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RESEARCH ARTICLE

On the experimental characterization of the fluid volume influence on the friction between rough surfaces

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Abstract: The load-bearing behaviour of lubricated contacts depends primarily on the normal force, the relative velocity, and the geometry. Thus, with the aid of the Stribeck curve, it is usually well possible to characterize whether hydrodynamics, mixed friction, or boundary friction is more likely to be present. The fact that the load regime can also depend on the fluid quantity is obvious, but has hardly been systematically investigated so far. Especially for contacts with microscopic roughness, the defined application of a very small amount of fluid is a very challenging requirement. In this paper, a very fundamental study shows how a pin-on-disc tribometer can be used to achieve the transition from dry friction via mixed friction to predominant hydrodynamics by the amount of supplied fluid. The experiments are carried out on samples filed with different coarseness. In addition, the simultaneous influence of partial filling and normal force as well as relative velocity is also shown. Very good reproducibility has been practically reached over the entire range of the tests. Regarding the quantities for the coefficient of friction (COF), it was concluded that close to full filling, a reduction of the fluid quantity has a similar effect on the COF as the reduction of the velocity. This property goes along with the common theory of starved lubricated systems. Such behaviour was not observed to the same extent for the normal force. In the vicinity of smaller fluid quantities, the COF increases very rapidly with further reduction in fluid quantity, far more disproportionately than that with reduction in velocity. With a deeper understanding of this problem, various practical issues such as idling or the run-up process in bearings can also be studied in a more focused manner.

Keywords: starved lubrication; Stribeck curve; pin-on-disc tribometer; fluid supply; experimental studies

1 Introduction

Friction is an omnipresent phenomenon that can strongly influence the functioning, dynamics, or even stability of machines or their components. Friction can be a desired effect, such as in brakes, clutches, or grinding, or it can be disadvantageous, such as in bearings or joints. In the latter group, friction leads on the one hand to mechanical power losses and thus to a reduction in efficiency; and above all, on the other hand to a considerable reduction in their service life due to abrasive or adhesive wear [1].

To avoid these effects, special coatings [2] or a proper lubricant is used in such systems. A conventional fluidic lubricant ideally separates the bodies from each other, thus reducing solid contacts. From an ecological and economic point of view, it is desirable to keep the amount of lubricant low, as this is often cost-intensive and also pollutes the environment. With this in mind, systems with insufficient lubrication, such as in idling or run-up scenarios, are becoming increasingly important. In these scenarios, there is an undersupply of the lubricating gap, which is consequently not completely filled with the fluid. This condition is not necessarily undesirable; however, because under certain conditions, it can be at least as

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effective as a condition under full filling [3]. So there are different examples of applications in the field of starved lubrication, such as thrust bearings [4], piston ring contact [5], and ball bearings [6].

There are also practical examples for technical systems that are designed to run under dry conditions but are wetted by a fluid. Such an example is a car brake that is slightly wetted with water due to rain. Experiences and measurements suggest that the coefficient of friction (COF) of this system is greatly altered by small amounts of fluid. The fluid is likely to be displaced or evaporated from the contact area during braking, but the initial response of the brake is significantly affected by the water volume on the disc.

Conventional characterizations of the friction regime are usually carried out via the (Neo-)Stribeck curve. Here, the external load, the relative velocity, and the viscosity of the lubricant define whether the load bearing is governed by a rather dry or boundary lubricated scenario (i.e., exclusively via solid body contacts), under mixed friction (solid and fluid bearing components), or (elasto-)hydrodynamic (exclusively via the fluid) [7].

Figure 1 demonstrates an example of the associated friction properties over the parameter (Viscosity × Velocity / External normal load). The larger this parameter is, the more likely the system is to bear hydrodynamically, while for small values, the system behaves like a dry system. Accordingly, the COF decreases from dry friction towards mixed friction

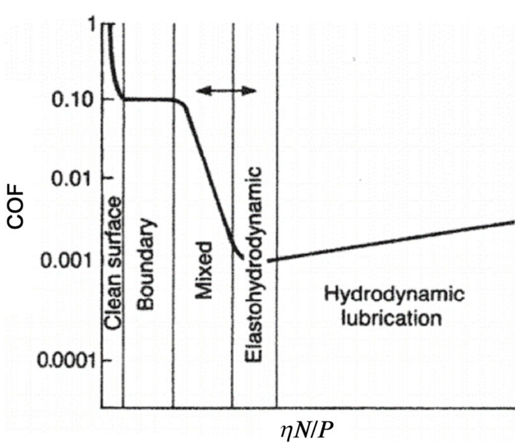


Fig. 1 Characteristic and friction regimes of the Stribeck curve. Reproduced with permission from Ref. [1], © John Wiley & Sons, Ltd 2013.

due to the decrease in solid friction and increase in the hydrodynamic load-bearing component before it increases again due to the viscous flow in the hydrodynamic range. Similar established representations are also used in various applications, such as with the Hersey number (inverse Sommerfeld number) for plain bearings, in which geometric variables such as the bearing clearance are also taken into account [8].

All these characterizations primarily consider load, kinematics, and viscosity, assuming an adequate supply of lubricant. On the other hand, it is obvious that a friction regime can also be determined by the amount of fluid in the gap. Without fluid there is obviously dry friction, and under full filling pure hydrodynamics can arise.

Here, a fundamental investigation of this question in terms of contact mechanics is to be carried out in the context of stochastic rough surfaces. In various numerical studies, it was possible to prove with a specially developed model [9, 10] that not completely filled gaps, i.e., already with an air content of 10%, can show significant differences in the load-bearing behaviour [11, 12]. Thus, for example, the resulting pressure is already significantly (magnitudes of order) lower for the same gap height. In addition, the influence of the filling level on the shear flow factor was also investigated, and it was discussed that this usually neglected effect can be relevant at the transition zone into the cavitation area.

The problem was not only investigated numerically, but also experimentally. Of particular interest, apart from measuring the COF, is the type of fluid transport as a function of the quantity and type of lubricant. Against this background, measurements were carried out in Ref. [13] on a scaled disc–disc test rig (gap heights = 100 μm–1 mm) in order to obtain an observable fluid flow. Here, the Stribeck curve has been detected not only for a variation of the velocity but also for a variation of the fluid quantity. Particularly remarkable in these studies was, on the one hand, the very strong decrease in the friction value for the minimum lubricant volumes (10% of the gap volume) and on the other hand, the type of lubricant transport or its distribution as a function of the friction regime. For example, it was proven that the lubricant collects in "fluid islands" is displaced by the asperites when solid-body friction is more present, whereas "fluid rings" form in this experiment with increasing hydrodynamics [13].

These studies give a good first insight into the mechanisms of partially lubricated contacts, but only allow limited conclusions to be drawn for technical contacts with microscopic roughnesses and correspondingly small gap heights. For this reason, initial feasibility studies with a pin-on-disc tribometer have also been carried out in Ref. [13]. This indicated that these measurements are possible in principle, but are also very challenging for various reasons. It is the core of this paper to start at this point and to present and analyze corresponding systematic experiments.

