Extended stribeck curves for food samples

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Abstract: Striebeck curves have long been used for understanding the lubricating behaviour of oils and greases, and in the recent years for applications ranging from ball point inks to synovial fluids. In the current work, an attempt is made to show to what one can read from Striebeck curves of food samples such as chocolate spread, sauce etc. Additionally, the effect of saliva – human and artificial – on the frictional behaviour has also been studied. The tests were carried out on an MCR Tribometer with a ball-on-three-pin configuration. Polydimethylsiloxane and glass were used to simulate soft contact conditions that exist in the human mouth. Results from the tribological tests are plotted in the form of extended Striebeck curves, wherein, the friction coefficient is plotted as a function of rotational speed. Since the tribometer is capable of speeds as low as a few nanometres per second, it is also possible to observe the build-up of static friction and its transition into the kinetic regime of friction. Results indicate that certain aspects of the Striebeck curve can offer an insight into the correlation between the frictional behaviour of food to their sensory feel.

1 Introduction

Streibek curves have for long been used to understand the tribological behaviour of engine and machine components and over the past few decades or so, there has been an increasing trend in applying them to gain insights into the tribological aspects of food and beverages [1, 2]. Food oral processing can be divided into the following six key steps [3]: first bite, comminution, granulation, bolus formation and processing, swallowing, and effects occurring due to the residues left on the tongue and the palate after swallowing. While texture analysis can be considered as a suitable measurement method to simulate the biting process, rheological tests offer information relevant for swallowing [4]. The step in focus here is when the tongue is pressed against the palate and moves relatively to it. During this process, the perceived mouthfeel is partially generated by mechano-receptors which are capable of detecting changes in the mouth [5]. Food mixed with saliva, which is known as a bolus, is akin to a lubricant between the tongue-palate tribopair. The properties of the bolus cannot be described in a straightforward manner since complex interactions between the saliva and the food structure take place yielding specific physical and microstructural characteristics of the bolus [6, 7]. Dispersion systems such as emulsions [8] or suspensions [9] need to be addressed even more carefully.

A schematic of the tribosystem consisting of tongue, bolus, and palate is shown in Fig. 1. As the tongue is pressed against the palate, with or without the presence of a bolus, the contact experiences contact pressures in the range of 3–27 kPa [10–12]. During food intake, the tongue moves relatively to the palate with speeds reaching up to 60 mm/s [10]. Findings from tribological tests such as extended Striebeck curves could be used to assess mouthfeel attributes of food [2, 4], for instance, for quality control or food design [13–16].

The current study presents a test methodology to obtain extended Striebeck curves for food samples. Additionally, this report also deals with the effect of additional components such as saliva and artificial saliva on the test results.

1.1 Extended stribeck curve

Simplified Striebeck curves depict coefficient of friction as a function of sliding speed, as seen in Fig. 2. These curves are usually divided into three lubrication or friction regimes – boundary, mixed, and hydrodynamic – depending upon the thickness of the lubricant film between the interacting surfaces. In the boundary regime, which occurs at low speeds, the lubricant film is not thick enough to separate the interacting surfaces, resulting in contact between the surface asperities, ergo the high-frictional resistance. In the mixed friction regime, the lubricant film is just enough thick to separate the surfaces and avoid asperity contact. In the hydrodynamic friction regime, the high relative velocity, there is enough lubricant entrained into the contact creating a hydrodynamic lift whereby the surfaces are well separated from each other.

The current study deals with the scenario wherein the Striebeck curve is extended into the static friction regime, as shown in Fig. 3, and therefore termed as extended Striebeck curve. These curves facilitate in visualising the frictional behaviour of the tribosystem as it transits from the static to kinetic state of motion. The value of friction factor in the static regime in Fig. 3, prior to the onset of macroscopic motion, only represents the frictional resistance offered by the contact to reach the set sliding velocity. In the static regime, the sliding velocity is a result of deformation – elastic and plastic – occurring predominantly at the contact.

1.2 Static and limiting friction

In simple terms, static friction is the friction experienced between two surfaces when there is no macroscopic relative motion between them, despite a force acting to that effect. Limiting friction is the peak of static friction, corresponding to the point of transition with the onset of macroscopic relative motion. However, the term static friction (µs) is very often used to denote what is actually the value of limiting friction.
2 Test methodology

Tribological tests were carried out on an MCR Tribometer (MCR 502, Anton Paar, Austria), with a ball-on-three-pin test configuration, see Fig. 4. Here the ball is fixed to the rotating shaft, which when lowered, comes in contact with the pins fixed in the sample holder. This holder is fixed on to a Peltier-based temperature control unit, which is equipped with a spring mechanism which allows for a certain degree of free movement in all three directions. This facilitates self-alignment of the pins with the ball, and it also damps unwanted vibrations during the test [17].

2.1 Specimen and samples

A set of specimens for each test comprises of one soda-lime glass ball and three polydimethylsiloxane (PDMS) pins. The PDMS specimens are made of a base and a curing agent (Sylgard 184, Dow Corning) mixed in 8:1 ratio. This mixing ratio has been found to be the most suitable for tribological applications on the MCR Tribometer setup [18]. For curing, the PDMS is placed in an oven at 70°C for 1 h. The glass and PDMS specimen are wiped with a tissue soaked in acetone before starting the measurements. The glass ball measures 12.7 mm in diameter and has an average surface roughness ($R_a$) of 0.5 µm. The PDMS pins are cylindrical in form measuring 6 mm in both height and diameter. The test surface of the PDMS pins has an average surface roughness ($R_a$) of 0.4 µm. Food samples tested here include a chocolate spread and cheese sauce. This study also presents a comparison between the frictional behaviour of water, saliva, and artificial saliva. The amount of sample used for each test is between 2 and 3 ml.

