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ORIGINAL PAPER

On the Elastohydrodynamic Film-Forming Properties of Metalworking Fluids and Oil-in-Water Emulsions

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Abstract
Oil-in-water (O/W) emulsions are water-based lubricants and used as fire-resistant hydraulic fluids and metalworking fluids (MWFs) in industry. The (elasto-)hydrodynamic film-forming properties of O/W emulsions have been studied extensively in literature. Typical elastohydrodynamic lubrication (EHL) behaviors are revealed at low rolling speeds followed by a starved EHL regime at elevated speeds. These emulsions are self-prepared and mostly stable only for a limited time ranging from hours to several days. By contrast, the film-forming behavior of water-miscible commercial MWFs (long-term stable O/W emulsions) has rarely been reported. This restricts the understanding of the lubrication status of many tribological interfaces in manufacturing processes, e.g., the chip-tool contact in cutting. In this work, the (elasto-)hydrodynamic film-forming property of two commercial MWFs is investigated by measuring the film thickness on two ball-on-disc test rigs using different optical interferometry techniques. For comparison, two self-prepared simple O/W emulsions with known formulation have also been investigated. Experimental results from the two test rigs agree well and show that the two self-prepared emulsions have typical EHL behaviors as reported in literature. However, for the two commercial MWFs, there is almost no (elasto-)hydrodynamic film-forming ability over the whole range of speeds used in this study. This could be explained by the cleaning and re-emulsification effects of the MWFs. The lubrication mechanism of the two MWFs is mainly boundary lubrication rather than hydrodynamic lubrication.

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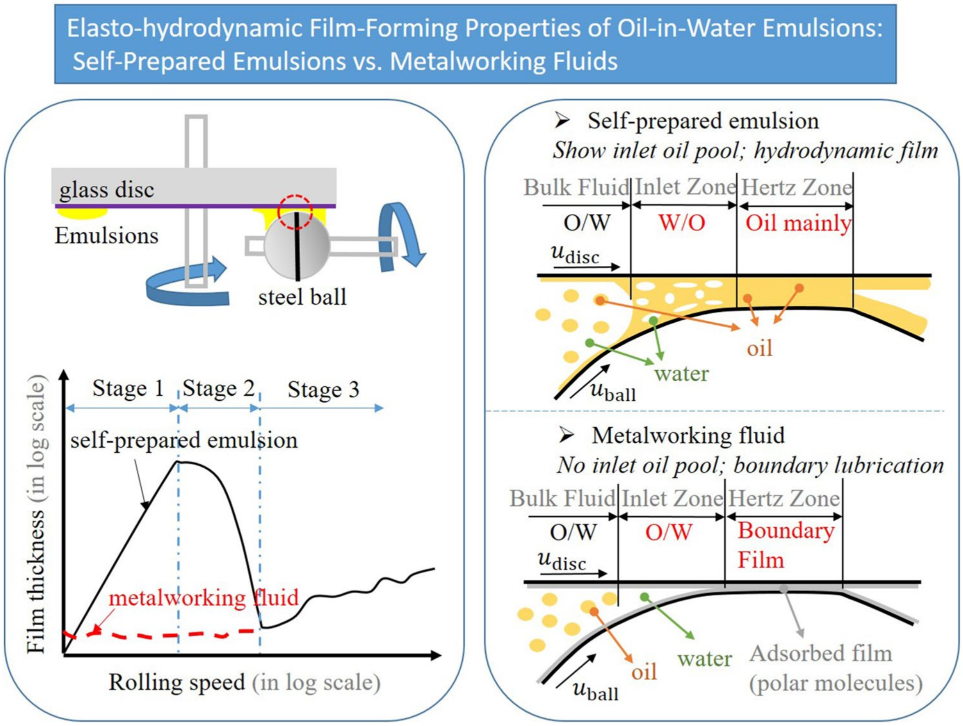
Graphical Abstract



Keywords Oil-in-water emulsion · Metalworking fluid · Lubrication mechanism · Film thickness

1 Introduction

Oil-in-water (O/W) emulsions are used as lubricants in some industrial applications and to meet extra requirements besides lubrication, such as the fire-resistant function of water-based hydraulic fluids in mining industry [1], the cooling and cleaning functions of water-miscible metalworking fluids (MWFs) in production engineering [2–5]. An emulsion is a colloidal mixture of two or more immiscible liquids, i.e., water and oil in most cases. For O/W emulsions, water is the continuous phase, while oil is the dispersed phase. The water phase helps to proof fire and/or to remove the generated heat because of its high heat capacity, while the oil phase is generally believed to work as lubricants to reduce the friction at the tribological interfaces. While hydrodynamic films and "boundary layers" are the two main mechanisms for lubrication, this work studies the (elasto-) hydrodynamic film-forming properties of different kinds of O/W emulsions.

The hydrodynamic film-forming behavior of O/W emulsions usually cannot be determined by their bulk properties such as the apparent viscosity, but is controlled by the components that are locally surrounding the contact zone [6–9]. Note that the formed lubricating film thickness (say less than 1μm) is usually smaller than the size of the oil droplets in an emulsion (typically 2μm- 50μm). The emulsion therefore cannot be simply treated as a homogeneous fluid in such a thin film lubrication regime. Besides, the empirical film thickness equations developed for elastohydrodynamic lubrication (EHL) of single-phase lubricants in the classical lubrication theory [10] do not hold for two-phase emulsions. The hydrodynamic lubrication performance of O/W emulsions depends largely on whether the oil phase can plate out and then be entrained into the tribological contact zone along the motion of surfaces [1, 8]. This is caused by the fact that the water phase is relatively weak to form a significant (elasto-)hydrodynamic lubricating film due to its low viscosity and low pressure-viscosity coefficient.

In literature, considerable efforts have been paid to study the film-forming property of emulsions by using an optical ball-on-disc setup, e.g., in [1, 6, 11–15]. The measured film thickness can be divided into three stages in terms of rolling (entrainment) speeds as schematically shown in Fig. 1 [11, 12, 16–18]. At low speeds (Stage 1), the film thickness increases linearly with rolling speeds on a double logarithmic scale. Such a linear film-forming behavior is like that of a single-phase oil in the classical EHL theory [10, 19, 20]. This can be explained by the plate-out theory of O/W

