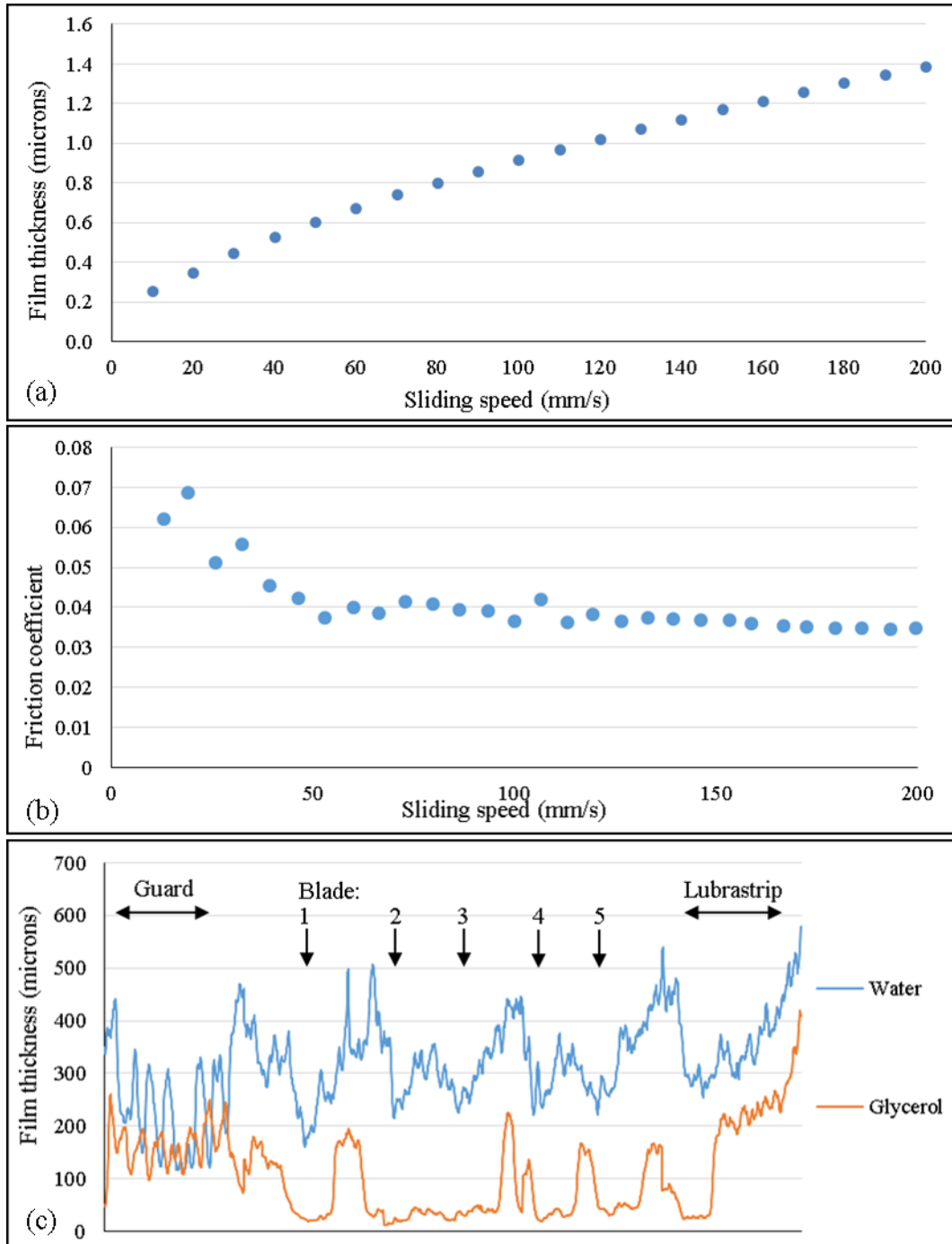


Figure 9.11: Glycerol solution results (a) calculated film thickness for MTM stainless steel ball/PDMS disc contact (b) MTM friction in an excess fluid, sliding contact (c) film thickness profile for razor a cartridge/glass disc contact at sliding speed 150 mm/s

It has been shown in studies of starvation and reflow in a point contact [15, 18, 19, 30] that the rolling action squeezes lubricant towards the track, which combined with surface tension forces creates a local lubricant supply to the inlet. This effect is known as capillary flow, and it increases with decreasing inlet size [31]. When a compliant counterface is present, deformation occurs around the contact

interface [32], causing decreased inlet size (Figure 9.12), which increases capillary flow by creating channels for replenishment, and is one reason for the differences in film thickness results between glass and silicone elastomer.

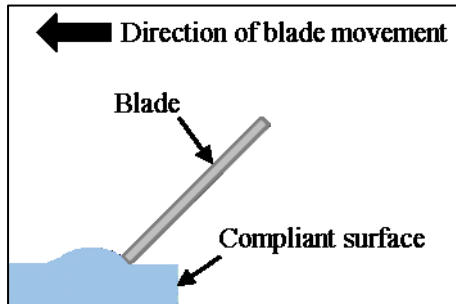


Figure 9.12: Compliant counterface deformation around the contact

The main film loss mechanisms are displacement of fluid from the inlet, and cross-flow from the contact, which (excluding an indirect effect via the film thickness) are speed dependent [13]:

- Inlet displacement loss is speed dependent, and once the inlet meniscus disappears this reduces.
- Cross-flow from the contact becomes increasingly small as the lubricant film thins.

Considering both of these mechanisms, the film thickness in the contact is therefore much the same as in the track [14]. As a result, the contact becomes increasingly efficient in retaining lubricant, and a flow-balance is reached. This has been demonstrated by a constant film level observed after many overrollings [15], and under these conditions only a very low quantity of lubricant reflow is required to maintain an equilibrium film [33].

Therefore, the equilibrium film level is a product of the lubricant flow balance: between lubricant lost from the contact and replenished from the reservoir at the side of the track. In this regime, increasing viscosity and increasing speed decreases film thickness, and the normal rules do not apply: conditions that increase film thickness in fully flooded conditions will reduce film thickness in the starved regime [11, 15, 20, 34].

From the foregoing discussion viscosity plays an important role in determining the onset of starvation. If Blade 1 film thickness is plotted against increasing viscosity for all fluids (reference and PEO) an overall decrease is observed for all fluids. This can be seen in Figure 9.13 for both glass (9.13a) and

silicone elastomer (9.13b) counterfaces. For most of the fluids film thickness at 50 mm/s is greater than film thickness at 150 mm/s. Both of these effects support the idea that fluid starvation occurs within the cartridge contacts.

In the confined contact geometry of the cartridge components, particularly when loaded against a soft counterface where significant deformation will occur, fluid replenishment will be driven by capillary reflow and surface wetting forces. However a second mechanism for restoring film thickness is possible with the PEO fluids: that of elastic rebound, which pulls fluid back into the trough zone after being stretched by the blades. Evidence for fluid reflow and elastic replenishment effects will be examined in the next sections.