2.2 Test profile

The Stribeck tests carried out during the current investigations comprise of three steps. In the first step, the measuring shaft is lowered until the ball comes into contact with the pins. The maximum load reached during this phase is restricted to 0.5 N to avoid shock loading or sudden impact on the surfaces. In the second step, the load is gradually increased until the normal force reaches the predetermined value of 1 N. The system is then held at the test load for 5 min. The stresses produced at the contact by the applied load are partially relaxed during this step. In the third step, the sliding speed is increased logarithmically from $10^{-5}$ to 1 m/s. Depending upon the sample, some tests were limited to lower sliding speeds. The second and third steps are repeated three times during each test without changing the sample and without breaking contact between the ball and the pins. In the first run, the running-in characteristics of the system are observed. Herein, the mating surfaces conform to each other to the extent possible either by plastic deformation, or wear, or both. During the second and third runs, the friction behaviour of the systems depends on the extent of running-in during the first run, and also on the formation of reaction films on the mating surfaces and structural changes within the sample.

3 Results and discussion

Fig. 5 shows the frictional resistance of a chocolate spread as a function of sliding velocity, along with the vertical displacement. Changes at the contact such as the thickness of the sample layer between the ball and the pins, elastic deformation of the pins themselves etc., can lead to changes in the position of the measuring shaft in order to maintain the set normal force, and this is depicted here as vertical displacement. The values of vertical displacement presented in Fig. 5 are normalised and do not indicate the actual thickness of the chocolate layer at the contact.
In Fig. 5, at low speeds, there is a gradual increase in the frictional resistance of the system with increasing sliding velocity. The value of friction coefficient up until the breakaway point only indicates the amount of resistance offered by the contact to reach the set sliding velocity. In principle, up until the breakaway point, there is no macroscopic motion at the contact, and in this static regime, the velocity depicted is contributed by the elastic deformation of the system including the PDMS pins, and the chocolate spread itself. Around the breakaway point, we also notice a steep drop in the vertical displacement, indicating that the measuring shaft is moving downwards. This movement is induced by the displacement of chocolate from the contact. As the layer gets thinner and the shear rate increases with increasing speed, there is lesser frictional resistance, and hence the downward trend in the frictional resistance at around \(5 \times 10^{-5}\) m/s. The sudden increase and fall of friction coefficient close to 0.001 m/s are due to the stick-slip events, and the increase in both the frictional resistance and the vertical displacement at high speeds indicates the transition into the hydrodynamic regime. These individual observations can help in building a profile of the sample and the system. One could also take it a step forward to compare a given set of samples and obtain a correlation between their tribological behaviour and sensory attributes.

### 3.1 Effect of running-in

During the first run, the surfaces of the specimen, especially those of the PDMS pins, are subjected to a running-in process wherein the surface asperities even out to the extent possible. This is achieved either by wear of material(s) or through plastic deformation. At times, this process might take longer and therefore, each sample is subjected to at least three runs during a test.

Fig. 6 depicts the first run from three repetitions from tests with a cheese sauce sample. These three repetitions vary significantly and do not show signs of reproducibility in the medium speed range. The lack of reproducibility during the first run is not given, and it strongly depends on the physical and rheological characteristics of the sample such as its viscosity, composition, homogeneity, presence of particles etc. The second and third runs from the tests presented in Fig. 6 are plotted in Fig. 7. All six curves in this figure show a high degree of reproducibility.

### 3.2 Effect of saliva

Saliva is an inseparable component of food oral processing and plays an important role in not just the chemical breakdown of food components, but also acts as a natural lubricant in the oral cavity [19]. Therefore, when modelling a test to mimic interactions taking place during food oral processing, one should consider saliva as an influencing factor. Since the characteristics of human saliva vary from person to person and also depend on numerous factors such as the time of the day, types of food and beverages consumed, physical activity, medical conditions etc. Tests were carried out with water, saliva, and artificial saliva, which is used as a remedy for dry mouth syndrome. The results are presented in Fig. 8, wherein the frictional resistance of water is the highest amongst the three over the entire speed range. Saliva, on the other hand, offers the least resistance, which is especially significant during the transition from the static to the kinetic regime, and low speed regimes.

To study the effect of saliva on the tribological behaviour of a chocolate sample, 3% w/w of freshly extracted human saliva was
saliva itself is not a standard entity, tests carried out with a chocolate sample itself. This effect, combined with the fact that tends to mask the individual frictional characteristics of the sample almost over the entire speed range. While this of human saliva significantly decreased the frictional resistance of the sample almost over the entire speed range. While this decrease is expected, based on the results presented in Fig. 8, it tends to mask the individual frictional characteristics of the chocolate sample itself. This effect, combined with the fact that saliva itself is not a standard entity, tests carried out with a mixture of sample and saliva did not yield satisfactory results.

4 Conclusion and outlook

This study presents a test methodology that can be applied for characterising the tribological behaviour of food and beverage samples. Extended Strieber curves offer insights into the frictional behaviour of the samples, especially in the extreme low-speed regime. This is important as the speeds experienced in our oral cavity during food oral processing lie below 150 mm/s. Also, sensory attributes such as stickiness can be associated with the breakaway point, wherein the system transits from the static to kinetic state of motion. Although these are not straightforward conclusions, efforts are on to optimise the test parameters for each individual sample set, based on their physical characteristics and rheological properties. With the help of systematic investigations and statistical tools, extended Strieber curves are expected to deliver direct correlations between the frictional behaviour of food samples and mouthfeel-dominated sensory attributes.

5 References

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