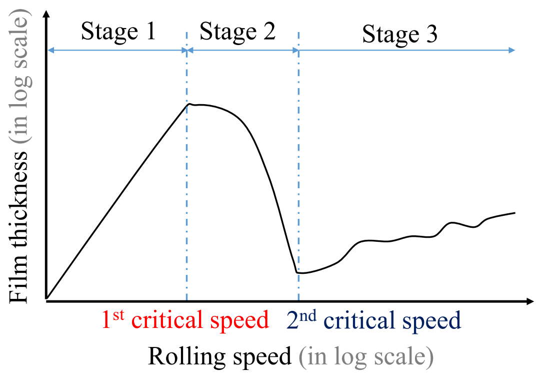


Fig. 1 (Elasto-)Hydrodynamic film-forming behavior of self-prepared short-term stable oil-in-water (O/W) emulsions at different rolling velocities according to measurements in [11, 12, 17, 18]

emulsions [1, 8], which means that the oil droplets displace the water, plate out to form an oil pool in the contact inlet. The process may be described with the concept of displace energy proposed by Kimura et al. [8] considering effects of the type and concentration of emulsifiers and the interfacial tension between oil droplets and solids [12, 17]. Experimentally, the inlet oil pool has been observed directly using optical ball/roller-on-disc test rigs [11–15]. When a critical speed is reached (the first critical speed marked in Fig. 1), the film thickness decreases dramatically with increasing rolling speeds, see Stage 2 in Fig. 1. The drop in film thickness is caused by the starvation effect [1, 6] when the formed oil pool in the inlet region is not large enough to supply sufficient lubricants to the contact zone. The starvation phenomenon with O/W emulsions looks quite similar to that widely occurs in grease lubricated rolling contacts [21]. In addition to the starvation mechanism, re-emulsification effects [12, 22] have also been reported to account for the film thickness reduction/collapse in Stage 2. This means that the inlet oil pool formed at low velocities in Stage 1 is partially re-emulsified into O/W emulsions in Stage 2. The re-emulsification effects may result from the emulsification function of the emulsifier as well as the higher mechanical flushing energy at high speeds. When the rolling speed is further increased, i.e., being larger than the second critical speed in Fig. 1 (about 2.5 m/s in [18], 10 m/s in [12], 0.5 m/s in [17]), the lubrication regime turns to Stage 3, in which the film thickness increases again. It is also a kind of EHL film which may be composed of either mostly oil [23] or O/W micro-emulsion [14, 18]. The former hypothesis of oil is proposed by Wilson et al. [23], and the lubrication regime is regarded as an elastic piezo-viscous regime [19, 24] based on the concept of dynamic concentration, while for the latter hypothesis of micro-emulsion, the lubrication status is thought to be in an elastic isoviscous regime. Recently, using a fluorescence technique, Hili et al. [11] showed an evolution in film composition from pure oil in Stage 1 to mostly water in both Stage 2 and Stage 3. This supports the view of micro-emulsion in Stage 3.

To sum up, EHL is shown to be the main lubrication mechanism for O/W emulsions in the literature. An (elasto-) hydrodynamic film could be formed even for an emulsion with extremely low oil volume of 0.005% [25]. Note that all these studies have been performed with self-prepared emulsions that are short-term stable, lasting for several hours to several days after preparation. In these cases, the oil phase might be easier to plate out to form an oil pool which enables a full-film (elasto-)hydrodynamic lubrication.

However, the film-forming behavior of long-term stable emulsions has not been reported, yet they are necessary in many engineering applications, e.g., the MWFs and the water-based fire-resistant hydraulic fluids. For a long-term stable emulsion system, the oil droplets might be hard to plate out. At least, more energy is needed to displace the water phase and then to adhere to the solid surfaces being lubricated. In a recent work of the authors, an abnormal phenomenon has been found for a long-term stable commercial MWFs (O/W emulsion) that it has almost no EHL film-forming ability [26]. In this work, the film-forming behavior of two widely used long-term stable MWFs is studied by comparing with two self-prepared model emulsions. The results show that the (elasto-)hydrodynamic film-forming behavior of commercial MWFs is quite different from that of self-prepared O/W emulsions. To make sure the repeatability of the results, the film thickness measurements have been performed on two optical ball-on-disc test rigs at two research institutes using different methods of optical interferometry, see Sec. 2. The possible lubrication mechanisms of commercial MWFs and self-prepared O/W emulsions are analyzed and discussed in detail.

2 Experimental Methods and Materials

The used two ball-on-disc test rigs, optical methods for film thickness measurements, and the formulation and properties of the four O/W emulsions are introduced in this section.

2.1 Optical Ball-on-Disc Test Rigs

The film-forming property of the four emulsions has been firstly measured on a ball-on-disc test rig at the IMKT institute of Leibniz University Hannover, see Fig. 2. The test rig follows the design in [27]. A 25.4 mm diameter AISI 52,100 steel ball is loaded against a glass disc showing a circular Hertzian contact. The disc is driven by a servo motor, and the disc drives the ball to achieve a pure rolling motion. The lubricant is supplied to the inlet region of the contact with a peristaltic pump.

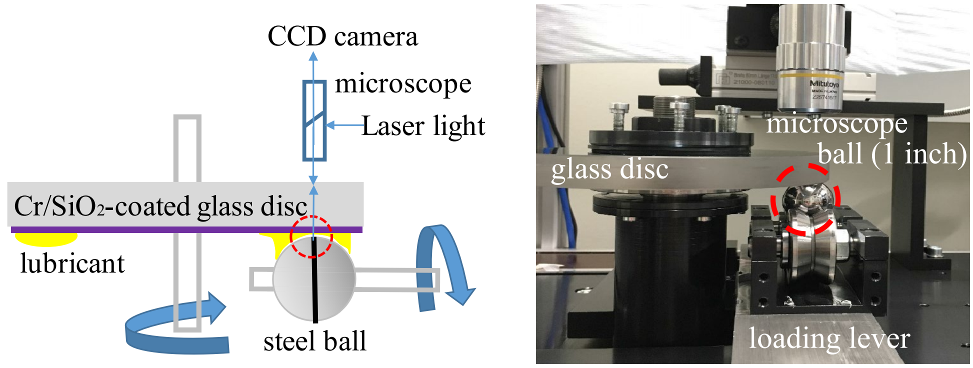


Fig. 2 Optical ball-on-disc test rig for lubricating film thickness measurement, **left**: diagrammatic drawing; **right**: photo of the ball-on-disc test rig at Leibniz University Hannover

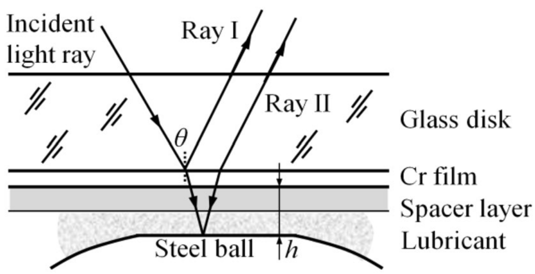


Fig. 3 Schematic of the principle of optical interferometry for lubricating film thickness measurement on the ball-on-disc setup (two beam interferometry is shown here for simplicity; two-color and multi-beam interferometry are used in the DIIM measurements and analysis [28])

The lubricating film thickness at the contact center is measured by optical interferometry as schematically shown in Fig. 3. A dichromatic intensity modulation method (DIIM) [28] has been used. Red-green lasers with wavelengths of 653 nm and 532 nm, respectively, are used as the light source. The film thickness at each pixel of a captured interferogram can be obtained based on intensity analysis with principles of multi-beam interferometry and heterodyne interferometry. To obtain interferograms of high contrast, the working surface of the glass disc is coated with a semi-reflective Cr layer of about 10 nm. On top of the Cr layer, there is a SiO_2 spacer layer of 200 nm. The RMS roughness of the glass disc is about 5 nm, and the Ra surface roughness of the steel ball is smaller than 25 nm according to the supplier (Grade 16, ISO 3290).