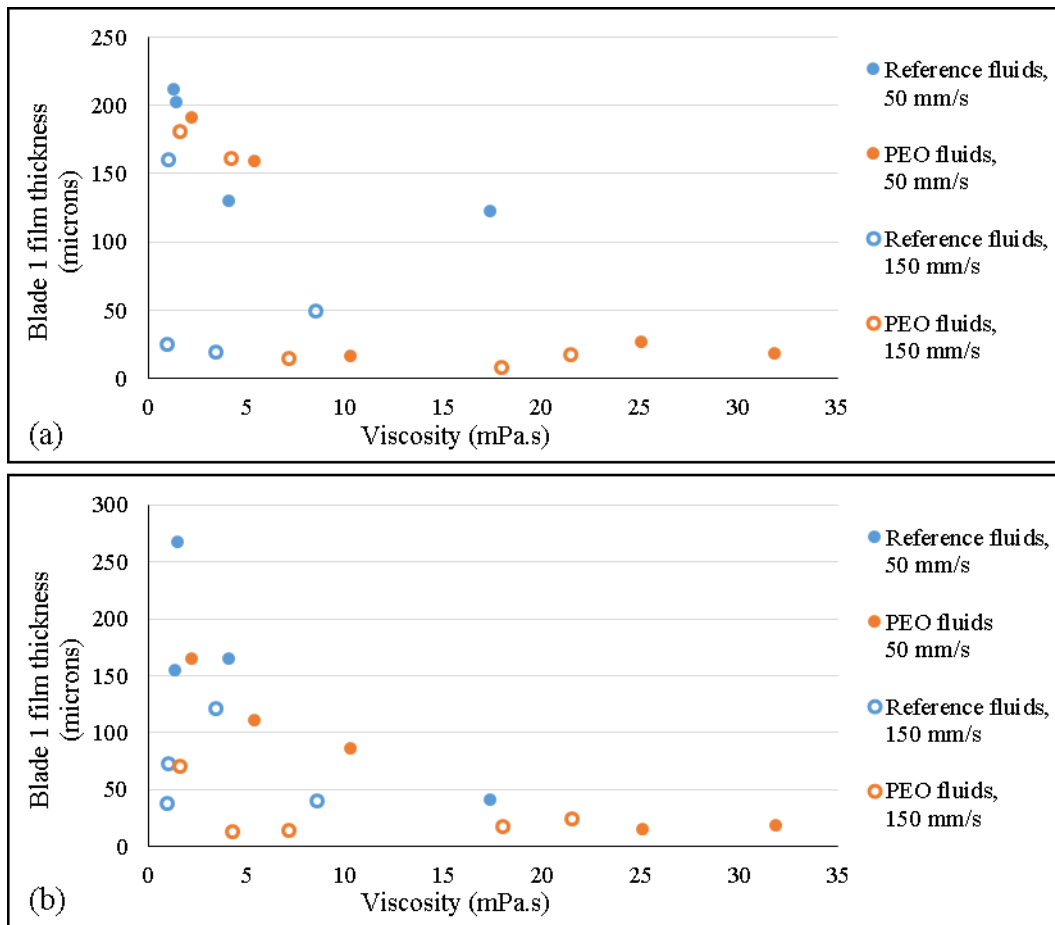


Figure 9.13: Relationship between Blade 1 film thickness and fluid viscosity (a) glass counterface (b) silicone elastomer counterface

9.4. Evidence of fluid reflow in the razor cartridge

In Chapters 7 and 8 the focus was on film thickness in the surface contact elements (guard, blades etc.). However when considering lubricant reflow it is useful to consider evidence from the out-of-contact troughs between the blades, in particular the guard/blade 1 zone. The role of the guard is to stretch the skin in preparation for shaving and to maintain a sufficient level of prep fluid to provide optimum friction in the blade region. Guard film thickness is highly variable for both hard and compliant counterfaces. It is made from a hyper elastic elastomer and consists of several highly elastic fins. These fins stretch and bend during a razor cartridge stroke, and as such do not maintain a constant geometry. This will affect entrainment into the contact and make it very difficult for a starvation/reflow equilibrium to be established. In most cases for the low viscosity fluids film thickness increases after the guard, suggesting capillary driven-replenishment, and is particularly marked for water-glass tests

The images from behind the guard were very different for the different fluids. Figure 9.14 compares lubricant flow from the combe (behind the guard) to the blade 1 cutting edge. Both PEO solutions pass through the channels in the combe and reach the first blade edge. Behind the combe the PEO fluid films appear to relax to form a more uniform film within the trough; this is more marked for 1×10^6 g/mol M_w fluid. The same does not occur for the reference fluids, which are held in the combe interface and the gap between the combe and blade 1 is not filled with lubricant. The behaviour of glycerol is interesting as the film appears to contract, pulling it away from the blade and back towards the combe. This again could be due to surface wetting effects and contributes to the anomalously low film thicknesses (150 mm/s blades 1 and 5 film = $< 50 \mu\text{m}$) measured for glycerol in the glass contact (Figure 9.15). Glycerol typically does not wet glass, and difficulties with wetting compared to other fluids have been noted in other work [28]. However in the cartridge/silicone elastomer system much thicker films are formed (150 mm/s blades 1 and 5 film = $150\text{-}200 \mu\text{m}$). The film thickness profiles for glycerol solution with both counterfaces are shown in Figure 9.15.

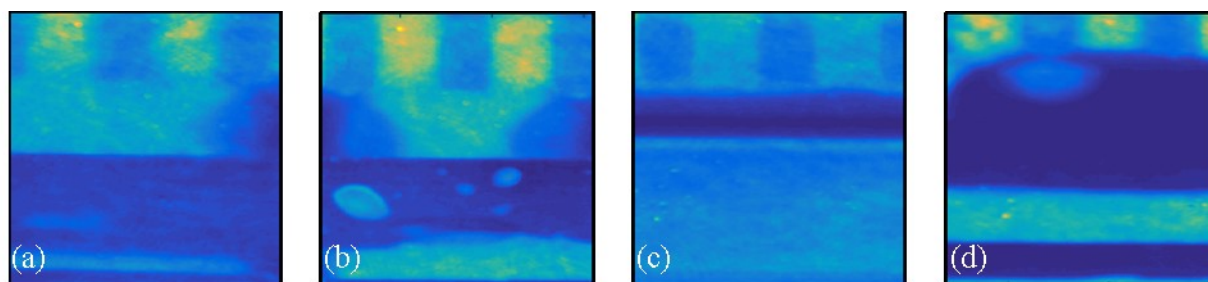


Figure 9.14: LIF images for lubricant flow at blade 1 for a glass contact lubricated by: (a) $1 \times 10^6 M_w$ PEO solution, sliding speed 150 mm/s; (b) $5 \times 10^6 M_w$ PEO solution, sliding speed 50 mm/s; (c) distilled water, sliding speed 150 mm/s; (d) glycerol solution, sliding speed 50 mm/s

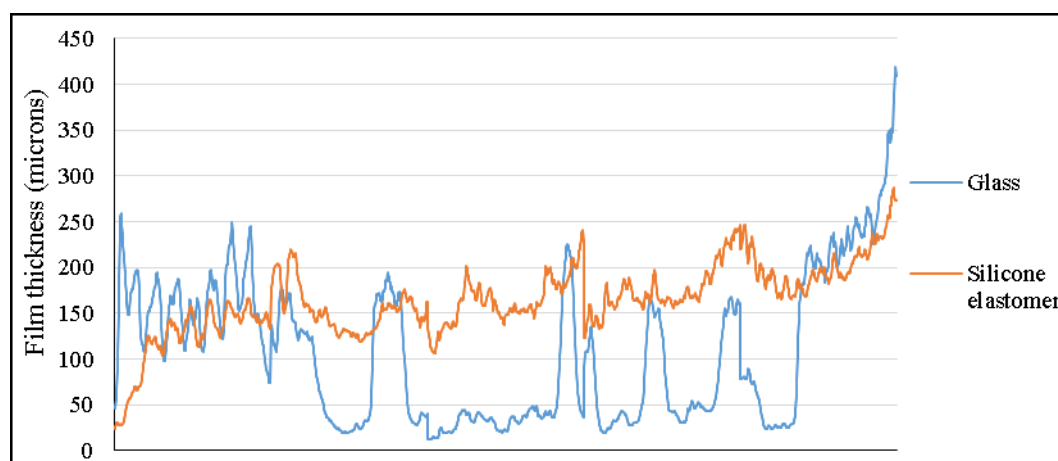


Figure 9.15: Razor cartridge film profiles for glycerol solutions at 150 mm/s for glass and silicone elastomer counterface