2 Test rig and measurement procedure

The experiments described in this section are based on the measurement concept of the experiments from Refs. [13] and [14]. The central part of the experimental setup is the high-load tribometer (HLT), which was first introduced in Ref. [15].

The tribometer consists of an extensively modified lathe with a rotating disc and a sample holder. Kinematically, this design corresponds to a classical pin-on-disc tribometer. The disc is driven by a 3-phase 15 kW motor and has a broad speed range of 10–2,000 r/min) due to a built-in gearbox. The normal and tangential forces are measured by a self-developed sample holder, which also contains the loading unit [15]. Figure 2 shows an overview of the tribometer used, with a detailed view of the contact zone and the sample holder.

The pin specimen of the contact is made of tempered Steel C45. For this purpose, a specimen piece is cut out of a flat steel profile of 20 mm × 10 mm and glued to the specimen holder. The bonding is carried out so that the longer side is oriented in the direction of the relative velocity. A commercial passenger car brake disc made of grey cast iron is used as the disc. With this material combination, the brake disc is softer than the pin specimen. Therefore, possible wear rather occurs on the disc. Figure 3(a) shows a side view of the sample.

Before starting the tests, a run-in is carried out to ensure that the sample is in a full and flat contact

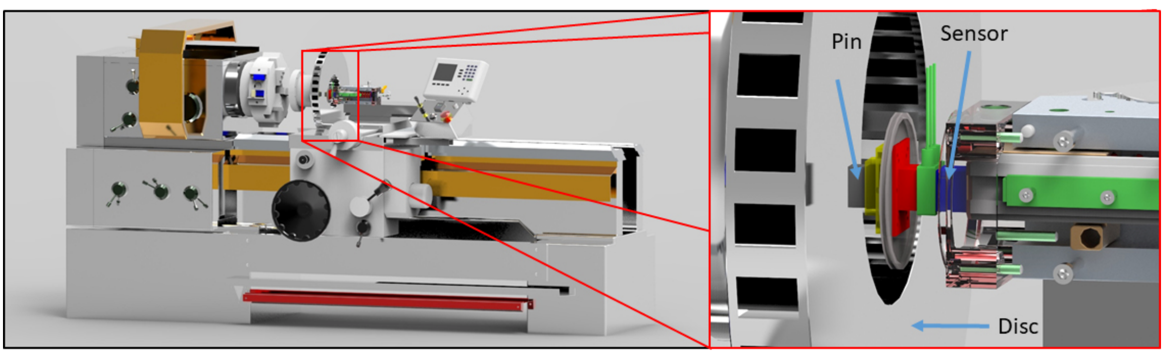


Fig. 2 Scheme of the tribometer used. Reproduced with permission from Ref. [13], © the authors 2018.

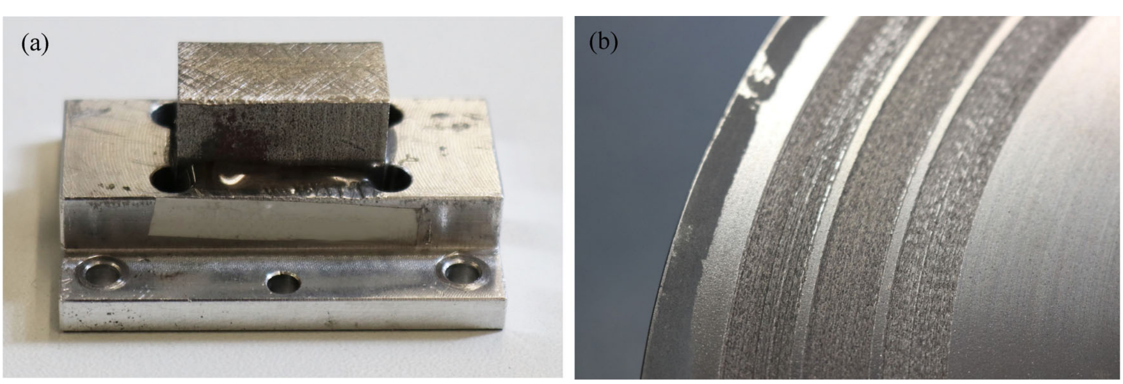


Fig. 3 Contact partners: (a) pin with sample holder and (b) disc with three friction tracks.

with the disc. It is performed at 100 r/min and 100 N normal force. The corresponding friction track has a mean radius of 0.141 m, so this speed corresponds to a sliding speed of approximately 1.48 m/s. It is clearly visible on the specimen which area has already been in contact. This area increases with the number of applications until the entire area is in contact. After about 70 applications (of 10 s each), the sample has been run in in this sense.

After the run-in, the friction surface of the specimen is carefully machined with a file to increase the roughness and gap volume. In the process, two different surface conditions are created. In the case of one sample, the surface is only lightly machined with the file; while on another, the surface is repeatedly filed with a coarse file. In all following explanations, the first method is called "finely filed", and the second method is called "coarsely filed".

Due to wear, a haptically detectable friction track is created on the disc during the run-in. Figure 3(b) shows such three friction tracks belonging to different measurement series: The innermost friction track originates from preliminary tests, the middle one belongs to the finely filed sample, and the outer one can be assigned to the coarsely filed sample.

The coarsely filed sample has a larger gap volume compared to the finely filed sample. As a result, the global filling ratio (as one of the crucial parameter of these studies, it represents the quotient of total fluid volume and total gap volume) of the coarsely filed sample is smaller than that of the finely filed sample at a constant, absolute fluid quantity.

With a larger gap volume, the filling ratio can therefore be varied in finer increments, as the minimum amount of fluid that can be applied cannot become infinitely small for practical reasons. Machining with the file is always carried out as cross grinding in two directions. In this way, two different topographies have been created, tribologically examined, and topographically measured. The variation of the surfaces and the roughness allows for broader conclusions on the influence of the surface topography on the tribological properties of the system.

The selection of the fluid and the variation of the fluid quantity are crucial components of the experiments shown, as the primary objective is to investigate the influence of the fluid quantity and fluid distribution on the friction regime.

In all experiments, food-grade glycerol in 99.5% concentration is used as a fluid. Glycerol typically has a density of 1,260 kg/m^3 and a dynamic viscosity of 1.48 Pa·s (both values at a temperature of 20 °C). The viscosity of the fluid is thus significantly greater than the viscosity of common lubricants, such as conventional engine oil. For the application of these experiments, however, the high viscosity has decisive advantages:

1) The transition between dry friction and hydrodynamic friction can be generated more easily, as the hydrodynamics are achieved at smaller relative velocities.

2) Due to the high viscosity, the fluid also adheres better to the disc and is not thrown off the disc by the rotation.

3) The slow flow also makes the fluid easier to apply.

4) The glycerol is water-soluble. This makes it easier to clean the disc from the glycerol.

The weight of the fluid that is applied to the disc is determined by differential weighing. For this purpose, the reservoir with the fluid and the brush which is applied to the disc with the fluid are placed on a precision balance (Quintix 224-1S, Sartorius). The accuracy of the balance is specified by the manufacturer as 10^{-7} kg. Before application, the total weight is stored. During application, the disc is in rotation via the manual mode (at approximately 4 r/min), and a brush soaked with the lubricant is pressed manually onto the disc. After a certain amount of fluid has been evenly applied to the disc over several complete revolutions of the disc, the brush and the storage container are weighed again. By calculating the difference between the two weights, it can be precisely determined how much fluid has been applied to the disc.