Note that the optical ball-on-disc setup has been widely used in the studies of EHL since 1960s [29]. To obtain the film thickness from optical interferograms, several methods have been developed based on spectrum analysis, colorimetry, and intensity digitization. The application of these techniques depends on the light source (e.g., white, monochromatic, dichromatic light) and the associated hardware (e.g., color, black/white CCD camera) in the optical system of the test rig. The DIIM method used in this study is based on intensity digitization.

The film thickness measurements were carried out at different rolling speeds from 0.01 m/s to 1 m/s at a constant load of 30 N corresponding to a Hertzian pressure p_H of 0.5 GPa. The flow rate of the pump was 45 mL/min. All tests were conducted at room temperature of 23°C. Each set of measurements was repeated three times and was performed from the lowest to the highest speeds for one run.

To confirm the film-forming properties, especially the abnormal film-forming behavior of commercial MWFs observed in [26], the central film thickness h_{cen} of all emulsions has also been measured on a commercial ball-on-disc test rig, EHD2 (PCS Instruments, UK), at University of Twente. The built-in spectrum analysis method [30] can detect the film thickness in-site for a specific spot of interest. The operating conditions were kept comparable to that of the IMKT rig in terms of rolling speed, Hertzian contact pressure, and experimental temperature. The diameter of the ball here is 19.05 mm with the RMS surface roughness of 3.5 nm. The ball was half immersed in the emulsion. During test, the emulsion was brought to the contact region by rolling motion of the ball. A fully flooded emulsion supply can be ensured. This way of emulsion supply is different from the one of injection lubrication on the IMKT test rig.

2.2 Model Emulsions and MWFs

Two commercial MWFs and two self-prepared model emulsions have been used in this work. They are all O/W emulsions diluted to a concentration of 10 Vol%, if not special specified. This is a typical concentration for MWFs in real applications. Before dilution, the concentration of the four fluids has almost the same kinematic viscosity of $65 \sim 70\text{mm}^2/\text{s}$ at 20°C. The formulation of the two commercial MWFs is unknown, while it is known for the two model emulsions. The composition and properties of the four fluids are listed in Table 1 and introduced below.

The first kind of commercial MWF (MWF-1, Vasco 6000, Blaser, Switzerland) is an ester-oil-based cooling lubricant, while the second commercial MWF (MWF-2, Zubora 67H Extra, Zeller + Gmelin, Germany) is a mineral-oil-based

Table 1 The formulation and properties of the four O/W emulsions

Item	Model-1	Model-2	MWF-1	MWF-2
Product name	–	–	BLASER Vasco 6000	ZELLER + GMELIN Zubora 67H Extra
Formulation of the concentration	T22 base oil 90% + CST-77 non-ionic emulsifier 10%	T22 base oil 80% + CST-77 non-ionic emulsifier 10% + EP/AW additive package 10%	Unknown (ester-oil based)	Unknown (mineral-oil based)
EP/AW additives	No	Yes	Yes	Yes
Viscosity (base oil at 20 ℃)	65 mm^2/s	65 mm^2/s	67 mm^2/s	70 mm^2/s
Emulsion concentration	10%	10%	10%	10%
Emulsion type	O/W	O/W	O/W	O/W
Oil droplet size	About 35 µm	About 4.8 µm	About 4.5 µm	< 1 µm
Status	Self-prepared; short-term stable	Self-prepared; short-term stable	Commercial MWF; long-term stable	Commercial MWF; long-term stable

semi-synthetic one. They are both supplied as concentrations containing a high proportion of additives for functions of lubrication, cleaning, anti-rust, and so forth. After dilution with deionized water, long-term stable O/W emulsions can be easily formed and used as cutting fluids in manufacturing. The two emulsions are marked as MWF-1 and MWF-2, respectively. The so-called long-term here means that the creaming time is several months or years, which is orders of magnitude longer than that of the self-prepared simple emulsions of only several hours to days.

The two self-prepared model emulsions, Model-1 and Model-2, share similar formulation. A hydrotreated naphthenic base oil T22 (NYNAS; API Group V) was used as the dispersed phase. It is widely used in the formulation of MWFs. Besides, it has similar viscosity to the concentrations of the two commercial MWFs. A non-ionic emulsifier Antarox CST77 (Solvay Solutions, the Netherlands; HLB value = 8) was blended into the base oil to form the concentration. The concentration of Model-1 is composed of 90% base oil and 10% emulsifier according to volume. For the concentration of Model-2, the only difference is that it has extra sulfur-containing additive package, Elco-2020WB (Elco Corporation, USA), giving additional properties such as extreme-pressure (EP), anti-wear (AW), and corrosion inhibition. In detail, the concentration of Model-2 is composed of 80% base oil, 10% emulsifier, and 10% additive package. Before the film thickness tests, the concentration was diluted with deionized water to 10 Vol%, and the mixture was stirred with a mixer at 100 rpm for 10 min.

The size of the oil droplets of the four O/W emulsions is shown in Fig. 4, observed with a microscope at a high magnification. MWF-1 has similar droplet size as that of Model-2, ca. 4.5µm. Model-1 has the largest oil droplet size, which is about 35µm. The droplet size of MWF-2 is smaller than 1µm and cannot be detected with the used optical microscope. To determine the film thickness, the refractive index of the film inside the contact zone is needed. But it may not be same as that of the bulk emulsion, for example, for the Stage 1 and Stage 2 in Fig. 1 where the lubricating film is mainly composed of the oil phase rather than water. For simplicity of the film thickness analysis, the refractive index was assumed to be 1.5, a typical value for oil, regardless of the composition of the film, and the lubrication stages might be at different speeds as shown in Fig. 1. Note that the uncertainty about the refractive index of the lubricating film would not affect the main findings of this work.