Film profiles at 150 mm/s for PEO fluids are compared in Figure 9.16 (9.16a: glass, 9.16b: silicone elastomer). Again, very clear differences are seen between the glass and silicone elastomer profiles. For the low molecular weight (low viscosity) PEO solutions the film thickness remains high throughout the cartridge. For 1×10^6 g/mol M_w and above, the film in the blade region collapses to less than 50 μm , although some recovery is seen in the blade troughs towards the rear of the cartridge – it appears the low molecular weight fluids are able to reflow around the blades. For the silicone elastomer counterface, the low molecular weight fluids have much lower film thicknesses and it is the 1×10^6 g/mol M_w PEO fluid that gives the thickest films.

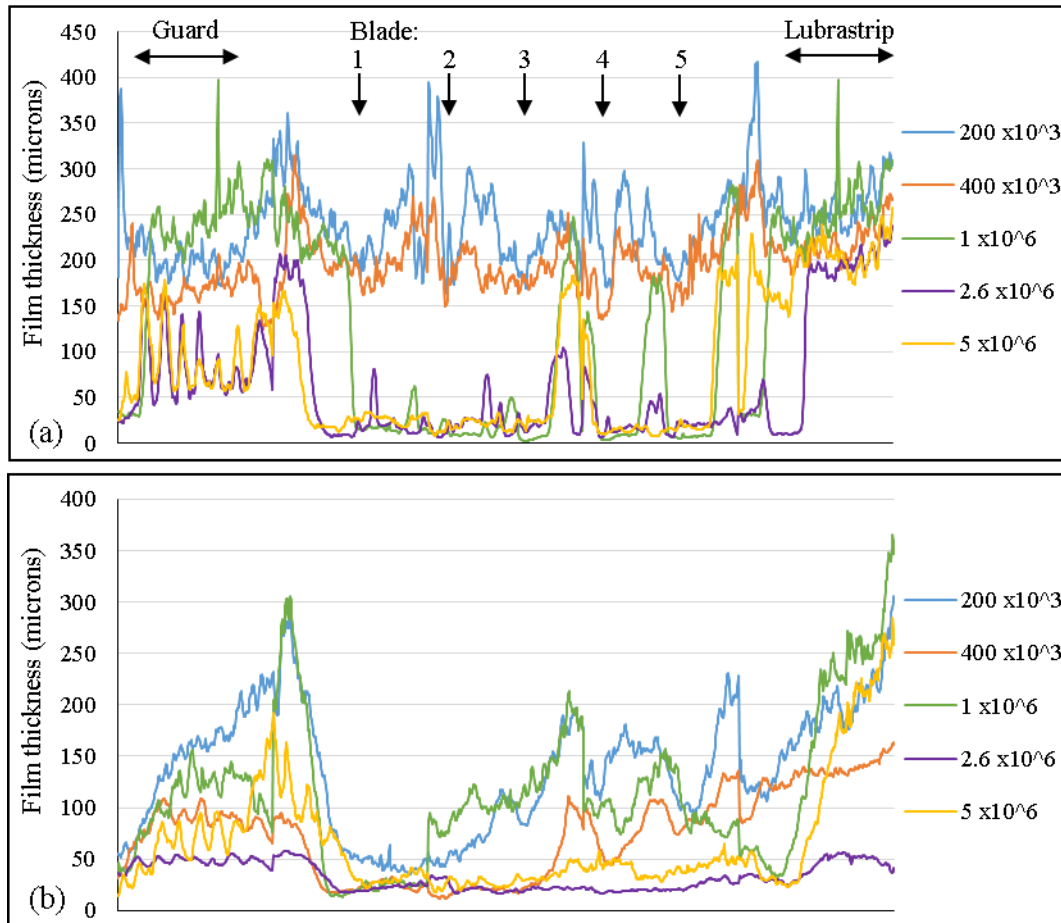


Figure 9.16: Razor cartridge film profiles for PEO fluids at 150 mm/s (a) glass counterface (b) silicone elastomer counterface

Speculation from the film thickness profile results has led to the theory that remaining lubricant, which does not pass under the blade cutting edge or around the cartridge, travels up the back of the blade, away from the counterface (Figure 9.17) and accumulates in the troughs. Lubricant distribution on the top of the blades (as shown in Figure 9.17) is unknown as this area was not visible in the LIF experiments.

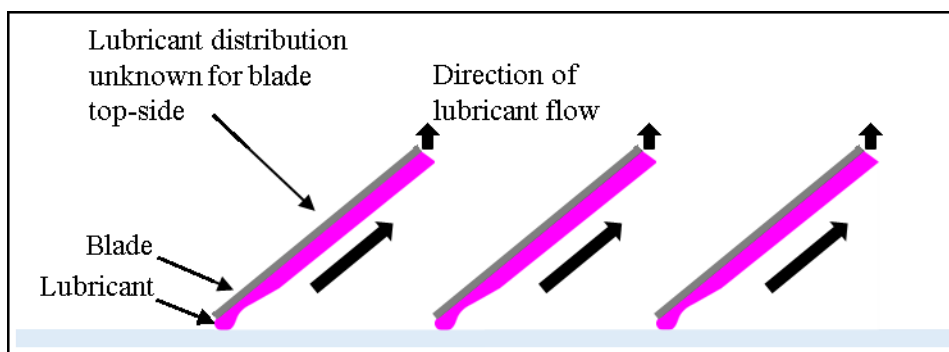


Figure 9.17: Suggested lubricant flow along the back of the blades

PEO fluids are used as the on-board shaving prep preloaded into the Lubrastrip because their viscoelastic properties are thought to provide more reliable lubrication in the cartridge-skin contact.

Figure 9.18 compares 1×10^6 g/mol M_w PEO solution with high viscosity reference fluids.

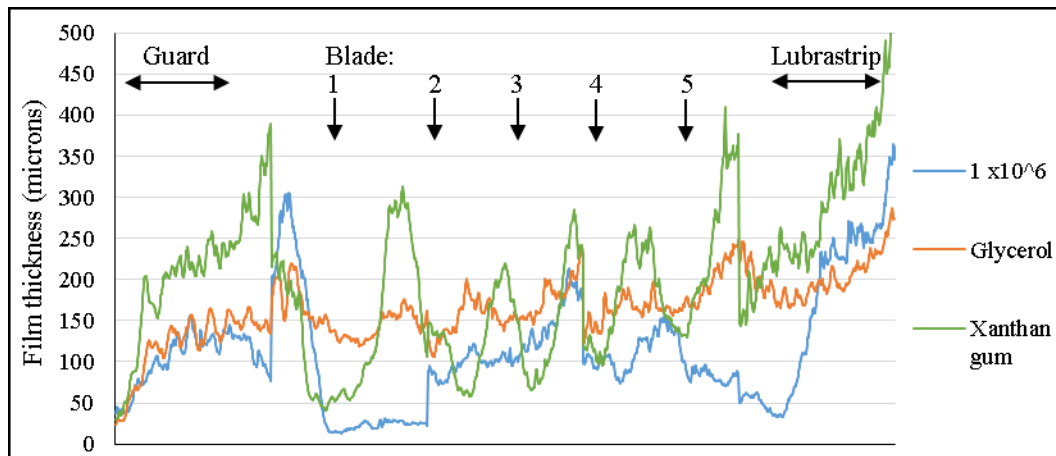


Figure 9.18: Comparison of glycerol, xanthan gum and 1×10^6 g/mol M_w PEO solutions profiles at 150 mm/s for a silicone elastomer counterface

The effect of viscoelasticity on starvation is less easy to quantify than only viscosity as reduced reflow (due to elastic effects) might contribute to reduced replenishment, but this may be balanced by the ability to resist short term pressure flow. Flow resistance increases with elasticity [35-37], and elasticity increases with molecular weight for viscoelastic fluids. Additionally, viscoelastic effects might become less visible due to the reduced quantity of fluid. Elastic forces enable the PEO solutions to resist flow and spreading, as well as stretching due to polymer extension [38], which creates the channels of lubricant that resist spreading across the width of the blade, but stretch across the length of the razor cartridge (Figure 9.19).

