Experimental study of free surface grease flow subjected to centrifugal forces

J. X. Li1*, L. G. Westerberg2, E. Höglund1, P. Baart3, P. M. Lugt3

1 Division of Machine Elements, Luleå University of Technology, SE-971 87 Luleå, Sweden
2 Division of Fluid and Experimental Mechanics, Luleå University of Technology, SE-971 87 Luleå, Sweden
3 SKF Engineering and Research Centre, Nieuwegein, The Netherlands

Abstract

In order to improve the understanding of grease flow in various applications such as gears, seals and rolling bearings, the free surface flow of different greases under different running conditions has been investigated. A rotating disc has been used to study grease flow as the grease was subjected to a centrifugal force. The grease flow and mass loss was measured for greases with different rheology on different surfaces and with surface textures. It is shown that the speed at which grease starts to move is mostly determined by grease type and yield stress, while the impact of the surface material and roughness is less pronounced. The mass loss is shown to be influenced both by the rheology of the grease and the surface material.

Key words: grease surface flow; rheology; adhesion

*Corresponding author: Jinxia Li (Jinxia.li@ltu.se).

1. INTRODUCTION

Lubrication plays an important role on the life time, energy losses, and maintenance of many mechanical systems. Due to its consistency, lubricating grease has many advantages compared to lubricating oil [1-3], e.g., it does not require pumps, filters, sumps etc., it has inherent sealing properties, and does not leak out into the environment. Limited life due to e.g. oxidation at high temperature is the main drawback of using grease, however, in many applications this can be overcome by re-lubrication [2]. The lubricating film thickness between the contacting surfaces is very small in machine elements like rolling bearings and gears. Excess lubricant is pushed away from the contact, sometimes leading to starvation. Proper replenishment of lubricant is then critical in order to provide enough lubrication before the parts engage again. In the case of oil lubrication, replenishment is normally no problem since the oil will easily flow back into the track. Grease, which exhibits viscoelastic properties, will not flow until a stress larger than the yield stress is obtained, meaning that a certain force has to be applied in order for the grease to start moving [4-14].

The excess grease often sticks to different parts like the bearing housing, seals and bearing cage; oil separation (often called ’bleeding’) will provide the contacts with lubricant. However, a forced flow or free surface flow of the grease itself caused by e.g., vibrations, and centrifugal forces may support the replenishment.

Two lubrication regimes are presented in grease lubrication [5]. A fully flooded regime appears when lubricant (being the grease itself, and/or bled oil) is continuously pushed back to the lubricating contact [6-7]. Here the film thickness is often higher than that provided by base oil only. After the initial churning phase, most of grease is pushed aside by the rolling contact, meaning that the lubrication regime may turn into a starved regime with a continuous decrease in film thickness as a consequence [8]. The film thickness is also much related to the worked grease near the track acting as a lubricant reservoir [9-10]. Chevalier, et al. [11] showed that the shape and thickness of the lubricant layer in the inlet significantly influences the film thickness in heavily starved contacts. In rolling bearings, such as in tapered or spherical bearings, centrifugal forces affect the layer thickness, especially during long term running [12-14]. In terms of different types of grease flow, a pressure driven Poiseuille grease flow has been experimentally and analytically investigated in straight pipes/channels [15, 16] and in pipes/channels with different restrictions [17-19]. Examples of studies on grease shear flow in concentric cylinder geometry can be found in refs. [20, 21]. The latter are related to the flow in bearings or seals. Models of free surface grease flow are scarcely represented in the literature. Free surface
oil flow in bearings can be found in refs. [12-15]; however, these models are only applicable for Newtonian fluids and cannot be used for fluids with complex rheology such as grease. Lubricating greases are semi-fluid to solid products of a thickener in a liquid lubricant [22]; this multi-phase system gives grease a non-Newtonian rheology, which directly contributes to the complex flow behavior of grease. The material and the surface roughness also influence the grease flow when wall slip occurs.