The exact application of a predefined fluid quantity is only possible to a limited extent due to this procedure, but is also not absolutely necessary in terms of the interpretation of the results. The defined parameter variation for the fluid quantity is therefore a target. The deviation of the actually applied fluid quantity from the target quantity is usually in the order of a few percent. The measured data are therefore always shown over the actually applied and measured fluid quantity and not over the target quantity.

Due to the run-in, the friction track on the disc is clearly visible. The brush can therefore be guided precisely on the disc while it slowly rotates as the fluid is applied. The aim is to create an even film on the disc. The resulting fluid film has been analyzed in various preliminary tests. The best results have been achieved by using a fine brush, as this allows the fluid release to be well controlled. Through preliminary tests, it was determined that the smallest amount that can be reliably and evenly applied is 1×10^{-6} kg. As an example, Fig. 4 shows a view of the applied fluid film at a total amount of approx. 2×10^{-4} kg glycerol (that corresponds to a rather large filling ratio) in the friction track. Due to the high viscosity of the glycerol and the moderate rotational speeds in all tests, centrifugal forces do not play a significant role, which is also confirmed in the measurements by the fact that the applied film does not move radially outward during rotation.

The main focus of the parameter variation is on the supplied amount of fluid. The measurement procedure is designed in such a way that dry applications are carried out in addition to the lubricated measurements, where they serve as a reference under solid state friction and should prove that the contact does not change significantly over the different filling ratios and repetitions. The sequence of measurement procedures is summarized in Table 1.

One friction application represents one test run on the disc with the sample. Therein, the normal force is maintained for 10 s. Between the applications, the pin is unloaded, and the disc continues to rotate; and for

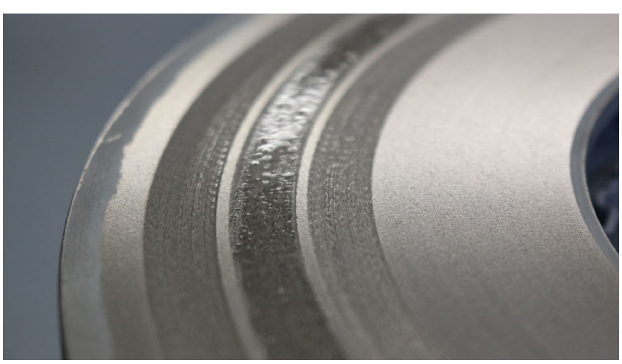


Fig. 4 Fluid film in the middle friction track at approximately 2×10^{-4} kg glycerol.

Table 1 Measurement procedures.

Step	Duration of applications	Number of applications
Filing sample	—	—
Cleaning disc and pin	—	—
Measurement under dry conditions	10	3
Cleaning disc and pin	—	—
Measurement with fluid amount 1	10	3
Cleaning disc and pin	—	—
Measurement with fluid amount 2	10	3
…	…	…
Cleaning disc and pin	—	—
Measurement with fluid amount *n*	10	3
Cleaning disc and pin	—	—
Measurement under dry conditions	10	3

technical reasons (memory processes in the measuring device, etc.), 10–30 s pass before the next application is run. The measurement procedure is repeated three times to examine the repeatability.

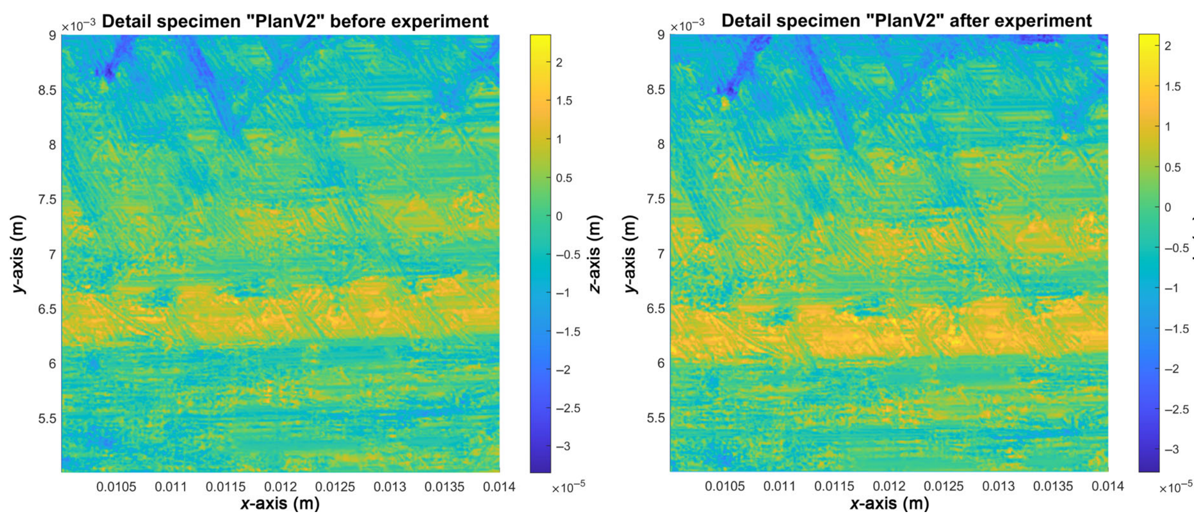
Cleaning is an important part of the chosen measurement procedure. The viscous fluid can only be removed from the friction surfaces with great effort. For this reason, a cleaning procedure was developed that guarantees the greatest possible cleaning result. With each cleaning, both the friction track and the sample are cleaned. As glycerol is well soluble in water, in the first step, the surfaces are cleaned with water that is applied with disposable cloths. Thereafter, the surface is cleaned with acetone, followed by dry cloths that are commercially available disposable paper towels. After these three cleaning steps, the surface is cleaned again with acetone and dry cloths. With the help of this procedure, a repeatable initial condition can be created. Both friction surfaces are practically free of fluids and wear particles after this cleaning procedure. The COFs of dry friction measurements following this cleaning procedure are repeatable at about 0.30 (finely filed) and 0.35 (coarsely filed, see Figs. 10–13 in Section 3).

The tests shown here are primarily intended to highlight the influence of the fluid volume at different loads at a given topography. For this reason, it is essential that the topographies do not change significantly during the load cycles. The relatively short load durations and few applications are designed to ensure that. To verify that this condition is met, exemplary topography images were taken with an optical measurement system before and after an entire procedure (containing approximately 100 applications).

A section of the corresponding pin topographies for the finely filed specimen is shown in Fig. 5. This section is in the area of the contact.