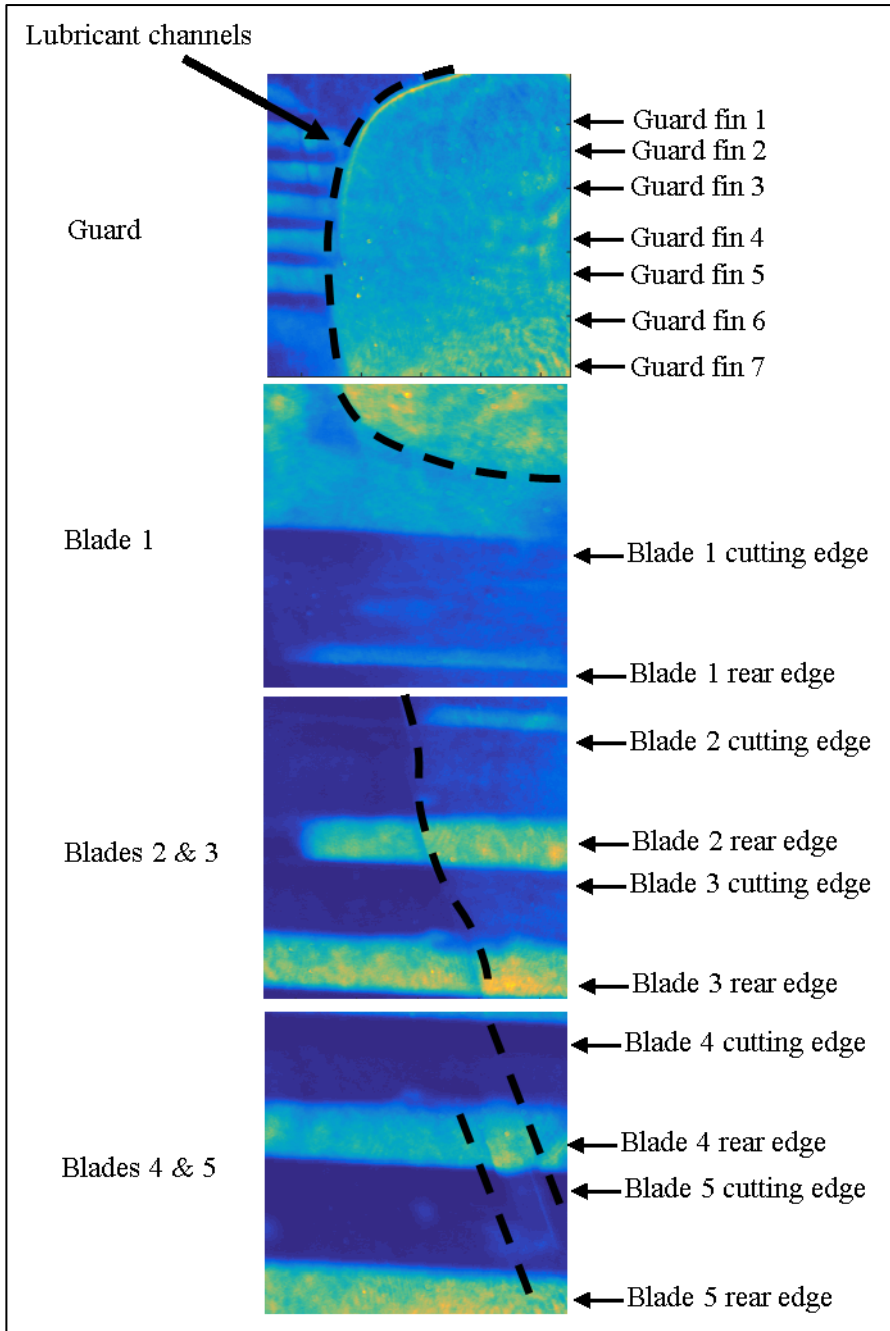


Figure 9.19: $1 \times 10^6 M_w$ PEO lubricant channels through razor cartridge/glass contact at sliding speed 50 mm/s

PEO relaxation time is the characteristic time required by the polymer coils to relax from a deformed state to their equilibrium configuration, and is a key parameter for characterising viscoelastic fluids [39]. At a sliding speed of 150 mm/s, the time elapsed between each razor cartridge component passing over a single point is shown in Figure 9.20.

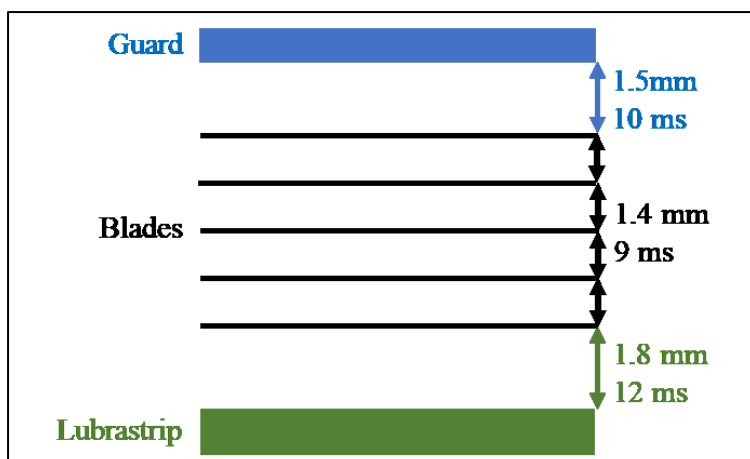


Figure 9.20: Time elapsed between razor cartridge components at sliding speed 150 mm/s

From these numbers, it would be expected that a suitable lubricant for the razor cartridge contact must have a relaxation time of 9 ms or less – this would allow the lubricant to relax to its undeformed state before the next contact interface. Relaxation times for 1×10^6 g/mol M_w PEO and 5×10^6 g/mol M_w PEO solution are 7 ms and 500 ms respectively (P&G), however the results showed that 5×10^6 g/mol M_w PEO solution can still form a relatively thick lubricating film (minimum film thickness = 7.2 μm) at a sliding speed of 150 mm/s (Figure 9.21).