Bramhall and Hutton [23] pointed out that wall slip is due to the displacement of matrix fiber aggregates, which means that the matrix concentration increases gradually from a low value at the wall to that of the bulk grease within the slip layer. Czarny [24] argued that there exists a condensed layer of matrix thickener at the wall due to the interactions between the particles of the grease thickener and a depleted thickener layer near the wall with low viscosity. Czarny also concludes that wall slip depends on the wall material and thickener type.

In this paper, free surface grease flow driven by a centrifugal force is experimentally investigated using a rotating disc. A high speed camera was used to capture the onset of the grease motion. Of specific interest is the yield behavior of the grease in terms of the required angular velocity to initiate the grease motion, the amount of grease leaving the disc, and the grease layer remaining on the disc. The experiments were conducted using greases with different rheology, different material surfaces and surface textures.

### 2. EXPERIMENTAL SET UP

#### 2.1 Greases

Two lithium greases with different consistency (NLGI Grade 2 and Grade 1) and a polyurea grease (PU, NLGI grade 2) have been considered. To describe their rheology, the Herschel-Bulkley rheological model [25, 26] is considered, including the yield stress- and shear thinning properties of the grease:

\[
\tau = \tau_0 + K \left( \frac{du}{dy} \right)^n. \tag{1}
\]

Here \(\tau\) is the shear stress, \(\tau_0\) the yield stress, \(K\) the consistency parameter of the grease, and \(n\) the Power Law exponent – which for a shear thinning material like grease is less than one. The rheological data for the greases is presented in Table 1.

#### 2.2 Test rig

The experiments have been carried out on a rotational steel disc with a diameter of 100 mm. On the disc four plates were mounted symmetrically, see Figure 1. A puck of grease was centered on each plate 27.5 mm away from the disc center. To prepare the samples, two PTFE rings with a diameter of 5 mm and height of 1 and 2 mm high, respectively, were put on the plate; see Figure 2. A syringe was used to fill grease into the ring carefully avoiding air bubbles. The upper surface of the puck was made smoothened using the upper surface of the ring (1 or 2 mm high), using a plastic rod. The ring was gently removed before the test. The setup allows for four grease samples to be run simultaneously.

Three different plate materials have been selected: bearing steel, brass and Polyamide 66 (PA 66). These materials are often used as ring and cage material in rolling bearings. The Ra values are 1.2 µm, 0.1 µm and 0.5 µm for the steel, brass and Polyamide respectively. In the test, the angular velocity of the disc was controlled by accelerating it with \(\pi/3 \text{ s}^{-2}\) to a maximum speed, which was 120% of the critical speed, being defined as the rotational speed of the disc when the grease sample starts to move (Figure 3b). The disc was kept at the maximum speed for 10 seconds and then ramped down to stand still during 1 minute. The motion of the grease has been recorded by a high speed camera from IDT Redlake and image acquisition was performed with the Motion Studio software. The evolution of the grease track as the rotation continued is shown in Figure 3.

### Table 1 Rheological parameters for the greases based on the Herschel-Bulkley rheological model and base oil viscosity for 3 greases.

<table>
<thead>
<tr>
<th>Grease</th>
<th>(\tau_0) [Pa]</th>
<th>(K) [Pa·s^n]</th>
<th>(n) [-]</th>
<th>Viscosity at 25°C [Pa·s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLGI 1</td>
<td>180</td>
<td>5.7</td>
<td>0.75</td>
<td>0.49</td>
</tr>
<tr>
<td>NLGI 2</td>
<td>500</td>
<td>8</td>
<td>0.7</td>
<td>0.25</td>
</tr>
<tr>
<td>PU</td>
<td>800</td>
<td>0.75</td>
<td>0.88</td>
<td>0.15</td>
</tr>
</tbody>
</table>

---

Figure 1. Overview of the test rig for the free surface experiments.
2.3 Measuring the layer thickness using Scanning Electron Microscopy (SEM)

The grease layer composition, forming the trace on the plate, was measured using an environmental (low-vacuum) scanning electron microscopy (SEM) with an accelerating voltage of 15kV and probe current of 10⁻⁶A. The Energy Dispersive Spectrum (EDS) was used to qualitatively determine the oxygen content in the surface track at different depth below the surface (1-2 µm and 3-4 µm). The SEM equipment used was a Jeol JSM-6460LV microscope fitted with Oxford Inca EDS software.