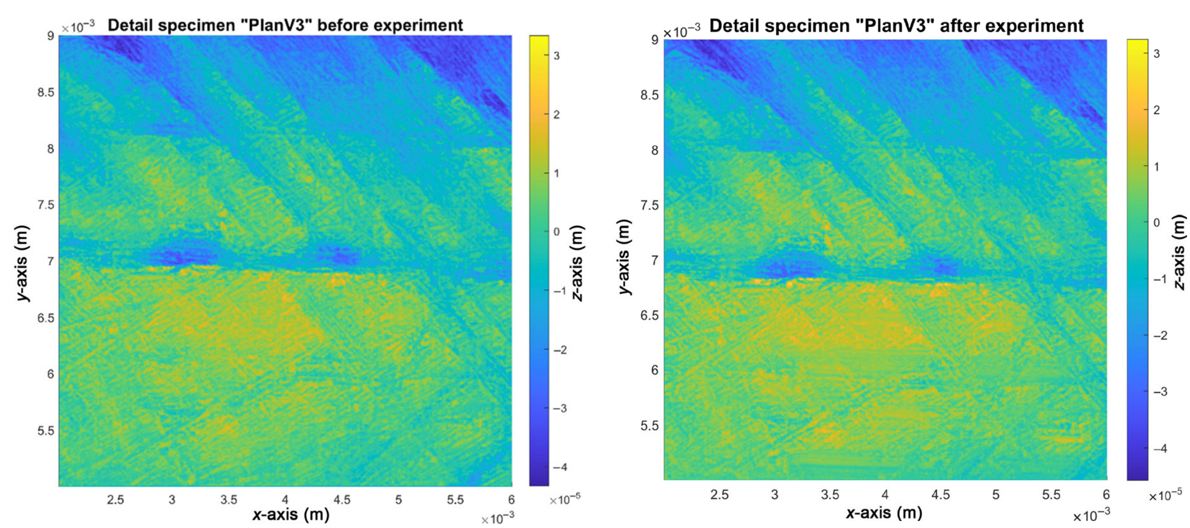
The measured topographies look very similar and have comparable root mean square roughness (S_q) values (the slight increase is most likely due to some aggregations of newly generated particles) so that it can be stated that the pin surface was not significantly changed by the friction measurements, and that the assumption that wear and surface removal are negligible is permissible.

Figure 6 shows the results for the coarsely filed specimen analogous to Fig. 5. Similarly, for the coarsely filed specimen, there is no major difference between the measurement before the test and the measurement after the test. The quantities for the root mean square roughness are also nearly equal. Again, it has been



Before the procedure, $S_q = 5.83 \times 10^{-6}$ m   After the procedure, $S_q = 6.47 \times 10^{-6}$ m

Fig. 5 Sections of the topographies of the finely filed specimen before and after the procedure.



Before the procedure, $S_q = 1.02 \times 10^{-5}$ m   After the procedure, $S_q = 1.09 \times 10^{-5}$ m

Fig. 6 Sections of the topographies of the coarsely filed pin before and after the procedure.

visually ensured that the considered section is in the area of contact with the disc.

In order to obtain a complete overview of the contact geometry, not only the pins but also the disc is examined. Since the disc was too large and too heavy for the pins' measurement system, a different device is used. So, the surface was measured optically with a sensor (MLAS201 3D, Wenglor). Figure 7 illustrates the section of the disc's friction tracks associated with the finely filed pin Fig. 7(a) and the coarsely filed pin Fig. 7(b) as the counterpart. Since the disc circumference is a multiple of the specimen length of 2 cm, it can be assumed that the disc is also rarely subject to wear, and thus topography changes during the friction tests are assumed to be negligible.

From the measured topographies of pin and disc, it is possible to roughly estimate how large the total gap volume is in the contact and total fluid quantity this corresponds to under the assumption of a homogeneous fluid distribution on the friction track. This estimate is not intended to provide a precise indication of the global degree of filling for a defined quantity of fluid added, but rather an approximate classification of the range of the fluid quantity for the transition from empty gap to full gap.

For the system with the finely filed pin, this volume amount $V_{\text{track,fine}} = 0.293 \times 10^{-6}\,\text{m}^3$, corresponding with ($\rho_{\text{Glyc}} = 1{,}260\ \text{kg/m}^3$) the mass $m_{\text{track,fine}} = 3.69 \times 10^{-4}\,\text{kg}$; and for the coarsely filed system, $V_{\text{track,coarse}} = 0.385 \times 10^{-6}\,\text{m}^3$, and $m_{\text{track,coarse}} = 4.85 \times 10^{-4}\,\text{kg}$, respectively.

Confirmation of this estimate is provided by the observation that for fluid quantities above this maximum quantity, a small drop of fluid forms on the friction sample, which does not drip off. This is exemplarily shown in Fig. 8, where the drop formation on the finely filed pin for an applied fluid mass of 0.4×10^{-3} kg is visible.

This is also an indication that there is the maximum amount of fluid that can be transported into the gap and be held by the friction contact.

During the procedure, the normal force (F_{N}) and tangential force (F_{T}) is measured by the piezoelectric force sensor (Type 9215, Kistler, Germany; that is located right behind the pin [15]) and recorded with a sampling rate of 1,000 Hz.

The corresponding COF (μ) is calculated at any sampling according to

$$\mu = F_{\text{T}} / F_{\text{N}}$$

In order to compare the COFs between different variations, they are averaged over time. Figure 9 illustrates this procedure and shows the COF vs. time for two different fluid quantities. In each case, one application (friction time = 10 s) is shown.

The COF is plotted for the period, in which at least 90% of the set normal force is achieved. In most cases, the course of the COF is uniform, as shown in

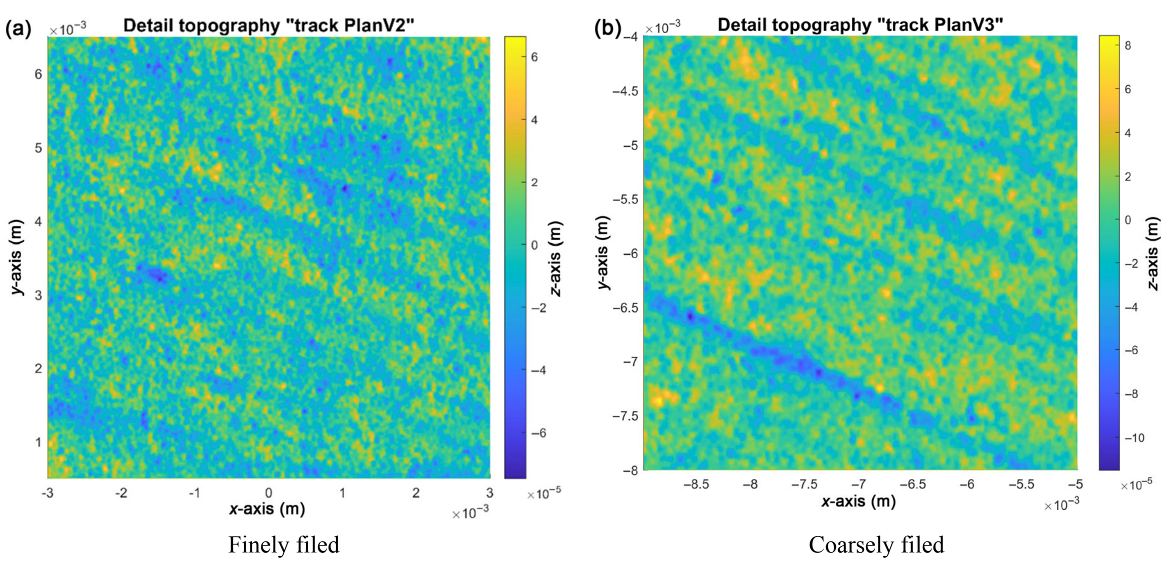


Fig. 7 Section of the topography of the disc friction tracks for (a) finely filed and (b) coarsely filed pin counterparts.