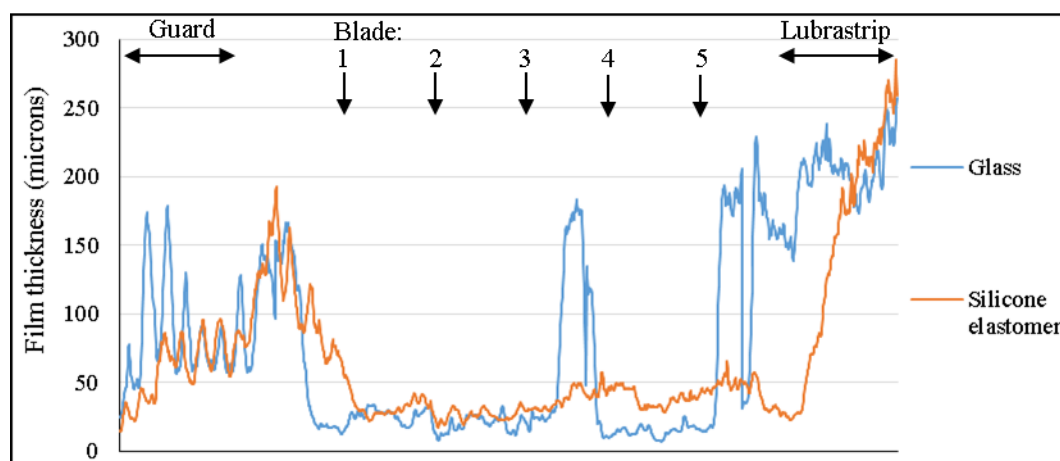


Figure 9.21: Razor cartridge contact lubricated by 5×10^6 M_w PEO solution at sliding speed 150 mm/s

The ability of PEO fluids to stretch across multiple contacts seems to reduce the importance of relaxation times on film formation. When viscoelastic fluids are stretched, they initially rapidly develop defects within their structure [40], but as the strain increases these defects level off and a “partial healing” occurs [40, 41]. It has been observed [42] that stretching a viscoelastic fluid causes thickening

in the transverse direction due to tensile stresses, which causes axial contraction. This explains why high molecular weight solutions are able to maintain a significant film thickness. Friction in a stretched viscoelastic fluid also decreases with increasing fluid elasticity [42, 43]; the MTM results showed that 2.6×10^6 M_w PEO and 5×10^6 M_w PEO solution friction increased with sliding speed, and this was attributed to an increase of shear forces as the film thickness increased with sliding speed. Stretching the PEO solutions across the cartridge contact may in fact lower the coefficient of friction for these fluids at higher speeds.

Relaxation time increases with molecular weight [44], and Figure 9.22 shows the relationship between relaxation time and average film thickness at blades 1 and 5. Viscoelastic replenishment occurs for 2.6×10^6 g/mol M_w and 5×10^6 g/mol M_w PEO solutions with high relaxation times: film thickness is low but stable across the blades and speed range. PEO fluids of 1×10^6 g/mol M_w and below show replenishment that is increasingly viscosity driven as molecular weight (and relaxation time) decreases. Film thickness across the blades is lower for 150 mm/s sliding speed than at 50 mm/s, and significantly higher at the back of the cartridge.

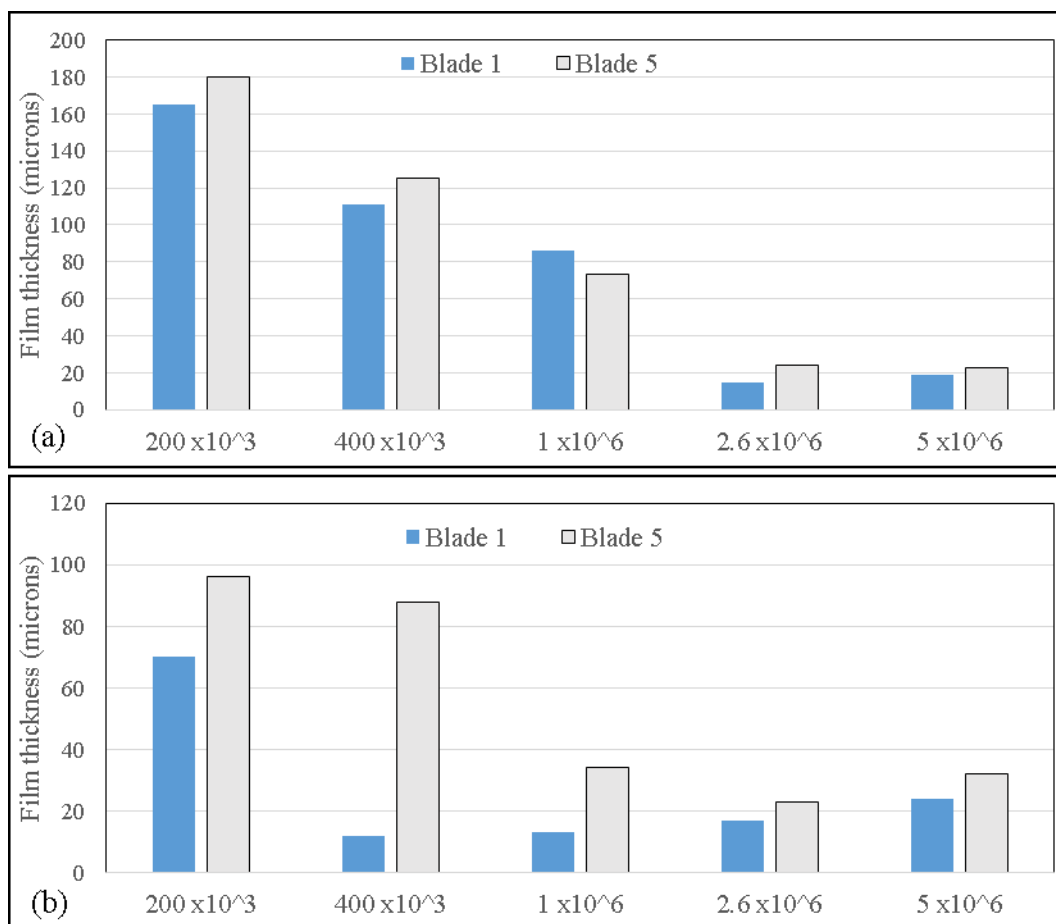


Figure 9.22: PEO solution average film thickness for razor cartridge/silicone elastomer contact at sliding speed (a) 50 mm/s (b) 150 mm/s

9.5. Comparison of MTM and LIF measurements

The MTM is currently used as a screening test for candidate shaving prep fluids where a speed sweep (10-500 mm/s) and a constant speed profile (150 mm/s) are used to measure friction coefficient at 200% SRR for a steel ball against a PDMS disc. In this project a range of test profiles were used to characterise the reference and PEO fluids, and the most consistent results were obtained with a SRR (100%) profile over a sliding speed range of 10-200 mm/s. Friction coefficient results are plotted for all fluids in Figure 9.23 in a Stribeck format (sliding speed x viscosity). Generally all fluids fall on a common Stribeck curve apart from glycerol, which gives much lower friction than expected at low speeds. The 1×10^6 g/mol M_w PEO fluid clearly forms the lowest friction film over the greatest range of conditions.

