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Soft tribology of oil-continuous emulsions

M. Douaire *, T. Stephenson, I.T. Norton

Department of Chemical Engineering, the University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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ABSTRACT

Lubrication behaviour of foodstuff is related to mouthfeel perception and consumer appreciation. Soft tribology of food related products has mainly been investigated with semi-solid food, polymer solutions and water continuous emulsions, and this is the first study aimed at investigating soft tribolocigal behaviour of oil continuous emulsions. All the emulsions considered here exhibit the same trends in terms of lubrication behaviour, where little boundary lubrication is observed at the entrainment speed considered. The volume of dispersed aqueous phase affects overall tribology of oil continuous emulsions via an increase in their dynamic viscosity. Increasing the phase volume leads to an increase in friction in the elastohydrodynamic regime whereas the lubrication in the boundary regime is improved. Elastohydrodynamic lubrication is independent of the aqueous phase composition and the type of emulsifier present at the water–oil interface. These parameters affect boundary lubrication of emulsion systems exhibiting droplet size bigger than the elastohydrodynamic oil film thickness. This is expected to have a significant impact on the design of low fat emulsions that match the lubrication properties of their full fat version.

1. Introduction

Tribological behaviour of many food and personal care products plays an important part in their sensory perception. It dictates how a cosmetic cream feels upon skin application, and relates to the mouthfeel of food products. Consequently, there is currently much ongoing research which attempts to use the field of tribology to accurately predict the mouthfeel properties of a semi-solid through the material's behaviour as a lubricant (Dresselhuis et al., 2007; Malone et al., 2003; van Aken et al., 2007). De Wijk and Prinz showed that oral perception of semi-solid foods is related to their lubrication behaviour (de Wijk and Prinz, 2005). This is of crucial importance for low fat food, since creaminess and thickness, attributes that are usually provided by the fat content, are perceived through friction.

Emulsions are ubiquitous in foods and cosmetic products and have proven useful in the areas of fat reduction and time/pressure dependent release of flavour compounds, nutrients or vitamins. Their frictional behaviour is not only related to the percentage of fat but also the viscosity of the emulsion (Bongaerts et al., 2007; van Aken et al., 2007). However, emulsions are mostly shear thinning, rending the prediction of their lubrication behaviour difficult.

In the area of tribological behaviour of food related products, several studies have been published, aimed at understanding lubrication of polymer solutions (Cassin et al., 2001; de Vicente et al., 2005, 2006a; Mills et al., 2013), fluid gels and gelled particles (Chojnicka et al., 2008; Fernández Farrés et al., 2013; Gabriele et al., 2010; Garrec and Norton, 2012) and oil in water emulsions (de Vicente et al., 2006b). Lubrication behaviour of mayonnaise, a fairly ubiquitous water continuous food emulsion, was examined by Giasson and co-workers (Giasson et al., 1997). Their results show that friction depends mainly on the properties of the dispersed particles, such as size, stiffness and hydrophobicity. de Vicente et al., 2006b showed that soft lubrication behaviour of water continuous systems also depends on the viscosity ratio between the two immiscible phases, with the dispersed phases determining the friction properties when its viscosity is high enough.

The tribology of water-in-oil emulsions has thus far only been studied in the context of aqueous impurities in an oil lubricant (Benner et al., 2006; Liu et al., 1994). Under heavy contact loads (hundreds of Newtons), and for conventional tribology it has been shown that water in oil emulsions behave as pure oil (Benner et al., 2006) for emulsions containing up to 30% water. The hydrodynamic film thickness is similar to pure oil systems for most emulsions, with the exception of emulsions containing dispersed water droplets which are smaller or of the same scale as the pure oil film itself, in which case the film gets thicker (Wan et al., 1984). Other studies suggest that bigger droplets form patches in the contact zone, decreasing the effective viscosity of the emulsion system (Kimura et al., 1996; Liu et al., 1994). Fat continuous systems

* Corresponding author. Tel.: +44 1214145284.
E-mail address: m.douaire@bham.ac.uk (M. Douaire).

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containing particles have also been investigated. Luengo and co-workers studied tribology of chocolate and related its lubrication behaviour to the constitution of the continuous fat phase and the average size of sugar crystals, cocoa solids and lactose particles (Luengo et al., 1997).

However, the above studies refer to tribological experiments using hard contacts (steel–steel or steel–glass), unlike most studies aimed at relating sensory perception to friction, which involves evaluation of the latter through soft tribology (steel–elastomer contact). This paper presents the first study, to the author's knowledge, of soft tribology analysis of water in oil emulsions. This study is aimed at investigating the effects of ball load as well as emulsion formulation, such as phase volume, emulsifier type and concentration, aqueous phase composition, on soft lubrication behaviour.

The above studies refer to tribological experiments using hard contacts (steel–steel or steel–glass) to characterise lubrication of oil continuous systems. However, most studies aimed at relating sensory perception to friction in food applications have been realised with the aid of soft tribology (steel–elastomer contact) to characterise the friction. This paper presents the first study, to the author's knowledge, of soft tribology analysis of water in oil emulsions. This study is aimed at investigating the effects of ball load as well as emulsion formulation, such as phase volume, emulsifier type, emulsifier concentration and aqueous phase composition, on soft lubrication behaviour.