Fig. 8 Close-up of drop formation on the finely filed pin.

Fig. 9(b). Less frequently, applications occur in which it is less uniform, as shown in Fig. 9(a). For all applications, therefore, only the first revolution is evaluated, starting 0.2 s after 90% of the set normal force has been reached. This procedure is illustrated in Fig. 9(b). One revolution takes place between the two red marks, and the average value is calculated in this area that is then used in Figs. 10–15 in Section 3.

3 Results

Studies on the fluid quantity variation on the finely filed and coarsely filed specimen are presented below. This is followed by a study of the influence of normal force and relative velocity on the system with the finely filed specimen.

3.1 Fluid quantity variation for the system with the finely filed pin

All studies in Sections 3.1 and 3.2 have been performed with a revolutionary speed of n = 50 r/min and a normal force of F_N = 50 N to ensure a constant topography and to avoid any centrifugal effects. These values are still far from exhausting the theoretical loads of the test rig. In order to investigate the universality of the influence of the fluid quantity in the sense of the Stribeck curve, tests were therefore also carried out with multiples of n and F_N, which had the same n/F_N ratio (e.g., n = 200 r/min and F_N = 200 N). Two problems became apparent. On the one hand, at higher speeds, the fluid tended to move outwards due to the centrifugal forces. This meant that homogeneous fluid distribution in the radial direction was no longer guaranteed. The bigger problem, however, came from the wear that set in due to the increased force and speed. This did not only change the topography (which is very undesirable in the context of these tests), but above all the increased abrasion effects caused a strongly changing lubricant (which became a glycerol-particle-mixture). This effect has been detected on the one hand in the changed topography and on the other hand in the friction value measurements, in which the latter phenomenon was expressed by a constantly

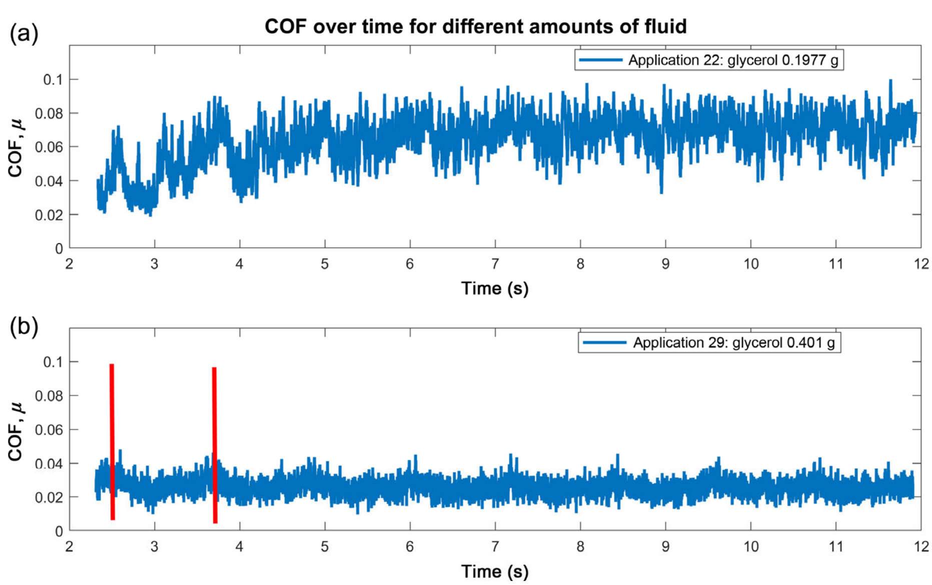


Fig. 9 COF vs. time for two different fluid quantities.

changing (increasing) COF over time. Since the present study is dedicated to the fundamental question, how the fluid quantity influences a mechanical contact with a given topography and a given lubricant, these mild loads were consequently chosen. Future work will deal with this question in a more focused way, e.g., by using harder materials.

Figure 10 shows the COFs for the finely filed specimen at different glycerol fluid amounts. The gradations of the fluid quantity are selected in such a way that the range of small fluid quantities is particularly finely resolved. Three repetitions of an identical measurement procedure are shown, indicated by different colors. The different markers represent the different applications, from the first (fluid freshly applied to the friction path) to the third applications.

The repeatability of the various measurement series can be regarded as very good for a friction measurement, which is particularly achieved by the precisely defined and documented procedures during the measurement, such as the specimen preparation, application of the fluid, and cleaning of the friction partners. As described in Table 1, the dry measurements are performed twice—once before the lubricated measurements and once afterwards. Therefore, six measurement points per measurement series are shown here (corresponds to the fluid amount of 0 kg). The repeatability of the dry tests is acceptable and confirms the assumption that the friction system does not change significantly over a series of measurements.

It can be seen that the COF decreases as the amount of fluid in the gap increases. This expectable drop is due to the fact that the contact ratio of the fluid increases. Since the hydrodynamic load-bearing component has a smaller COF, the COF of the overall system decreases. These are effects from the friction regime of mixed and boundary friction. The COF asymptotically approaches a minimum at 0.03, where additional fluid—at least in this system—does not lead to its further reduction. The low COF that is about 1/10 of the dry COF is a clear indication that the friction regime is certainly hydrodynamic. In the context of the rough calculations for the gap volume, the applied fluid quantity of 4×10^{-4} kg corresponds to a fully filled gap that confirms this consideration. Figure 10 thus represents the transition from a dry contact to a state in which the gap is fully filled or can no longer hold any further fluid.

Figure 11 shows a zoomed-in view of the area of small fluid volumes (in terms of the glycerol mass $m_{\text{glycerol,fine}}$; the first 10% of Fig. 10). It is noticeable here that the COF already drops significantly at the smallest fluid addition. The smallest amount of fluid applied is 5×10^{-6} kg or 3.97×10^{-9} m^3. The COF is already halved from 0.35 to 0.16 in comparison to the value for dry friction. This shows the great sensitivity of the system to small changes in the lubrication condition. At this point, it should be mentioned again that the measurement data shown are plotted above the measured fluid volume and not above the target volume for this variation. So, for example, the nine points on the right of Fig. 11 belong to the intended fluid quantity of 4×10^{-5} kg glycerol. In fact, the actual amount of fluid plotted, as determined by weighing, deviates slightly from this. However, this deviation is marginal in view of the manual application of these

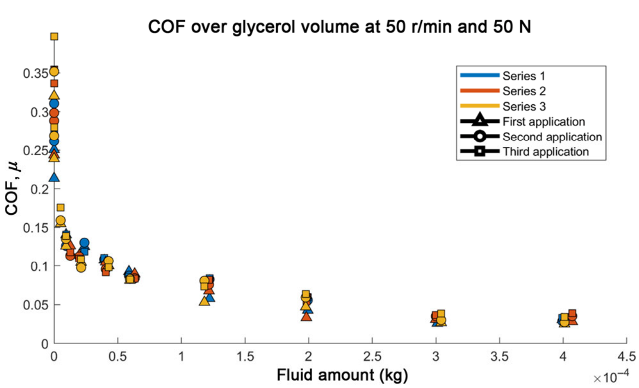


Fig. 10 COF vs. amount of fluid for the system with the finely filed pin.