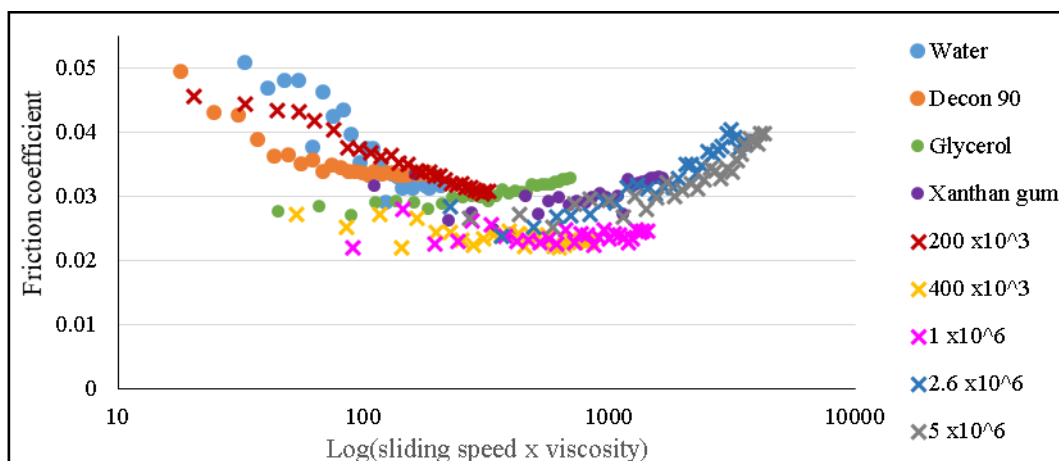


Figure 9.23: Coefficient of friction for all fluids (reference and PEO) plotted against log (sliding speed x viscosity)

The LIF film profiles indicate that film thickness in the razor cartridge is much greater than achieved in the MTM friction tests. For example MTM calculated film thickness for 1×10^6 g/mol M_w PEO was $1.8 \mu\text{m}$ and for 5×10^6 g/mol M_w PEO it was $3.5 \mu\text{m}$ at 150 mm/s , both of which were less than the LIF measured values of $20\text{--}30 \mu\text{m}$. Another consideration is increased drag in the high film thickness troughs between razor blades, which was seen to some extent for all test fluids. However the Stribeck curve does indicate that the 1×10^6 g/mol M_w PEO solution gives the lowest friction values over the speed range, and this agrees with reported user evaluation (P&G) of shaving comfort with the different molecular weight PEO fluids.

9.6. Skin mimic

Throughout this project, problems with surface wetting have occurred in the MTM and LIF results, particularly for some of the higher viscosity fluids. As discussed earlier in this Chapter, surface wetting is very important in controlled film formation and replenishment and in this respect simple silicone skin mimics are not suitable.

To realistically replicate the razor cartridge/skin contact the mimic should be dual layered, with an elastic, thick lower layer (dermis mimic) and a protective, thin upper layer (epidermis mimic) that swells when hydrated. The surface roughness would also match that of skin furrows. The furrows play an

important mechanical [45] role in the structure of skin, which may have implications for cartridge lubrication:

- By (partially) smoothing out, they allow the skin surface to extend [25].
 - Increased skin compliance may increase contact deformation and therefore capillary flow.
- The furrows also act as channels for sebum and sweat [25].
 - The furrows may act as lubricant channels, increasing contact replenishment.

Skin surface acidity is in the range pH 4.2-6.1 [46], and sebum is secreted onto the surface where it seeps into the main skin furrows [47]. Sebum is beneficial to cartridge lubrication because of its amphiphilic wettability [25] – further developing the chemical surface properties of the skin mimic may reduce wetting problems.

Developing a realistic skin mimic for use in both MTM and LIF experiments would improve comparability between the results. It would also be especially interesting to record the effects of skin furrows on cartridge lubrication.

9.7. Optimum conditions for shaving

Razor cartridge lubrication can be likened to bearings and grease bulk churning in terms of replenishment and starvation. Lubricant close to the track feeds local replenishment, which is largely driven by capillary flow. This is further facilitated by deformation of the compliant counterface (skin/silicone elastomer), which decreases the inlet size. Starvation occurs through displacement and cross-flow, and increases in viscosity and speed reduce film thickness. Viscoelastic reflow allows lubricant films to form across the cartridge contact, without high trough film thickness.

From the results of this project we can begin to specify what is required of a shave prep for optimum shaving lubrication. User evaluation has identified 1×10^6 g/mol M_w as the preferred PEO fluid. Therefore, recognising key behaviours for this lubricant will form a basis of recommendations for identifying an optimum shave prep.

In MTM tests (Figure 9.22) 1×10^6 g/mol M_w PEO solution produced the lowest friction values across the speed range, and remained relatively unchanged with speed. This indicates that the lubricant should produce a fairly low (~ 0.02) and stable friction coefficient across the speed range.

Film thickness profiles for the razor cartridge/silicone elastomer contact lubricated by 1×10^6 g/mol M_w PEO solution (Figure 9.24) showed that there should not be too much fluid in the contact, either under the blade edges or in the blade troughs, minimising trough rebound. Minimum film thickness ($13.33 \mu\text{m}$) occurred under Blade 1 at sliding speed 150 mm/s . The maximum trough film thickness at the same speed was $199.33 \mu\text{m}$. Although 5×10^6 g/mol M_w PEO solution has low and more consistent film thickness profile through the cartridge contact, the MTM tests showed that friction is variable with speed. It is therefore important to consider both aspects when choosing a lubricant.

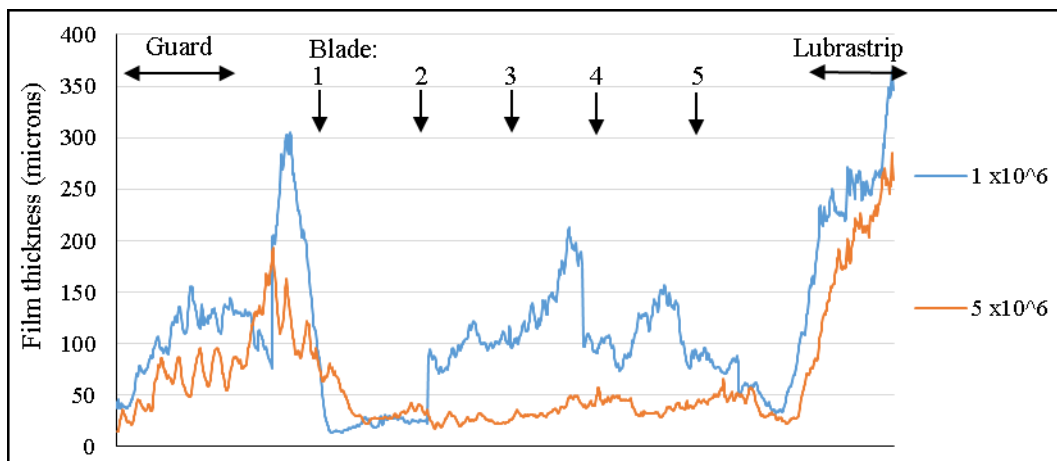


Figure 9.24: Razor cartridge/silicone elastomer disc lubricated by PEO solutions at sliding speed 150 mm/s

9.8. Conclusion

Fluid film distribution in the razor cartridge/skin contacts is complex and film thickness varies depending on contact conditions (counterface and sliding speed), fluid properties and cartridge component. In summary:

- Film thickness through the blades generally decreases for high viscosity fluids and at high speeds suggesting starvation of fluid flow.
- Razor cartridge lubrication is a balance between lubricant flow into the contact (capillary flow and squeeze effects) and starvation by displacement and cross-flow. Starvation is directly

related to film thickness, and the extent to which this occurs depends on lubricant viscosity, quantity and distribution, as well as time between subsequent contacts.

- Differences in lubricant behaviour were seen for compliant and hard counterface materials. A compliant counterface has greater contact deformation than a hard countersurface, and this encourages capillary flow into the contact, increasing lubricant supply to the contact and film thickness.
- For PEO solutions, increased molecular weight and increased viscoelasticity reduces in-contact film thickness. However, despite significant relaxation times in higher molecular weight solutions (as much as over 50 times larger than the minimum time between razor cartridge components), elastic forces allow PEO solutions to maintain a consistent lubricant film across the razor cartridge contact.
- PEO solutions were shown to be a superior lubricant for a razor cartridge contact compared to the reference fluids. Lubricant film thickness across the contact was less erratic and a relationship between film thickness and molecular weight was established. Visual evidence for viscoelastic effects in PEO solution lubrication was shown in the LIF images, and the viscous and elastic effects were separated. This was also achieved for the film thickness results.