3. RESULTS AND DISCUSSIONS

This part will present results for the critical speed, grease loss, and grease film left on the plate for different combination of the three greases and solid surface material. Every test comprises four grease samples; the average value and confidence interval are presented for critical speed and grease loss. Furthermore, SEM pictures for the NLGI 2 grease are presented and discussed.

3.1 Critical speed for greases

Figure 4 presents the critical speed for the three greases on respective surface materials for both the 2 mm samples (Figure 4a) and the 1 mm samples (Figure 4b); and here the two cases represent the initial height of the grease cylinder (puck). It was found that critical speeds were not varying significantly with the different surface materials for NLGI 1- and NLGI 2 greases. This result is likely due to an adhesion force between grease and plate exceeding the yield stress. This means that the grease is sheared at a certain distance into the bulk of the grease, rather than at the contact between the grease and the surface. It follows that the critical speed for the PU grease is higher than for the NLGI 1- and NLGI 2 greases, which in turn is a consequence of its higher yield stress value; see Table 1. Unlike the behavior of the NLGI 1- and NLGI 2 greases, the critical speed for the PU grease is different depending on the surface material: For the 1 mm samples it is shown that the steel plate with highest roughness gives the highest critical speed, while brass with the lowest roughness gives the lowest critical speed. For the 2 mm samples it follows that the highest critical speed is needed for the steel plate with no significant difference between brass and PA. This indicates that the adhesion between the PU grease and the plates influences the critical speed, especially for 1 mm samples, even though the yield stress is the dominating factor. An explanation for this observation is that for the 1 mm sample, the grease is sheared so close to the solid surface that the adhesive forces to some extent add to the yield forces needed to shear the grease. For the 2 mm sample the grease is sheared at a distance from the solid surface exceeding the influence of the adhesive forces at the solid/grease surface. The influence of the adhesive forces on the 1 mm sample is also supported by the observation that for all three greases used the critical speed for the 1 mm samples is about 1.5 times higher the critical speed for the 2 mm samples.
The relationship between the yield stress presented in Table 1 and the critical speed on the steel plate for the three greases is shown in Figure 5. The critical speed increases as the yield stress increases for the three greases tested in this study. This phenomenon may be explained by the visco-elastic properties of greases: the grease starts to flow as the centrifugal force exceeds the grease yield stress which determines the critical speed.

The grease loss is defined as the mass percentage of grease leaving the plate compared to the initial grease sample mass. The grease loss for the three greases and the three surface materials is shown in Figure 6. For the 2 mm samples (Figure 6a) it follows that the general trend for the presented mean values is an increasing grease loss with an increasing yield stress value; cf. Table 1. The results for the 1 mm samples (Figure 6b) also clearly show that the grease loss is higher for the PU grease. The impact of the surface roughness on the grease loss is less pronounced. Figure 6 indicates that the roughest surface (steel) tend to decrease the grease loss from the disc. An explanation for this is that on the rougher surface more grease will adhere to the plate. As presented in §3.1 the PU grease has the highest critical speed, which combined with the observed grease loss concludes that it has the most prominent yield behavior which also is supported by the measured rheological data (Table 1). The larger grease loss for the PU grease indicates that the viscous layer remaining on the plate is thinner, which also couples to the yield stress of the grease. The PU grease with the high yield stress only starts to flow at a high critical speed. This implies that the centrifugal forces at that moment are much higher than for the greases with lower yield stress and consequently more grease flows off the disc. At low centrifugal forces (low critical speed) the grease is smeared on the disk surface, while at higher centrifugal forces (high critical speed) the grease moves as a plug.