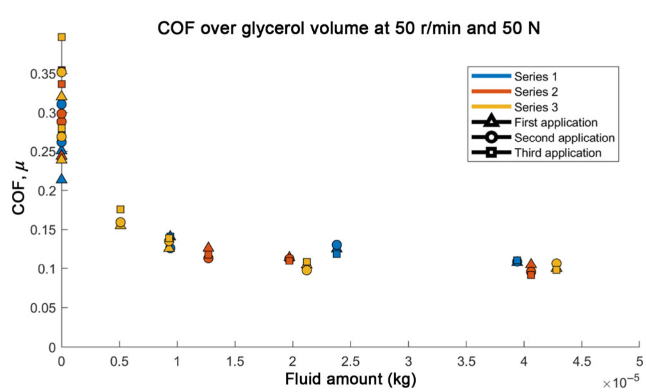


Fig. 11 COF vs. amount of fluid for the system with the finely filed pin, zoomed in range of $0 \le m_{\text{glycerol,fine}} \le 5\times10^{-5}$ kg.

smallest quantities and insignificant for the quality of the measurement data and the conclusions that can be drawn.

3.2 Fluid quantity variation for the system with the coarsely filed pin

As documented in the Section 3.1, the transition from the completely dry state to first lubricating effects is still rather coarsely resolved. Even the smallest amount of applicable fluid leads to a halving of the COF. To improve this situation, the use of a scenario with higher gap volume is effective. Beside the study of the roughness influence, this can be realized by investigating the coarsely filed system. Figure 12 shows the corresponding COFs at different glycerol fluid amounts. The form of the plot is analogous to Fig. 10.

Here, the significant and distinct reduction of the COF with increasing fluid quantity can also be seen. In comparison with the finely filed specimen, the influence of the greater roughness and the larger gap volume can be seen. The reduction of the COF with small fluid quantities is less pronounced. For the finely filed specimen, the COF already drops at 1×10^{-5} kg (corresponds approximately with 2.5% of the gap volume) to a value below 0.15; while for the coarsely filed specimen, this value is achieved at a fluid quantity of approximately 4×10^{-5} kg. For fluid masses larger than 1×10^{-5} kg, the variance of the different measurement series is still rather small, but significantly larger for smaller fluid masses. Figure 13 shows the zoomed-in range of the small fluid quantities.

The same fact can be observed for the differences between individual applications at the same fluid volume (deviations between triangle/rectangle/circle of the same color). In this range, the increase of the COF over the applications is distinctive. This is an indication that the contact is much more sensitive to small differences in the local fluid distribution. Due to the manual application with a brush, it is possible with small fluid quantities that in the coarsely filed system, the fluid film is more uneven with regard to the radial distribution in the friction path.

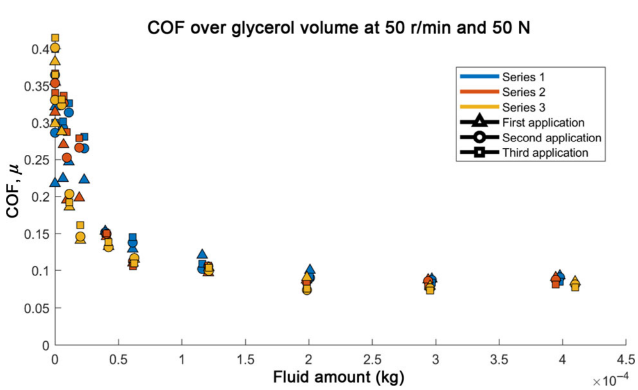


Fig. 12 COF vs. amount of fluid for the system with the coarsely filed pin.

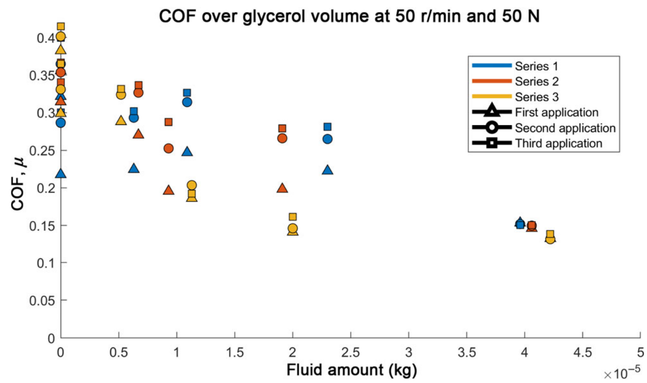


Fig. 13 COF vs. amount of fluid for the system with the coarsely filed pin, zoomed in range of $0 \le m_{\text{glycerol,coarse}} \le 5 \times 10^{-5}$ kg.

The smallest COF for the coarsely filed sample is 0.07, about twice that of the finely filed sample. It should be noted here that the greater roughness does not necessarily cause a proportionally higher COF. The measured values for the dry friction track, e.g., are in a similar range (0.30 for finely filed and 0.35 for coarsely filed).

In the case of the coarsely filed specimen, the decrease in the COF is less pronounced with the addition of fluid. With the smallest amount of fluid, the COF decreases only very slightly on average. From this, it can be concluded that in terms of the amount of fluid, this procedure allowed the transition from dry to hydrodynamic to be better resolved.

In Section 3.2, a first understanding of the friction system was obtained with respect to the applied fluid volume. Based on these findings, in Section 3.3, further variations are carried out considering the influence of the relative velocity and the normal force as the two crucial parameters determining the friction regime (as established in the Stribeck curve).

3.3 Variation of the relative velocity and the normal force

Sections 3.1 and 3.2 documented experiments with a revolutionary speed of n = 50 r/min and a normal force of F_N = 50 N that serves as a reference for the following measurements. With the last mentioned load, a further study has been carried out with the finely filed system and varying the supplied fluid volume and the relative velocity.