9.9. References

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10. CONCLUSIONS AND FUTURE WORK

Summary

A review of the research project is carried out in this Chapter. The major findings are summarised and recommendations made for improvements to the experimental methods and future work.

10.1. Review of research project

The purpose of this project was to gain an understanding of shaving tribology within the razor cartridge/skin interface. The razor cartridge/skin contact is complex due to the variability in cartridge materials and geometry, as well as the mechanical properties of skin. It is important to understand the razor cartridge lubrication mechanisms as user comfort is strongly linked to friction (P&G). It was thought that the ideal shaving lubricant is able to: flow through the guard without being wiped away by the guard and resist starvation under multiple, successive razor cartridge components. By developing model experiments to simulate lubrication during shaving, the results have provided some guidance on choosing a suitable shaving prep.

The objectives were to understand the two aspects of shaving tribology: friction and film thickness:

1. MTM: Friction properties of shaving fluids in a model skin-cartridge contact.
2. LIF: Visualisation of lubricant flow and measurement of film thickness at the contact interface.

Considering the friction, lubricant flow and film thickness results, the suitability and effectiveness of PEO as a shaving lubricant has been assessed.

10.2. Summary of main findings

MTM friction tests for a stainless steel ball/PDMS contact were carried out for all test fluids under three conditions: excess fluid (pure sliding), restricted fluid (pure sliding) and excess fluid (sliding/rolling). Tests were also run with changes to surface chemistry (artificial sebum) and for the Lubrastrip. Comparison between original P&G profiles and modified profiles illustrated the effect of load on

friction for two PEO solutions – it is therefore important to match “real life” shaving conditions as closely as possible.

Pure sliding test profiles produced results with poor repeatability and surface wetting problems. A sliding/rolling contact improved this, and trends between lubricants could be identified. Using a scraper reduced starvation in pure sliding conditions for high viscosity fluids, although if the time elapsed between the scraper and contact was less than the fluid relaxation time, this caused starvation.

All test fluids were found to form full films. For fluids with lower viscosities, friction coefficient decreased with increasing sliding speed due to increased entrainment into the contact creating a thicker lubricant film. For higher viscosity lubricants, friction increased with increasing sliding speed which was attributed to shearing of this progressively thick lubricant film.

1×10^6 g/mol M_w PEO solution, which is the PEO currently used on the Lubrastrip, does not produce a significant change in friction across the speed range, despite the calculated film thickness increase from 0.44-2.15 μm . This may be a reason as to why it is the preferred lubricant by users.

Surface chemistry (sebum) was found to have a significant effect on the lubrication properties of some fluids, and should therefore be considered when selecting a lubricant. Decon 90 solution was very effective at removing sebum from the track, and the results proved why soap solutions are used as shaving preps. Lubrastrip lubrication was found to be dependent on hydration, and friction decreased with increasing speed.

Following on from the MTM, proof of concept ball-on-disc LIF experiments were carried out. This was successful, and it was possible to visualise fluid flow and measure film thickness in compliant contacts. The lower measurable limit was found to be $2 \pm 0.36 \mu\text{m}$ for a glass counterface, and $2 \pm_{-2}^{+3.1} \mu\text{m}$ for the silicone elastomer, with a measured calibration film thickness range of 2-135 μm . A polynomial equation derived from the measured calibration film thickness was used to calculate experimental film thickness, and the measurable upper limit is reliant on the maximum fluorescence intensity from the dye. It was observed that thicker lubricant films are formed in compliant/compliant contacts than

compliant/hard contacts, and film thickness increases with speed. PEO solutions formed thicker films than reference fluids, and their film thickness increased with molecular weight.

Further developing the LIF method, a razor cartridge contact was incorporated into the rig. Excellent image clarity was shown and film thickness was measurable for a hard and a compliant counterface. It was found that the guard and Lubrastrip maintain relatively thick and consistent lubricant films across the speed range, with minimum films formed at the blade cutting edges. The presence of the guard improved razor cartridge lubrication by stabilising film thickness across the blade cutting edges.

Film thickness typically decreased with increasing sliding speed. At blade 1 this decrease was from 41-268 μm to 19-160 μm for reference fluids. PEO solution film thickness at blade 1 decreased from 15-191 μm to 8-180 μm . Fluid viscosity had a significant effect on lubrication through the razor cartridge, with much lower films measured at high speeds for the high viscosity solutions.

Higher molecular weight PEO solutions produced visible channels of lubricant, which stretch across the cartridge contact. This was not seen for reference fluids.

Upon completion of the MTM and LIF experiments, results were compared to begin to establish the razor cartridge lubrication mechanisms and characteristics for a preferred shave prep. Film thickness through the blades generally decreases with increasing viscosity and speed, which suggests starvation of fluid flow. Razor cartridge lubrication is a balance between lubricant flow into the contact (from capillary flow and squeeze effects) and starvation (by displacement and cross-flow). Differences in lubricant behaviour were seen for compliant and hard counterface materials; a compliant counterface has greater contact deformation than a hard countersurface, and this encourages capillary flow into the contact, increasing lubricant supply and film thickness in the contact.

For PEO solutions, increased molecular weight and increased viscoelasticity reduces in-contact film thickness. Although elastic forces allow PEO solutions to resist starvation and maintain a consistent lubricant film across the razor cartridge contact. Visual evidence for viscoelastic effects in PEO solution lubrication was shown in the LIF images, and the viscous and elastic effects were separated. This was

also achieved for the film thickness results. PEO solutions were shown to be a superior lubricant for a razor cartridge contact compared to the reference fluids.

10.3. Suggestions for future work

This project has highlighted many areas with scope for further investigation. Improvements can be made to the current experimental procedures, which will improve methodological application to other case studies, as well as to the simulation of shaving. For example, a full understanding of viscoelastic contact or fluid lubrication allows the simulation other compliant surface lubrication systems e.g. windscreen wipers [1], elastomer o-ring seals [2, 3], tyres on a wet road [4] or friction within biological systems [5], which usually occurs between compliant and hydrated tissues that are mediated by viscoelastic polymer fluids (e.g. mucus and synovial fluid). The following sections list further improvements that can be made to the experimental methods.

10.3.1. General improvements

1. Skin mimic: surface wetting

Problems with surface wetting occurred throughout this project. Development of a more realistic skin mimic to overcome this is recommended. The ideal mimic should be dual layered, with an elastic, thick lower layer (dermis mimic) and a protective, thin upper layer (epidermis mimic) that swells when hydrated. This may be hydrocarbon or collagen based rather than silicone, which is hydrophobic and does not absorb water. The surface roughness (i.e. furrows) and surface chemistry (i.e. acidity and sebum) would also match that of skin. It would be especially interesting to record the effects of skin furrows on cartridge lubrication, as these already act as sebum and sweat channels [6].

2. Skin mimic: hair

A second improvement to the skin mimic is to implant hairs, and measure the effect on friction and film thickness. This would be done during the curing of the mimic so that they are fully embedded in the material. Initially the hairs could be made of a synthetic material that is consistent and easy

to work with, such as nylon. Although preferably a representative hair mimic with mechanical and chemical properties comparable to human hair would be used.