2. Material and methods

2.1. Emulsion preparation

PRPG and kCarrageenan were obtained from Cargill (US), Tween 80, alginate and potassium chloride from Sigma (UK) and hydrophobic silica particles from Wacker Chemie AG (Germany). Sunflower oil was bought from the local store. Emulsions were realised with a high shear mixer (Sylverson, UK) with emulsifying time (up to 10 min) and rotation speed (up to 10,000 RPM) adjusted depending on the desired droplet size.

2.2. Physical properties

The droplet sizes were measured using a High Performance Particle Sizer (Mastersizer, Malvern Instruments, UK). Sample viscosity was measured using a Gemini HR Nano stress-controlled rheometer (Malvern Instruments, UK).

2.3. Tribology

The friction coefficient (a measure of lubricity) of a material can be determined through the use of a tribometer. The working part of a tribometer is composed of two moving components; for soft, semi-solid samples these are usually a ball and a disk. These components rotate in the same direction such that any fluid or semi-solid material placed in the sample chamber will be entrained between the two moving parts. Depending on the entrainment speed and especially the viscosity of the sample, the mode of lubrication can be determined.

Frictional properties were measured using a Mini Traction Machine (MTM, PCS Instruments, UK). A 3/4 in. AISI 400 stainless steel ball (PCS Instruments, UK) was loaded against the face of a silicone flat disc (Samco Silicone Products Ltd, UK). These selected materials are known to provide a strong correlation between frictional data and oral response (Malone et al., 2003). The load (W) was set to 3N except when testing the effect of load on friction, where it was set to either 1, 3 or 7N. The Slide-Roll Ratio was set to 50% for all experiments and each set of measurements was performed in triplicates to ensure repeatability.

Frictional behaviour is usually shown in the form of a Stribeck curve (Fig. 1) as presented in the works of Chen and Stokes (2012), Selvway and Stokes (2013) and de Vicente et al. (2006a), where three main regimes of lubrication can be observed: boundary (at low entrainment speeds and low viscosities), mixed (moderate entrainment speeds and viscosities), and hydro/elasto-hydro-dynamic (high entrainment speeds and viscosities). Boundary lubrication is prevalent when there is very little fluid between the surfaces, meaning that there is a large amount of contact between the two surfaces themselves. The hydrodynamic regime exists at higher entrainment speeds, where there is enough lubricant of sufficient viscosity entrained between the surfaces to ensure that the pressure in the fluid prevents the surfaces from touching (Dresselhuis et al., 2007).

The parameters investigated in this study, as well as details on emulsions preparation, are summarised in Table 1.

3. Results

3.1. Effect of ball load on Stribeck curves

The friction coefficient as a function of entrainment speed for 40% water in oil emulsions at various ball loads is shown in Fig. 2. In the case of water in oil emulsions, the region where the boundary regime is observed is limited, if not nonexistent, indicating that for the range of entrainment speeds studied, fluid is entrained between the ball and disc. As the entrainment speed increases, fluid entrainment becomes more significant, thus reducing the friction coefficient. Considering the high variability of data in this so-called mixed regime, the decrease in friction coefficient cannot be statistically attributed to the load variation. A further increase in entrainment speed results in even more fluid entrained, leading to an increase in friction coefficient; this is the hydrodynamic regime. The entrainment speed required to enter the hydrodynamic regime is increased for higher loads. This is because the film of fluid created between the moving parts needs to be able to sustain an increasing load, therefore requiring higher fluid pressure. However, the friction coefficient is somewhat higher for reduced load. Depending on the applied load, the transition to elastohydrodynamic lubrication occurs at different entrainment speeds: 60 mm s^{-1} for loads of 1N and 3N, and 100 mm s^{-1} for

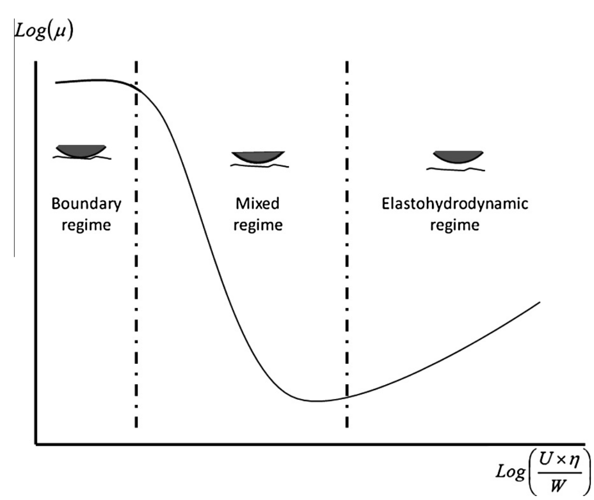

Fig. 1. Idealised sketch of a Stribeck curve, where μ is the friction coefficient (–), U the entrainment speed (mm s^{-1}), η the fluid dynamic viscosity (Pa s) and W the applied load (N).