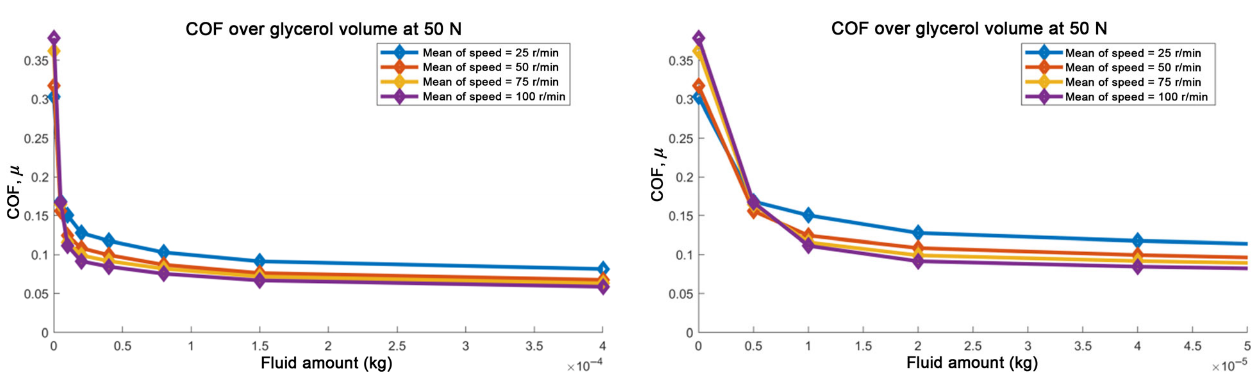
For this purpose, the speeds of 25, 50, 75, and 100 r/min are selected. The choice of this speed interval is based on the one hand by a minimum speed that can be reliably driven by the motor (25 r/min) and on the other hand to guarantee that no fluid is pushed out of the friction track by the centrifugal force (100 r/min). For these tests, a new sample is prepared from the same material, and a new brake disc is used. The run-in and the measurement procedure are identical to the procedure in Section 3.1. The COFs during the run-in and the dry comparison tests are also similar. All measurement series are carried out three times in the same configuration to assess repeatability. The good repeatability of the measurements is very similar to those of Figs. 10 and 11 in Section 3.1 so that for a better clarity, the associated mean value of the three measurement series with three applications each is illustrated in the following. The fluctuations, i.e., the standard deviation in the averaging, among the individual measurement series with the same configuration are small (usually less than 10% of the mean).

Figure 14 shows an overview of the measurements with the variation of the revolutionary speed. The chart shows the COF with clearly recognizable trends. As already described in Section 3.1, it decreases with increasing fluid volume as the glycerol influences the friction system by wetting the surfaces even with the smallest amounts. Comparing the trend at 50 r/min to Fig. 10, the minimum achievable COF is slightly higher. This is most likely due to the effect that there is a new sample and disc with its own run-in as well as possible variations in the surface finish.

In the tests, in particular the influence of the speed is to be analyzed. The COF decreases slightly with increasing speed. This effect is observable in particular between 25 and 50 r/min and less pronounced for higher speeds. For example, from a fluid quantity of 2×10^{-5} kg, an increase in speed from 25 to 100 r/min lowers the COF by 25%.

The influence of speed on this friction experiment allows some conclusions to be drawn, firstly with regard to the Stribeck curve. The fact that the COF falls with increasing speed is an indication that the investigated friction condition belongs to the mixed lubrication part in the Stribeck curve, and therefore left from the minimum of the COF (Fig. 1). However, the absolute value of the COF indicates an already significant load-bearing part by the hydrodynamics. Therefore, it is concluded that the friction regime is close to that minimum.

On the other hand, conclusions are possible with regard to the Reynolds equation considering partial filling. In very simplified terms, the conventional equations using a local filling ratio (θ) [16, 17] assume that the effective density and also the effective viscosity of the fluid are the products of θ and the actual fluid density or fluid viscosity. From this, it follows the velocity to have the same influence as the filling ratio. This would mean, e.g., that halving the velocity leads



Overview, $0 \le m_{\text{glycerol,fine}} \le 4\times10^{-4}$ kg   Zoom-in, $0 \le m_{\text{glycerol,fine}} \le 5\times10^{-5}$ kg

Fig. 14 COFs for varying fluid volumes and relative velocities.

to a similar friction regime as halving the filling ratio. Whether this is the case in the performed studies or not is discussed in the following.

Starting from the condition with the highest speed and the largest amount of fluid, the COF increases from 0.0586 to 0.0651 when the amount of fluid is halved (increase by approx. 11%). Halving the velocity leads to an increase to 0.0675 (increase by approx. 15%). A further halving of the fluid quantity and the relative velocity, respectively, leads to 0.0753 (fluid quantity, increase by approx. 29%) and 0.08146 (relative velocity, increase by approx. 39%). It can therefore be stated that the influence of filling ratio and speed is rather similar in this range. However, when the filling ratio and speed become small, the assumption no longer fits, and the influence of speed and filling ratio is different. At small filling ratios, e.g., a reduction in the filling ratio leads to significantly greater COFs than a reduction in relative velocity.

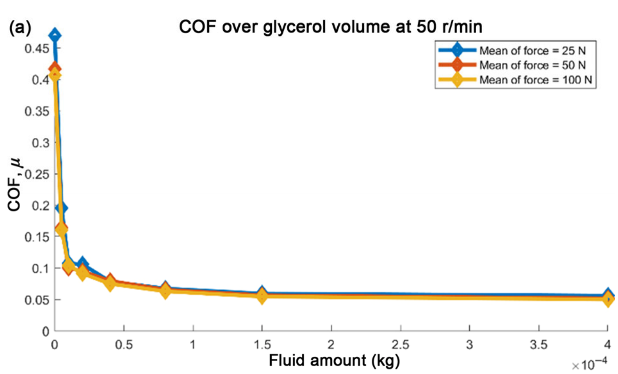
In summary, it can be concluded that the speed has a significant influence on the COF. Certainly, the velocities studied in this parameter set do not seem to have a fundamental influence, on which friction regime is present or dominant (e.g., the system does not switch to dry scenarios including high COFs with a velocity reduction). However, the comparable influence of velocity and filling ratio as assumed by the Reynolds equation is found in the experiments at least when the hydrodynamic friction regime is dominant.

In addition to the speed, the normal force is varied. In these tests, the speed is constant at 50 r/min and the pin is finely filed (as the system in Section 3.1). The run-in and the measurement procedure are equal to those of the speed variation. The COF of the dry tests is practically identical. The disc and the friction track are also identical.

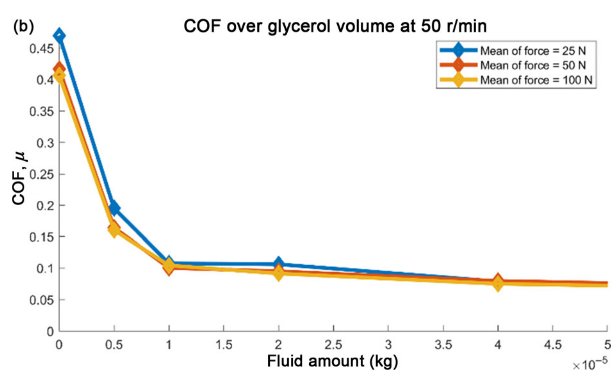
In addition to the normal force of 50 N, two further forces (25 and 100 N) are measured. The smaller force is chosen so that the friction force can still be reliably measured by the force sensors. The higher normal force is limited by the requirement that the friction contact should have the lowest possible wear, to ensure that the surface remains unchanged during the friction test.

All variations are repeated three times, analogous to the speed variation procedure. Figure 15 shows an overview of the measurements with the variation of the normal force.