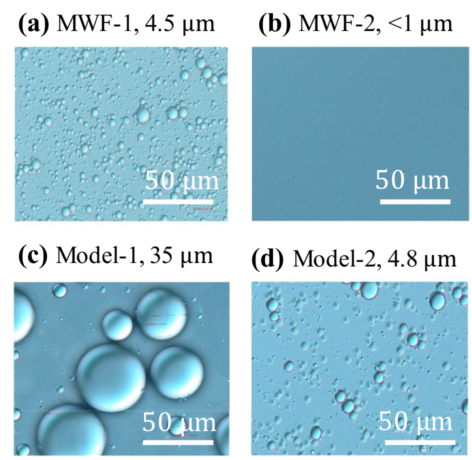


Fig. 4 Oil droplet size and distribution of the four O/W emulsions

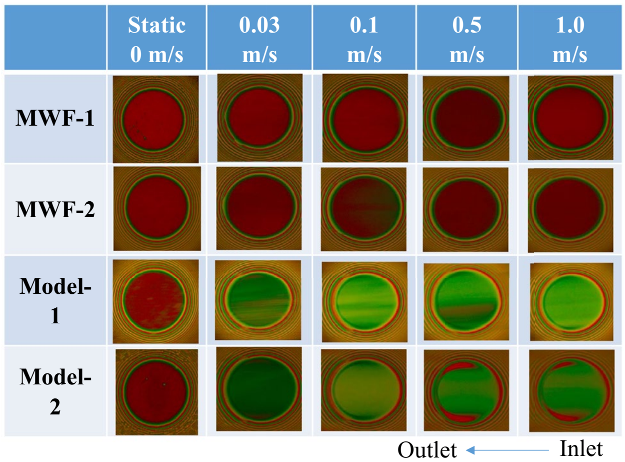


Fig. 5 Captured interferograms representing film thickness in the pressurized ball-on-disc contact at different rolling speeds lubricated with two commercial MWFs and two model O/W emulsions. (IMKT ball-on-disc rig, $p_H = 0.5$GPa, diameter of the circular contact zone is 240μm)

3 Results and Discussion

3.1 Hydrodynamic Film-Forming Behavior

The interferograms for the four O/W emulsions captured on the IMKT ball-on-disc test rig are shown in Fig. 5. The four emulsions are at the same concentration of 10%. The Hertzian contact pressure is 0.5 GPa, and the rolling speed varies from 0.01 m/s to 1.0 m/s. The first column shows the interferograms at zero speed (static contact) characterized by a red color in the circular contact zone. In principle, zero entrainment speed leads to zero hydrodynamic film thickness. Hence, the red interference color from these static cases (fringe order 1) could serve as a zero-film reference for other interferograms recorded at different rolling speeds. For the two model fluids, Model-1 and Model-2, the contact zone is in green, which indicates the formation of a thin (elasto-)hydrodynamic lubricating film. A typical horse-shoe-shaped EHL film is visible for Model-2 and Model-1 at higher speeds such as 0.5 m/s and 1.0 m/s. For Model-1, the horse-shoe-shaped contacts are slight deformed and asymmetrical relative to the entrainment direction. This indicates a starvation process, which can be seen on the variation of the central film thickness at the corresponding speeds in Fig. 8. However, for the two commercial MWFs, MWF-1 and MWF-2, there is no significant hydrodynamic film build-up over the whole range of rolling speeds, as the color of the contact zone is always in red like that of a static contact.

Quantitatively, the central film thickness has been analyzed with the DIIM method for the four emulsions, and the results are plotted as a function of rolling speeds in Fig. 6.

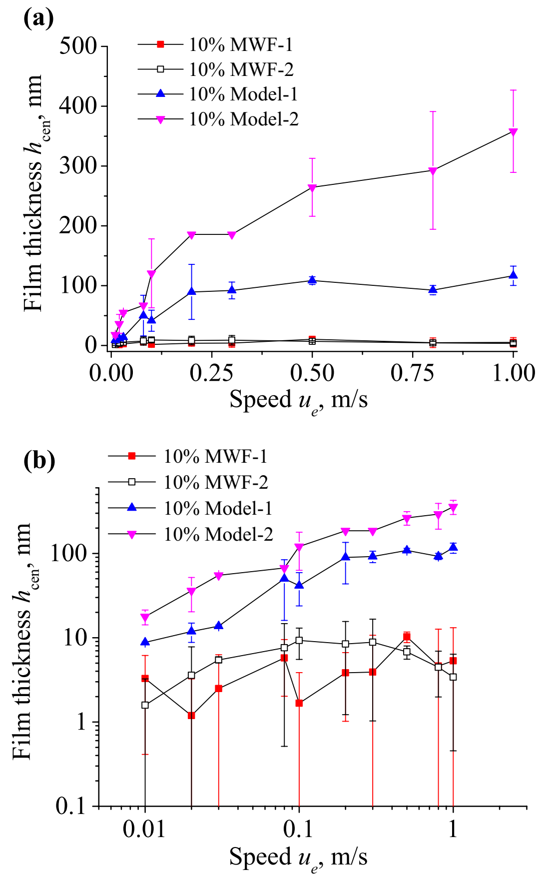


Fig. 6 Central film thickness at different rolling speeds for the four O/W emulsions, **a** in a linear scale; **b** in a log–log scale. (IMKT ball-on-disc rig, $p_H = 0.5$GPa)

From the linear scale plot in Fig. 6(a), it can be seen that the film-forming behavior of the two MWFs is quite different from that of the two model emulsions. For the two commercial MWFs, the film thickness is very low in the whole range of speeds, and there is almost no (elasto-)hydrodynamic film build-up. This does not follow the reported hydrodynamic lubrication behavior of self-prepared O/W emulsions in literature as shown in Fig. 1, Sec. 1.

The different film-forming behaviors of the four emulsions can also be seen clearly on a double logarithmic scale in Fig. 6(b). Remind that the film thickness increases linearly with speeds on a double logarithmic scale for neat oil according to the classical EHL theory. The two self-prepared model emulsions give a linear film-forming behavior following the typical feature of an oil, see Stage 1 of Fig. 1. Besides, Model-2 with the additive package shows higher EHL film thicknesses than Model-1. However, the two commercial MWFs fail to generate a hydrodynamic film even for the maximum entrainment speed of 1.0 m/s used in the test. The film thickness is always lower than 20 nm, which is roughly the same as the surface roughness of the steel ball.

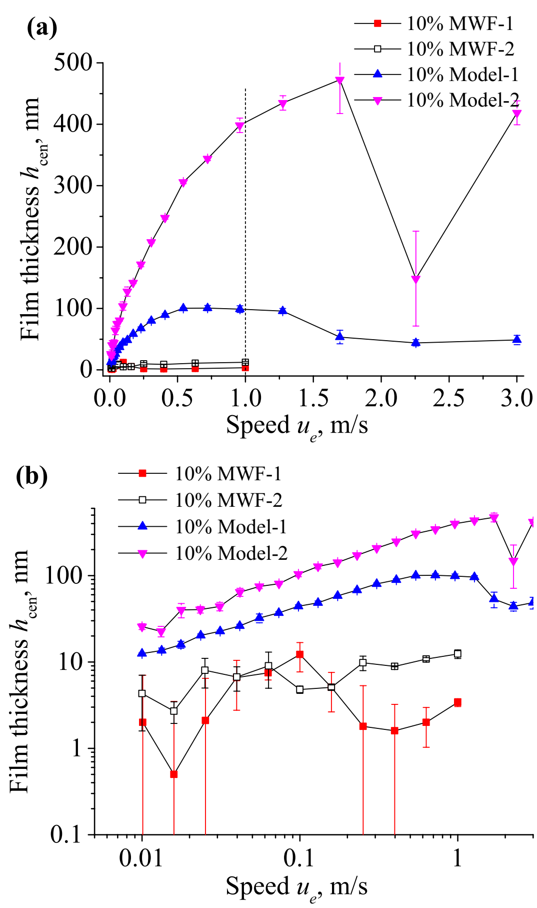


Fig. 7 Central film thickness for the four O/W emulsions at different rolling speeds, **a** in a linear scale; **b** in a log–log scale. (EHD2 ball-on-disc rig, $p_H = 0.5$GPa)