The thickness of the remaining layer on the plate has also been measured using an optical microscope. It was shown that for the NLGI 2 grease the thickness is around 130-170 µm for the 2 mm samples and 75-110 µm for the 1 mm samples. For the NLGI 1 grease the corresponding values are 140-160 µm and 60-80 µm for the 2 mm and 1 mm samples respectively. The thickness of the layer for the PU grease was not possible to measure with the present technique as the layer profile is highly irregular and the layer seem to locally disintegrate. This behavior may be due to the high yield stress causing the sample to more or less solely behave as a solid and just locally shear in connection to the solid surface. The observation can also be explained by a the yield stress force which is of the same order of magnitude as the adhesive forces between the sample and the solid surface, resulting in a negligible deformation of the grease sample.

Concluding the observations presented in this section: if the yield shear force needed to shear the grease is
lower than the adhesive forces (i.e. $F_S < F_A$) in the contact between the grease sample and the disk surface, the grease sample will shear and flow off the disk with a thick layer remaining, called free surface flow. And if $F_S > F_A$ the grease bulk will not shear, only in a thin viscous layer close to the solid surface, and the grease sample (puck) will move on top of this thin layer.

![Image](image.png)

**Figure 6.** Grease loss for three greases. (a) 2 mm initial height of the sample, and (b) 1 mm. The error bars represent the 90% Confidence Intervals.

### 3.4 SEM pictures and EDS on grease left on the steel plate

In order to investigate the grease left on the plate, SEM and EDS have been used to analyze the grease-air surface layer microstructure. The NLGI 2 grease sample with an initial height of 2 mm was selected to be investigated Visual observations of the grease layer indicated that there is an oil layer on the surface. This is confirmed by the EDS measurements. In Table 2, EDS results show a lower oxygen content close to the grease surface compared to 3-4 micrometer below the surface. Since the mineral base oil molecules for the NLGI 2 grease contains less oxygen compared to the lithium 12-hydroxy stearate thickener molecules it is concluded that there is a higher concentration of oil in the top layer of the surface, thus a lower thickener concentration. A similar gradient in the thickener concentration is expected to be present at the grease-disk interface, resulting in a slip layer. This is in line with the results of Bramhall and Hutton [23].

![Image](image.png)

**Table 2** Concentration of elements in the grease left on the steel plate [Atomic %]

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>O</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2µm below surface</td>
<td>96.83</td>
<td>2.74</td>
<td>0.02</td>
<td>0.12</td>
<td>0.29</td>
<td>-</td>
</tr>
<tr>
<td>3-4µm below surface</td>
<td>91.82</td>
<td>7.79</td>
<td>0.03</td>
<td>0.10</td>
<td>0.23</td>
<td>0.04</td>
</tr>
</tbody>
</table>

### 4. SUMMARY AND CONCLUSIONS

In this paper the free surface flow of lubricating grease on plates of different materials, placed on a rotating disc, has been investigated using high speed photography to monitor the motion of the grease. In addition measurements with optical microscope, scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) were done to analyze the grease layer left on the plates. Three different greases have been used: two lithium based greases with NLGI grade 1 and 2 respectively, and a polyurea based grease (PU). The experimental setup comprises grease samples placed on a circular disc which were subjected to an increasing angular velocity, i.e. increasing centrifugal force. The speed at which the grease started to move (the critical speed) and the amount of grease remaining on the plate were measured. It has been concluded that the critical speed and amount of grease left on the plates, including the thickness of the remaining layer on the plates, is closely related to the yield stress of the grease: higher yield stress results in higher critical speed. This results in a thinner grease layer left on the plate. Furthermore, it is shown that the surface roughness has less impact on the grease loss than the yield stress. The tendency is that the grease loss is smallest for the roughest surface. From this it can be concluded that the surface roughness, and the adhesive forces between the grease and the disc, have limited effect on the grease flow. It is mainly the rheological properties of the grease which determine the grease surface flow on the disc.

### 5. ACKNOWLEDGEMENTS

This work is funded by the Swedish Research Council (VR). We would like to thank Mr. A.J.C. de Vries, Director SKF Group Product Development for his permission to publish this paper.
6. REFERENCES:


21. J. X. Li, L. G. Westerberg, E. Höglund, P. M. Lugt, P. Baart, Lubricating grease shear flow and boundary layers in a concentric cylinder configuration, to be Submitted