3. Effect of load

The test profiles developed in this study focussed mainly on the effects of speed, lubricant quantity and slide-to-roll ratio. During shaving there are also fluctuations in load, both between individuals and as the user shaves over different areas of the face. The effect of load on friction in compliant contacts has been previously reported [7], as well as being observed in comparisons between the original P&G MTM test profiles and the modified profiles. Development of tests in the MTM and LIF to capture lubricant response to changes in load would add further criteria to the “ideal” lubricant requirements.

4. Incorporating more complex fluids

This project has only looked at the effects of a single lubricant in the razor cartridge at any one time. Shaving preps typically consist of active ingredients (to improve general skin health), moisturisers, foaming agents (it is reported that users prefer a shave prep that foams (P&G), lubricants and preservatives [8, 9]. The effect of a complete shaving prep on cartridge lubrication is unknown.

5. Friction model

The results from this project can be used to validate and improve existing models for razor cartridge lubrication. Previous work [10, 11] has looked at windscreen wipers and the relationship between wiper friction and squeal noise. Dimensionless equations were derived to describe the effect of different contact conditions on the total friction force in the windscreen wiper/glass contact. Similarly, a simple equation – e.g. Equation 10.1 – can be developed to act as a guide to friction response with changing conditions such as different speeds, loads, lubricant chemistries and Lubrastrip ageing etc..

$$Friction\ force = Friction_{guard} + Friction_{blades} + Friction_{Lubrastrip} \quad (10.1)$$

10.3.2. MTM

1. Contact geometry

The MTM pin-on-disc arrangement does not represent the line contact seen in shaving, or the complexity of the cartridge contact. Replacing the ball with cartridge parts (either individually or as a complete set) would produce friction results closer to what is experienced in the “real-life” razor blade/skin contact. The raised blade height due to the clips would need to be taken into account.

2. Scraper

From the LIF measurements, incorporating a scraper to restrict inlet film thickness to 100 μm is an appropriate value. However the effect of this was partially related to the fluid’s relaxation time. Adjustments to the experimental layout to change the scraper position so that it reflects that of the guard to blade 1 time/distance would give more realistic results on the effect of the inlet film height reduction on friction at blade 1.

10.3.3. LIF

1. Contact deformation

Due to the nature of the razor cartridge contact, deformation is difficult to measure experimentally. But there is capability within the LIF method to achieve this. By marking a surface layer of the silicone elastomer with fluorescent dye (and using an unmarked lubricant), deformation of the contact would be measured instead of lubricant quantity.

2. Particle tracking

Fluorescent probes can be tagged to specific nano-particles, which are dispersed within a lubricant [12, 13]. This would make it possible to measure the flow rate through the cartridge (as it is not currently possible to quantify this), which would provide further information as to the effect of fluid chemistry on reflow and starvation.

10.4. LIF development

The current LIF rig is a modified EHL rig, and errors in loading and laser fluctuations can be designed out by redeveloping this method. Replacing the laser with light emitting diode (LED) is a simple way to improve the LIF method as it reduces health and safety risks as well as providing a compact and efficient light source [14]. LEDs have been widely used as light sources due to their high energy efficiency for producing monochromatic light and the ability to change their spectral region [15, 16], which increases their sensitivity and applicability for a fluorescence system [17]. The traditional light sources used in LIF spectroscopy are typically expensive and complicated [18, 19], and as such are often replaced by various LEDs or LED arrays [18]. LED induced fluorescence is already used for a wide range of applications such as microscopy [20], teeth inspection [21] and environmental monitoring [22].

The LIF rig in this project uses a solid-state, diode-pumped pulsed laser with an excitation wavelength of 532 nm. This light source could be replaced with a Dino-Lite Premier digital microscope (Dino-Lite, Netherlands), which uses high intensity green LEDs with an excitation wavelength of 570 nm designed for observation of orange and red fluorescence. The Dino-Lite microscope provides superior image quality, is equipped with a 1.3 megapixel sensor and object magnification of up to 200x. Figure 10.1 shows an image of a razor cartridge/glass contact captured using a Dino-Lite microscope for LED induced fluorescence. Not only is image clarity excellent, but the field of view is large enough to capture the entire cartridge interface.

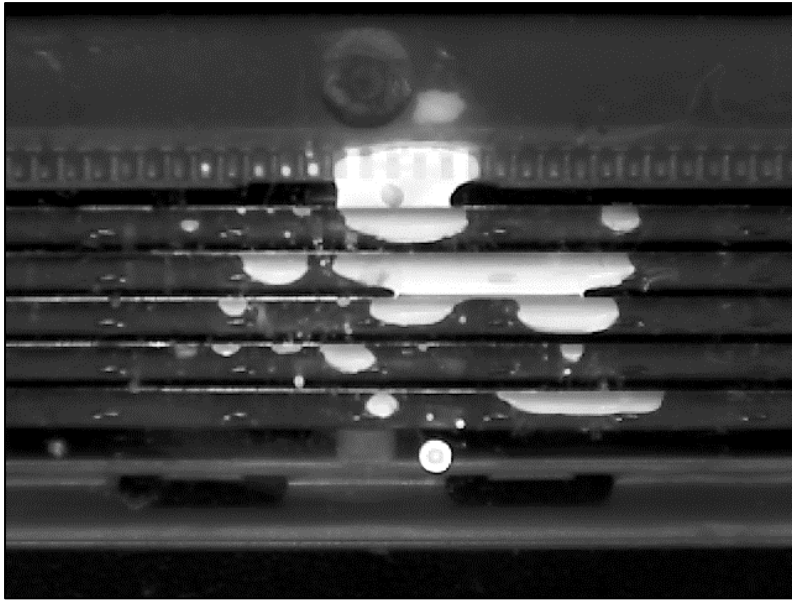


Figure 10.1: Dino-Lite image of induced fluorescence image of a razor cartridge/glass contact lubricated with glycerol solution

A second consideration is the movement of the cartridge. The cartridge is currently loaded against a disc, which rotates to create entrainment into the contact. However shaving occurs in a linear motion. Similarly, in “real life” the cartridge is not in constant contact with the skin; the user lifts the cartridge off the skin at the end of each stroke and reapplies. The ability to mimic these motions in a test rig would give more realistic results on lubricant replenishment and starvation.

Finally, incorporating tools to measure normal load and drag during fluorescence experiments would relate film thickness directly to friction, and could be used to confirm the friction response of potential lubricants after initial MTM screening.

10.5. Improved modelling of the razor cartridge/skin interface

In this project, it has been useful to compare theoretical film thickness for a ball-on-disc contact with experimental results for validation and improved understanding. It has not been possible to predict film thickness for the razor cartridge contact. As well as the lubricant replenishment and starvation mechanism discussed in this project, the razor cartridge/skin contact is complex to model due to its materials and geometry:

- The cartridge consists of multiple contacts, which will produce different contact pressures for the same load due to location on the cartridge and compliant/hard material properties.
- The guard fins are hyper elastic and very flexible, so the contact area and spacing between fins is not constant.
- The blades are lifted away from the counterface by the clips, and the cutting edge is angled towards the front of the cartridge.
- The blades are coated to protect them from damage and corrosion, which may affect lubricant replenishment.
- Lubrastrip composition and geometry changes during shaving due to the loss of lubricant.
- Skin will deform around the guard/blades/clips, and this will change depending on the cartridge component material (compliant/hard) and geometry, as well as the spacing between each component.

Previous studies have explored the methods required to begin to model this contact, such as bearing starvation and reflow, compliant contact deformation and line contact pressure and film thickness. A detailed model that could predict razor cartridge contact pressure and film thickness for the cartridge as a whole and for selected components could be used to validate the work in this research project, as well as further experimental development into the tribology of shaving.

10.6. References

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