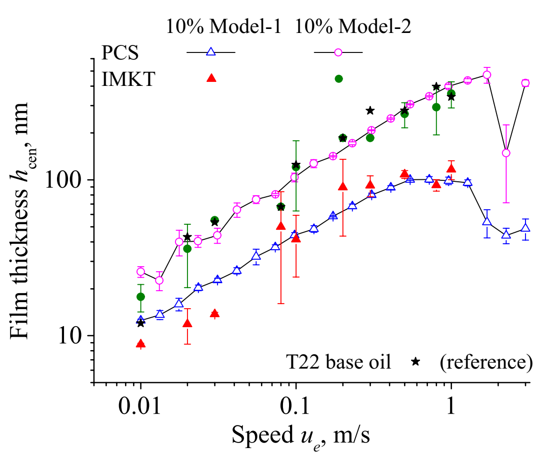


Fig. 8 Comparison of the central film thickness measured on two optical EHL test rigs for two self-prepared model O/W emulsions at different rolling speeds. The film thickness of their base oil T22 is also shown as a reference. ($p_H = 0.5$GPa)

During the film measurements for the two MWFs, moderate scratches were noticed on the rolling tract of the glass disc.

To confirm the above observations regarding the weak (elasto-)hydrodynamic film-forming property of MWFs, the central film thickness of these four emulsions has been measured again on a commercial ball-on-disc test rig, the PCS EHD2 at University of Twente. The testing conditions are kept comparable to the previous tests on the IMKT test rig in terms of the Hertzian contact pressure of 0.5 GPa and at room temperature. For the two self-prepared model emulsions, the maximum rolling speed is increased to 3 m/s. However, for the two MWFs, the maximum speed is kept at 1 m/s to avoid any severe surface damage to the SiO_2/Cr coatings on the glass disc. The measured central film thickness at different rolling speeds is shown in Fig. 7(a) and b on a linear and on a log–log scale, respectively. It confirms the observation (on the IMKT test rig in Fig. 6) that the commercial MWFs behave differently to the two self-prepared model emulsions regarding the film-forming property. There is almost no hydrodynamic film-forming ability for the two MWFs, and the central film thickness is always lower than 20 nm, see Fig. 7(b). For the two self-prepared emulsions, Model-1 and Model-2, the first critical speed (Fig. 1) has been reached at 1.0 m/s and 1.75 m/s, respectively, and since then the film thickness decreases with speeds following the trend of Stage 2 in Fig. 1. For Model-2, the second critical speed and thus the lubrication regime of Stage 3 in Fig. 1 may have also been reached. To make sure this transition, more measurements should be carried out for speeds between 1.75 m/s and 3.0 m/s. However, the film-forming behavior of emulsions at high speeds is not the focus of the current work. Interested readers are referred to [11, 12, 18].

Figure 8 compares the measured film thickness on the two test rigs for the two self-prepared model emulsions. As can be seen, the results agree with each other well, at least within the range of the error bar. In the figure, the film thickness of the base oil of the two emulsions, T22 oil, has been shown with stars. The film thickness of Model-2 is close to that of the base oil before starvation occurs. This indicates that the additive package in Model-2 may benefit the formation of an oil pool in the inlet region of the contact, i.e., reduce interfacial strength and boost the transition from the O/W emulsion to a local W/O emulsion or even close to pure oil phase in the EHL inlet as shown schematically in Fig. 9(a). This will be explained in detail in the following section.

3.2 Lubrication Mechanisms and Discussion

The possible mechanism accounting for the different film-forming properties of the self-prepared model emulsions and the MWFs is analyzed in this section. According to the EHL lubrication theory, the film thickness is governed by the volume of the fluid that can be entrained into the contact

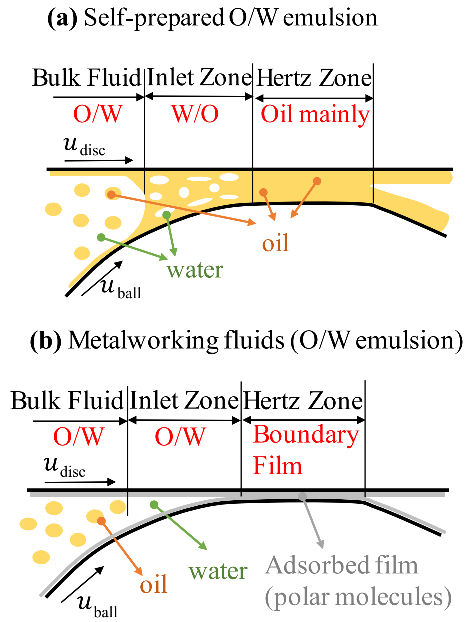


Fig. 9 Schematic of the lubrication mechanisms of **a** self-prepared O/W emulsions and **b** commercial metalworking fluids

zone by surface velocities. Taking a single-phase lubricant (typically an oil) as an example, the EHL film thickness depends mainly on the entrainment velocity u ($h_{cen} \propto u^{0.67}$), the effective viscosity η ($h_{cen} \propto \eta^{0.67}$), the pressure-viscosity coefficient α ($h_{cen} \propto \alpha^{0.53}$), and the amount of lubricant in the inlet, while it is not sensitive to the load ($h_{cen} \propto w^{-0.067}$) [10, 19]. To analyze the film-forming ability of the two-phase O/W emulsions, two assumptions have been made,

(1) Only the oil phase can form an (elasto-)hydrodynamic film.
(2) The oil phase or an oil droplet can only be brought into the contact zone to form an EHL film by adhering to the solid surfaces.

The first assumption should be reasonable for the relatively low speeds used in this study. Compared to the oil phase, the water phase in an emulsion has a negligible EHL film-forming ability due to its low viscosity and low pressure-viscosity coefficient. Note that the maximum entrainment speed of 1 m/s here is not high enough for the emulsions to reach the Stage 3 in Fig. 1, where the bulk micro-emulsion contributes to the formation of an (elasto-) hydrodynamic film (i.e., elastic isoviscous lubrication regime). The second assumption is made concerning the experimental observations of the behavior of oil droplets in O/W emulsions in a lubricated converging gap. The oil droplets are classified into three types according to [14, 15]: (a) stay droplets, (b) reverse droplets, and (c) penetration droplets. Through experimental observations with a high-speed camera, Yang et al. [15] found that the penetration droplets are those primarily attached to solid surfaces or joined the oil pool. This observation was supported for oil droplets of different size from 2μm to 10μm and for rolling speed from 0.015 m/s to 1.5 m/s. If an oil droplet is detached from the solid surface, it is easy to be flushed away by the surrounding water phase in the backflow in the inlet region, and finally the droplet would mainly flow around the circular contact zone rather than pass through it. Similar observations of back and side flow have been reported by Strubel et al. [31] in the study of particle contaminated lubricants in point contacts using fluorescence and PIV techniques. The study of Cambiella et al. [32] also verified that the interactions between metal and oil droplets rule the mechanism of lubrication.