As expected, the influence of the fluid quantity is very similar to the previous studies. The standard deviation (not shown) is again less than 10% of the mean value. The comparison of the mean values of the different force levels shows that the COF decreases slightly with increasing forces. With a normal force of 25 N and a fluid weight of 4×10^{-4} kg, a COF of 0.056 is measured. As the normal force increases to 100 N, the COF drops by 10% to 0.05. With smaller fluid volumes, this influence slightly increases (for the dry contact, the decrease is from 0.47 to 0.41, which equals 15%). This distinguishes the influence of the normal force from the speed, with the latter having a larger impact to the COF. With regard to the parameter (Viscosity × Velocity / External normal load) plotted on the abscissa in the Stribeck curve, there is therefore a certain inconsistency here—The velocity and the viscosity (or the filling ratio) show a significantly different influence in these measurements than the



Overview, $0 \le m_{\text{glycerol,fine}} \le 4\times10^{-4}$ kg



Zoom-in, $0 \le m_{\text{glycerol,fine}} \le 5\times10^{-5}$ kg

Fig. 15 COFs for varying fluid volumes and normal loads.

normal force. Apart from this point, the decrease in the COF with increasing normal force, as determined here, would be an indication that the friction state is in the hydrodynamic range (right from the minimum). This observation is somehow opposite to the conclusion for the variation of the speed (range left from the minimum). This further indicates that the examined state is most likely near the minimum when a small amount of lubricant is present.

4 Discussion, summary, and outlook

This paper described fundamental experiments on a pin-on-disc tribometer focusing on the transition from dry contact to lubricated friction for rough surfaces. The practical and technical challenges for repeatable measurements with the smallest fluid quantities have been discussed and solved in the present studies. For this purpose, special focus is on the sample preparation, run-in, the loading conditions, fluid supply, and cleaning procedure.

With a roughly calculated value, it was possible to estimate the applied fluid volume, with which the gap is completely filled. The minimum fluid volume that could be evenly applied in the friction gap was significantly below this value, so that a targeted partial filling was achieved by using the method presented. In addition to the fluid quantity, the relative speed and the normal force were also varied. The samples of different coarseness were used to vary the available gap volume. The aim of these studies is to characterize the friction regime in terms of the Stribeck curve, paying particular attention to the fluid quantity.

With this procedure, for the first time, it has been possible to carry out fundamental and systematic investigations of partially filled friction contacts over the entire range of the global filling ratio. It turned out that the friction system reacts sensitively to small changes in the amount of fluid, and even the smallest amounts of fluid fundamentally change the contact. As expected, the system with a larger gap volume shows a larger COF and a more pronounced area of transition.

Here, even very small amounts of fluid (accounting for less than 10% of the gap volume) are sufficient to reduce the COF to about one third of the dry system. An absolutely comparable effect was found in the measurements on the mesoscopic scale published in Ref. [13] (Fig. 16(a)) with ornamental glass panes (roughness in the range of a few 100 μm). In these measurements, videos of fluid movement showed that even very small amounts of fluid can settle between the asperities, and thus significantly lubricate the contact [13]. If the viscosity of the lubricant is high enough, when the asperities approach, there is no pure displacement to the side, but also a load-bearing effect by the fluid takes place. Transferring the results of a mesoscopic scale to a microscopic scale, as it is present in this paper, must of course be viewed very critically. However, as the authors were able to

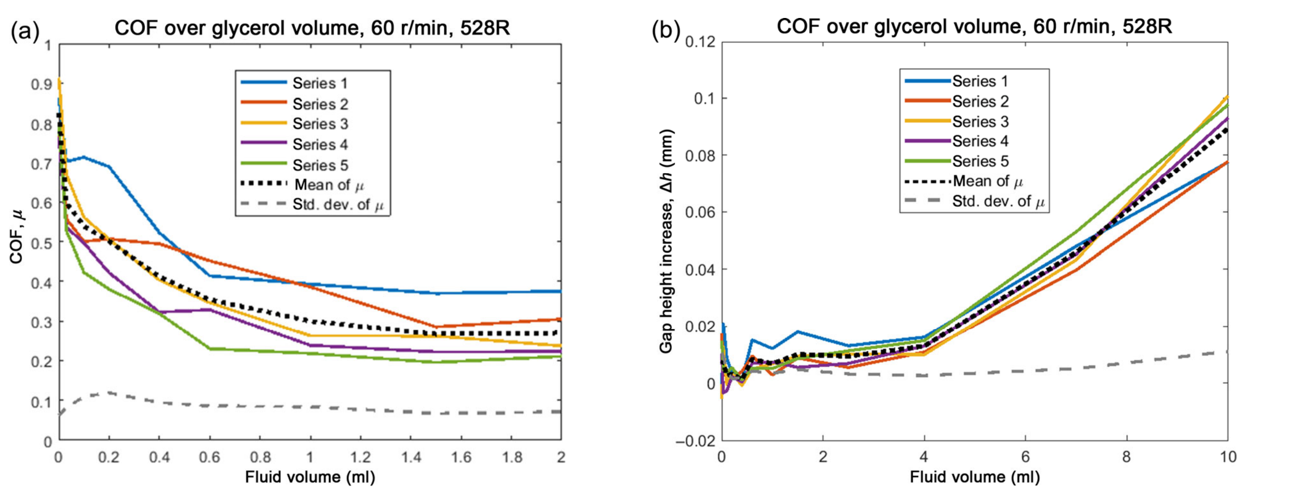


Fig. 16 Results with macroscopic glass surfaces: (a) COFs for varying fluid volumes (1 mL corresponds to approximately 10% filling ratio), (b) gap height increases (GHIs) due to supplied fluid volumes. Reproduced with permission from Ref. [13], © the authors 2018.

demonstrate quantitatively, e.g., with the reduction in the COF for very small quantities, it seems that corresponding conclusions are indeed possible to a certain extent.

On the mesoscopic scale, for example, the GHI over the fluid quantity has been measured with the help of a laser sensor (ILD2300-200, Micro Epsilon, Germany; Fig. 16(b)), whereby an associated increase has been proven [13]. This measuring principle is not suitable in the present pin-on-disc tribometer due to the accuracy requirements. Uncovering a corresponding correlation between the fluid quantity and the gap height on the microscopic scale is one of the essential next steps. For the present setup, precise methods are required in order to be able to provide absolute and relative values in the sub-micrometre range. Ultrasonic sensors or electrical impedance measurements could be used for this purpose, for example.

Furthermore, it has been demonstrated that for larger filling ratios, reducing the velocity has a similar effect as reducing the amount of fluid. This behaviour goes along with classical theories describing partially filled gaps. For smaller filling ratios, this behaviour is no longer observable. A reduction in the filling ratio leads to a strongly disproportionate increase in the COF. A change in the normal force, on the other hand, did not have much effect.

Furthermore, it is planned to reduce the fluid quantities even further in order to detect the transition area even better resolved. For reasons of measurability, the change in the mean gap height due to the addition of fluid has not yet been carried out. In the future, it is aimed to draw conclusions about the gap height that occurs in the associated friction regime.

In addition, models are being developed, with which such contacts can be modelled. This also requires a more detailed description of the contact mechanics, as presented for dry contacts already in Ref. [18].

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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