Based on the above assumptions, the film-forming behavior of the two different kinds of emulsions (model emulsions and MWFs) can be analyzed based on the film thickness results in Figs. 6–8. The focus is the inlet region where the pressure and thus the (elasto-)hydrodynamic film are built. Schematically, the lubrication mechanisms of the two self-prepared emulsions and the two MWFs are shown in Fig. 9(a) and Fig. 9(b), respectively. For the self-prepared emulsions, the film-forming behavior in Figs. 6–8 is in line with the Stage 1 and Stage 2 in Fig. 1 or elsewhere in literature, e.g., [1, 8, 11–15, 17, 18, 21, 22]. An EHL film can be formed owing to the phase reversion of the O/W emulsion to a W/O emulsion and hence the formation of an oil pool in the inlet region, as shown in Fig. 9(a). The oil phase of the two model fluids is the same, sharing the same viscosity as well. It is interesting to see that the film thickness for Model-1 is always smaller than that of Model-2 in Figs. 6–7. This is the case even at low rolling speeds and cannot be explained by the size of the oil pool in the inlet; otherwise, the film thickness should be similar at low speeds. The only difference in the formulation is the use of composite additive package in Model-2. Some additives inside may work as co-emulsifier to give a fine oil droplet distribution (Fig. 4). As a result, Model-2 emulsion should be more stable than Model-1 if we judge through the size of the oil droplets. However, in literature, there is not yet agreement on the relation between oil droplet size (and thus emulsion stability) and the film-forming performance of emulsions, see for example [32, 33]. Here, the results are not in favor of the opinion that emulsion with lower stability and larger droplet size would provide better film-forming ability as observed in [32] with rolling emulsions. For our case, it is more likely related to the composition of the formed W/O pool in the inlet region, e.g., the water-to-oil ratio and the local effective viscosity therein. At the outlet of the EHL zone, a thin oil layer may stay on the solid surfaces to replenish the next rolling contact, while the rest of the oil film would be re-emulsified into oil droplets (and thus O/W emulsion) again depending on the interfacial affinity between the oil layer and the solid surfaces, rolling speeds, and compositions of the O/W emulsion.

As a contrast to the self-prepared emulsion, there is almost no (elasto-)hydrodynamic film-forming ability for the two commercial MWFs, as tested in Figs. 6–7. This is confirmed by the two different optical methods at two institutes, even though the method of emulsion supply is different. As schematically shown in Fig. 9(b), the oil droplets fail to attach to the ball/disc solid surfaces in the inlet, and no oil pool can be formed. The contact zone is mainly surrounded by the water phase, and the measured central film thickness is mostly lower than 10 nm throughout the speed range used in the study. Considering the influences of the surface roughness, such a thin film may be treated as a boundary lubrication film, composed of adsorbed molecules and additives.

3.3 Cleaning and Re-Emulsification Effect

Through the above analysis, it can be known that the (elasto-)hydrodynamic film-forming properties of O/W emulsions are mainly governed by the oil plate-out behavior in the inlet. The self-prepared emulsions are not as stable as commercial MWFs. The creaming and broken time for the former is usually several hours to several days (short-term stable), while that for the commercial MWFs is usually several months to years (long-term stable compared to the time cost in the film thickness tests). The interfacial strength between the oil droplets and the water phase in self-prepared emulsions might be easier to be broken to facilitate the formation of an oil pool in the inlet, as suggested in [8]. However, there is different opinion on the relation between emulsion stability and the film-forming behavior. Cambiella et al. [32] showed that macroscopic stability of emulsions and the droplet size distribution do not seem to affect the lubrication. For the two commercial MWFs used in this study, it is interesting and important to know why such an inlet oil pool and thus hydrodynamic lubrication cannot be formed.

In [32], three different types of emulsifiers, i.e., nonionic, cationic, and anionic, have been used to prepare the model emulsions. All prepared emulsions showed good EHL film-forming behavior. This indicated that the type of emulsifier is likely not the main cause of the weak film-forming behavior of the two commercial MWFs.

In our previous work [26], it has been known that the oil concentration is not the dominant factor governing the weak film-forming ability of the tested MWFs. The central film thickness of MWF-1 at three concentrations of 10%, 90%, and 100% was measured at pure rolling conditions. Results showed that only the straight oil (100% concentration) has a hydrodynamic film-forming ability. Even at a high oil concentration of 90%, only a thin boundary film can be formed, showing almost no difference to the case of 10%.

The importance of oil droplet size on the film-forming ability has been emphasized in many studies [15, 33]. Yang et al. [15] found that the droplet size has a strong effect on the oil pool when the droplet sizes are below 5 μm, and at larger sizes, the influences are less significant. By contrast, Cambiella et al. [32] believe the droplet size distribution and thus the macroscopic stability are not important for lubrication. In the current work, Model-2 and Commercail-1 have similar droplet size, but the EHL film-forming behavior is totally different. The effect of oil droplet size on emulsion lubrication remains an open question.

To find out why the oil droplets do not adhere onto the solid surfaces for MWFs, a special experiment is carried out here. First, a thin (elasto-)hydrodynamic lubricating film is achieved with a single droplet of MWF-1 on the optical ball-on-disc rig at starved conditions. Then, the next step is to know how does this thin film collapse in case of a large amount of MWF supply.

A volume of 6μL MWF-1 at 10% concentration is added to the ball-on-disc contact region with a pipette. The load is 10 N, and the rolling speed is kept constant at 6 mm/s. At the beginning, the contact vicinity is fully surrounded by the MWF, as shown in Fig. 10(a). The contact center is in red, indicating a near zero-film thickness. As the disc rotates, the limited volume of MWF-1 is distributed on the whole rolling track of the glass disc leading to starved lubrication as the liquid–air meniscus is approaching the edge of the contact zone, see Fig. 10(b). The contact center is still in red.

After about two circles of rotation of the glass disc, the meniscus reaches the boundary of the contact edge, and rightly since then a thin lubricating film appears in the contact zone as indicated by the shallow green interference color in Fig. 10(c). The residual oil droplets/layer on the rolling track, perhaps because of the water evaporation, serve as lubricant resulting in the thin lubricating film. Interestingly, the film cannot be formed as long as the liquid–air meniscus does not reach the contact edge, i.e., when a tiny amount of MWF emulsion is in the inlet region, for example for the case in Fig. 10(b). Now, by adding a new droplet of 10% MWF-1 or supplying a huge amount of MWF-1 to the inlet region by turning on the pump, the thin film collapses, and the lubrication status goes back to boundary lubrication again. We call this cleaning effect or re-emulsification effect of MWFs. The thin lubricating oil film and the oil layer adhered to the solid surfaces are cleaned or re-emulsified into O/W emulsions.

Through this experiment, it has been shown that the adhered oil droplets on the solid surface can form a thin lubricant film at starved/parched lubrication conditions, see Fig. 10(c). However, once there is enough amount of MWF surrounding the inlet region, the cleaning or re-emulsification effect is so strong that the oil droplets detach from the solid surface. Therefore, no oil pool can be formed in the

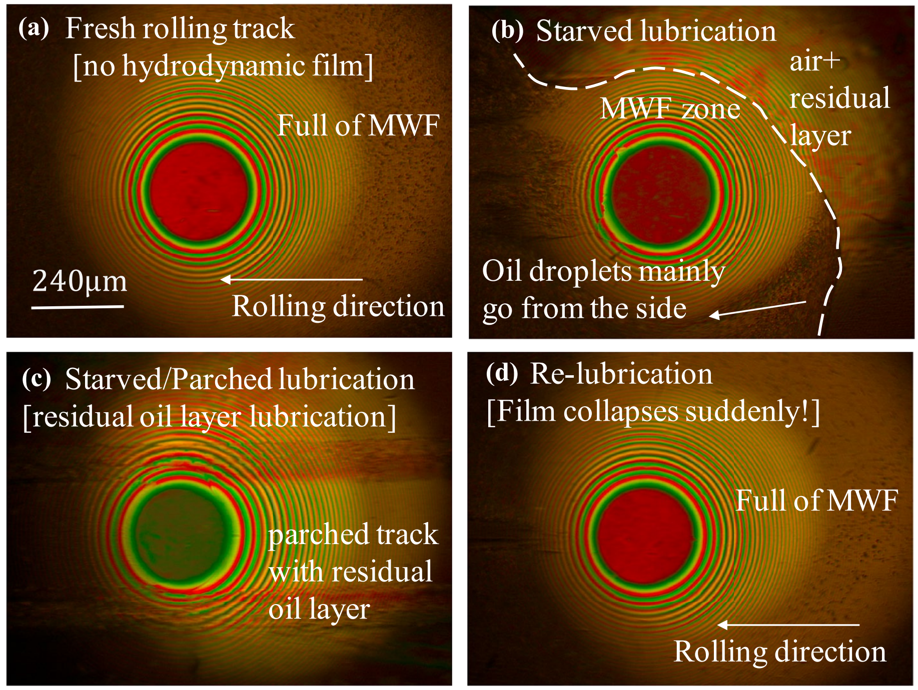


Fig. 10 Single droplet experiment used to demonstrate the cleaning and re-emulsification effect of commercial MWFs on lubricating film formation (MWF-1, 6μL, IMKT ball-on-disc test rig, $p_H = 0.35$GPa)

inlet region with a large amount of MWF. In Fig. 11, this experiment is carried out again with an even smaller initial volume of MWF-1 of 3μL and at a higher load of 30 N on the IMKT ball-on-disc test rig. An objective lens of low magnification is used to give a larger field of view of the contact vicinity. The same phenomenon as shown in Fig. 10 has been observed. The formed EHL film in Fig. 11(c) collapses once a large amount of MWF is supplied as a result of cleaning and re-emulsification effects, see Fig. 11(d).

Similarly, Boure et al. [34] found that no oil pool has been observed in the inlet of an EHL contact in the EHL experiments with water-based lubricants having a microscopic lamellar structure, e.g., drawing emulsion and self-prepared one based on lamellar fatty acid. The contact is starved, and

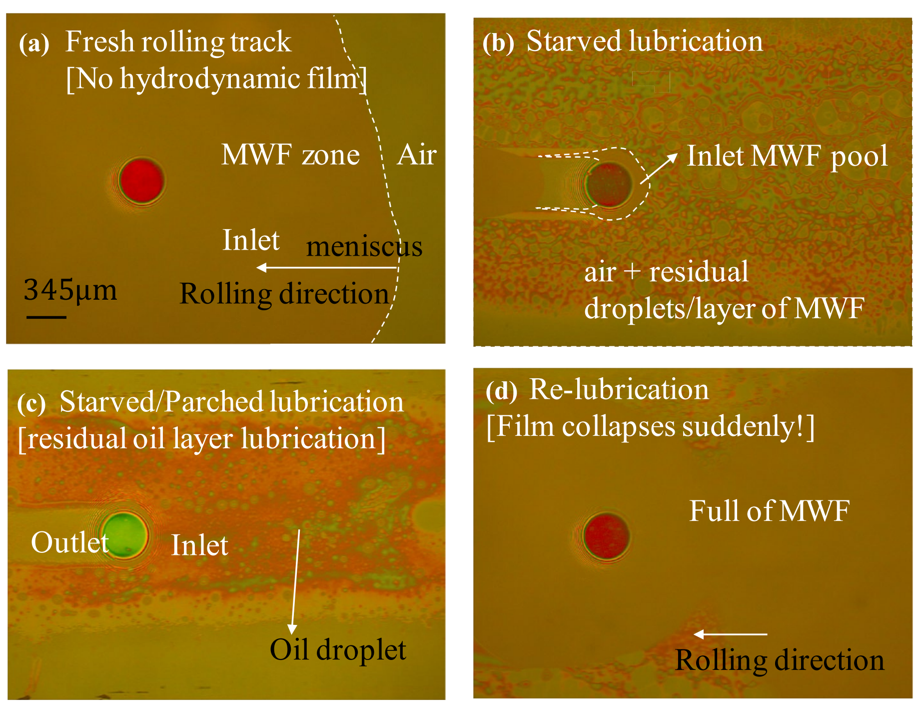


Fig. 11 Single droplet experiment used to demonstrate the cleaning and re-emulsification effect of commercial MWFs on lubricating film formation at a larger field of view (MWF-1, 3μL, IMKT ball-on-disc test rig, $p_H = 0.5$GPa)

interestingly, a thick adherent boundary layer can be formed over time on the surfaces when a critical speed is reached. The boundary film is formed gradually. For example, at pure rolling of 0.4 m/s, the boundary film grows up to 175 nm in 20 min and then levels out to a stable state. The boundary layer results from the dispersed lamellar fatty acids particles used in the formulation. The layer is modeled as a combination of high viscosity with a low pressure-viscosity coefficient, i.e., starved and thick boundary layer growth [35]. Such a time-dependent boundary layer lubrication mechanism cannot be applied to the four emulsions used in the current work. Figure 12 shows the film thickness variation in three repeated tests for each fluid with 15 min. The repeatability is good, and no significant evidence of boundary film growth. The weak film-forming ability of the two MWFs should be attributed to the re-emulsification effect.

In literature, re-emulsification effect has been shown to contribute to the film thickness reduction in Stage 2 of Fig. 1 for self-prepared O/W emulsions in [12, 13]. This effect should be highly related to the type and concentration of emulsifiers/surfactants in the emulsion, e.g., the critical micelle concentration proposed by Ratio et al. [17, 32]. In this study, with the two commercial MWFs, direct experimental evidence has been provided to show the significance of the re-emulsification effect on the hydrodynamic film formation.

Indeed, cleaning is an intrinsic function of MWFs in addition to cooling and lubrication. The cleaning effect of MWFs is achieved by surfactants, which can penetrate the interfaces between iron powder/oil droplet and tool/workpiece to remove them therein. This can not only help to keep tools and other components clean, but also can help to avoid unwanted surface damages to the newly machined surfaces. Such surfactant additives for cleaning effects are believed to result in the boundary lubrication condition for MWFs. There might be a balance between the cleaning and lubrication effects in the formulation of MWFs. The hydrodynamic film-forming ability of the two MWFs used in this work seems to be totally counteracted by cleaning effect. As a contrast, the self-prepared O/W emulsions have a single type of emulsifier and might do not have such a strong cleaning effect, and therefore, an (elasto-)hydrodynamic lubricating film can be formed. See Fig. 13 for a general comparison of the film-forming behavior of MWFs and self-prepared emulsions at different rolling speeds.

4 Summary and Outlook

In this study, the film-forming properties of two MWFs and two self-prepared model emulsions have been measured at pure rolling conditions on two ball-on-disc EHL

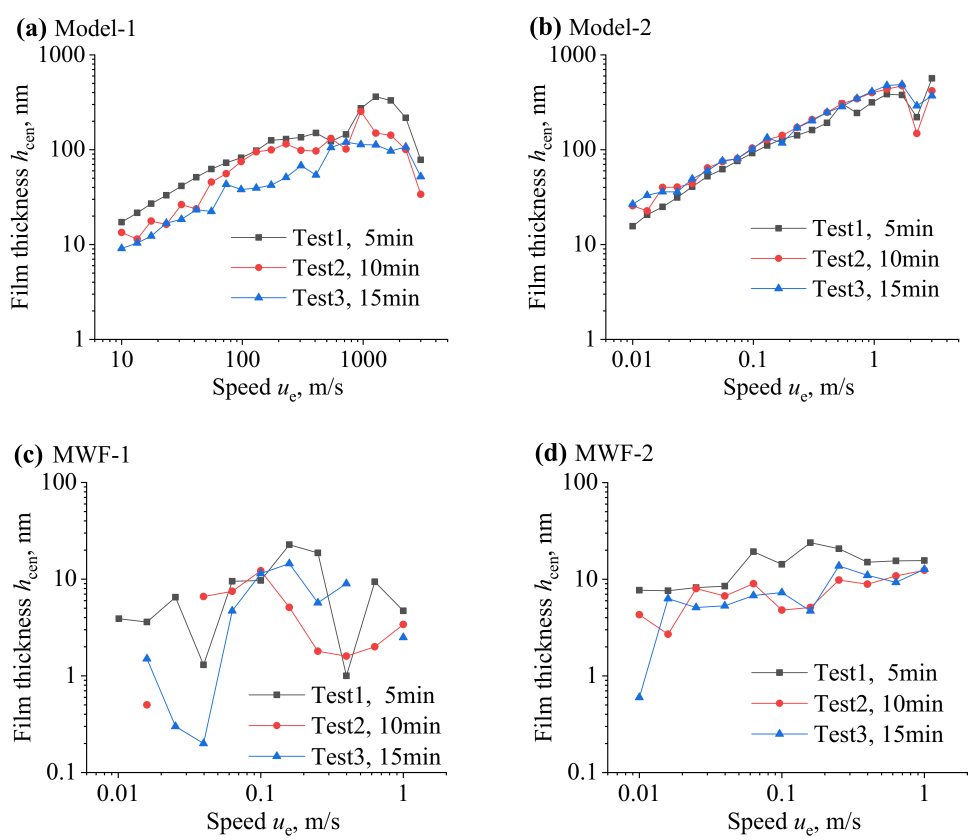


Fig. 12 Film thickness measured at repeated three runs for the four O/W emulsions. There is no significant time-dependent film variation or boundary film build-up. **a** Model-1, **b** Model-2, **c** MWF-1, **d** MWF-2. (Each run is performed from low to high speed and takes 5 min; note that the maximum y-axis scale is different for Model fluids and MWFs)

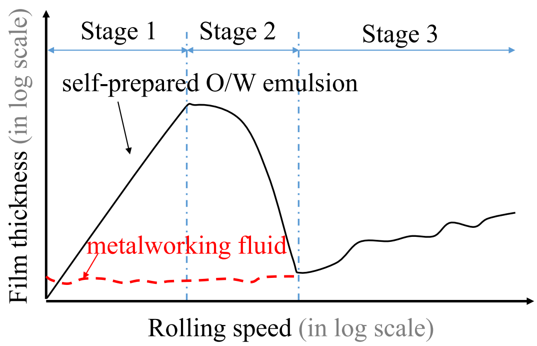


Fig. 13 Comparison of the lubricating film-forming behavior of MWFs and self-prepared O/W emulsions. MWFs: boundary lubrication below the 2nd critical speed; self-prepared emulsions: three-stage (elasto-)hydrodynamic lubrication

test rigs with different optical interferometry methods. These four fluids are all O/W emulsions at 10 Vol%. The measured film thickness on the two test rigs agrees well with each other showing that the film-forming behavior of MWFs is quite different from that of self-prepared emulsions. The lubrication mechanisms of the two commercial MWFs and the self-prepared O/W emulsions have been discussed based on the two assumptions in Sec. 3.2. The main conclusions are as follows:

1. For the two commercial MWFs used in this study, the measured central film thickness is always lower than 20 nm over the whole range of speeds (1 m/s maximum). No (elasto-)hydrodynamic lubrication film can be formed. This is explained by the strong cleaning or re-emulsification effects of the commercial MWFs (cutting fluids). The lubrication mechanism of MWFs can be regarded as boundary lubrication rather than hydrodynamic full-film lubrication.
2. For the two self-prepared model emulsions, the film-forming behavior is similar to that has been widely reported in the literature, i.e., the speed-dependent three-stage (elasto-)hydrodynamic film behavior shown in Figs. 1 and 12. This suggested that the oil droplets are easier to adhere onto the solid surface and thus be brought into the contact zone to form an EHL film in the self-prepared emulsions. This might be related to the short-term stable nature of them. However, the relation between emulsion stability (or droplet size) and film-forming ability is still an open question.
3. It can be learnt that the self-prepared short-term stable emulsions would fail to represent the lubrication characteristics of MWFs in highly loaded contacts. If the target is to study the lubrication properties of MWFs such as in metal cutting, long-term stable cutting fluids should be used rather than self-prepared simple emulsions.
4. Through the single droplet and re-lubrication experiments, direct experimental evidence has been given to show the evidence of re-emulsification effects in emulsion lubrication.

The lubrication mechanisms of emulsions are complex and can be influenced by many factors, e.g., the type and concentration of emulsifiers, the interfacial physic-chemical action between solid surfaces and components in the emulsion. The influence of these parameters on lubrication should be further studied. The boundary friction properties of MWFs and model emulsions shall be characterized at sliding conditions.

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Data Availability The data that support the findings of this manuscript are available from the corresponding author upon request.

Declarations

Conflict of interest There are no conflicts to declare.

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