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## “Frictional behaviour of a greased contact under low sliding velocity condition”

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### KEYWORDS

Lubricated contact; Grease; Friction; Stick-slip;

### ABSTRACT

In greased contacts, the complex rheology of a grease, depending on thickener, base oil and additives, becomes a key point for understanding and controlling the evolution of friction coefficient at extremely low sliding velocities. Such velocity range (from 0 to few mm/s) is of main relevance for several issues, such as unstable friction-induced vibrations, which can occur as well in the case of lubricated interfaces.

In this paper, a greased contact at low sliding velocities is then reproduced and analysed on a dedicated tribometer, under well controlled boundary conditions. Static and dynamic friction coefficients, as function of velocity, are obtained, considering either dry and lubricated contact, with both the grease and its base oil. The effect of DLC surface coating is analysed too. The contributions of the lubricant components on the frictional and dynamic response have been then discussed, showing a non-trivial trend of friction, with respect to speed, within the investigated velocity range.

### 1. Introduction

In sliding contacts, as a function of the boundary conditions [1, 2, 3], the rheological contributions of the different components of a grease are still not completely understood. A grease is a multi-phase lubricant mainly composed by a fluid, the base oil, and a thickener, usually a soap made of metal fibers. It is generally composed of 85-80% base oil, 5-10% thickener, plus additives (~5%) [4, 5]. The thickener traps the oil allowing the lubrication of the parts and it determines the temperature operational window. When a stress is applied to the grease, the lubricant response depends on the elastic and viscous properties of both the thickener fibers and the oil respectively. The elastic characteristic prevents the grease from leaking, while its fluidity is essential to establish a lubricating film at the contact interface [4, 5, 6, 7, 8]. While thickening is the result of the physical interaction between thickener material and lubricating oil, the consistency of the grease is a function of the thickener concentration and the manufacturing process. On the other hand, the lubricity of conventional greases is governed

mainly by the base oil and additives [6, 9]. Consequently, the overall friction-velocity characteristic of a grease is a complex result of the synergy between several rheological and physiochemical contributions. Despite the use of lubricants has been promoted to reduce friction, stabilize the contact response and guarantee an adequate life of the components, the non-trivial trend of friction at low sliding velocities can promote other unwished phenomena such as unstable Friction-Induced Vibrations (FIV) [10, 11, 12].

Modelling friction and prevent the related vibrational problems (e.g. stick-slip) requires a multiscale approach where the dynamic response of the system has to be associated to the local frictional response at the contact [13]. For this reason, the trend of the friction-velocity characteristic is often crucial in problems related to unstable FIV, and a detailed investigation of the frictional trend at low velocities, when dealing with a greased contact, is here proposed. Focusing the attention on the stick-slip phenomenon, the trend of the friction coefficient within the low velocity range, together with the difference between static and dynamic friction, can bring to alternating motion characterized by a periodical switching between sticking and sliding [14]. This phenomenon of macroscopic oscillating motion, during the relative movement between bodies in contact, is defined as stick-slip. Since stick-slip is a recurring impulsive event, exciting periodically the system dynamics, it may be perceived as vibration or noise. The presence of lubricant at the interface increases the complexity of the phenomenon, from both a tribological and a dynamical point of view. Moreover, when the lubricant is a grease, its complex rheology, function of both the thickener and oil response, becomes a key point for the occurrence and evolution of the stick-slip phenomenon, by driving the overall frictional response as a function of velocity. The friction force and sliding velocity are linked by the formation of a fluid interface, where the degree of separation of the surfaces determines the lubrication regimes: boundary, mixed and hydrodynamic regimes [15]. The Stribeck effect governs the transition between these regimes. Then, the friction-velocity curve, characterized by a negative friction-velocity slope when passing through boundary and mixed contact regimes, can collaborate in the appearance of contact instabilities, increasing the possibility of the occurrence of the stick-slip phenomenon.

Many studies can be recovered in literature on contact instabilities [16, 17, 18, 19, 20, 21]. Nevertheless, the literature presents few works [1, 3, 15, 22, 23, 24] available on the role of grease, and its rheological response at the contact interface, related to the stick-slip promoters, such as the difference between static and dynamic friction coefficient, the slope and more in general the frictional trend within imposing low-sliding speed.

More in detail, there are no experimental works dealing with the frictional response of a greased contact, within the very low sliding velocity range (from 0 to few mm/s), which is the most relevant range for the stick-slip phenomenon and the related noise issues. Few studies are focused on molecular simulations [25, 26] or theoretical mathematical models [27, 28], with the aim of giving clues for the understanding of the phenomena, but rarely are then applied to a real case studies. There is then a lack of information about the macroscopic frictional response of a greased contact within the sliding velocity range investigated in this paper.

In this context, to investigate the frictional response of a greased contact, within the velocity range of interest for stick-slip occurrence, this paper presents the results of frictional

experiments, conducted in presence of lubricant, when a controlled low relative velocity is imposed. The starting benchmark of the analysis are the effective working conditions of a commercial mechanical brake, used in tubular electric actuators [29], which can generate frictional instabilities due to the grease lubricated contact between the two main brake components [24]. The brake system under investigation is mainly composed by an external fixed cylinder (i.e. drum) in which a torsional spring is tightened. The contact interface between the drum and the spring is lubricated with a commercial grease. The grease aims to decrease wear and stabilize the friction between the components. During the braking phase, the widening of the spring assures the braking, thanks to the increase of the contact pressure (and of the resulting frictional force) at the greased contact between the fixed cylinder and torsional spring. The local frictional contact response of such system is reproduced and analysed on a dedicated tribometer, in order to retrieve the evolution of friction as a function of the imposed boundary conditions. The recovered frictional responses are then analysed with respect to the sliding velocity, in order to reproduce a Stribeck-like curve. Concerning the stick-slip phenomena, the difference in static and dynamic friction coefficient and the trend of its slope, with respect to the imposed velocity, are underlined and investigated. Aiming to highlight the influence of each grease components, used as lubricant in the case study: thickener (Lithium Complex), oil (PAO), and additives, the frictional response is investigated by testing the different types of lubrication conditions, corresponding to dry contact, oil lubrication with the base oil of the grease and greased contact, both with and without Diamond-Like-Carbon (DLC) coating. The results are reported for two different operational temperatures (25°C and 80°C), corresponding to the temperature range observed on the investigated application.

The results aim to provide information on how the different components of the grease affect the local frictional behaviour and, consequently, the propensity of the system to the stick-slip dynamic instability. While the well-known roles of additives and thickener are observed, i.e. lowering the overall friction within the boundary and mixed conditions, a non-trivial trend of the frictional response of the greased contact is observed, within the extremely low velocity range, which has still not been observed in the literature.

## **2. Materials and method**

As shown in previous studies [14, 30], the stick-slip phenomenon is extremely influenced by the friction force variation at low speeds. The present study is focused on experimental tests performed under a low sliding velocity range, 0-20mm/s, where a lubricated contact is mainly affected by boundary or mixed contact conditions. The reference configuration is the one used in the analysed braking application [29], with a commercial Lithium Complex grease and DLC coating at the interface. First, the influence of the DLC coating has been investigated, testing the contact samples, with and without coating. Then, in order to decouple the influence of the grease thickener, the base oil and the additives, the performance of the base oil with and without additives has been investigated and then compared with the greased contact.

## 2.1. Experimental equipment

The principle of the experiment is shown in Figure 1. The upper sample is a coil section (semi-circular section) of a steel torsional spring, with spring diameter equal to 32.6mm and wire diameter equal to 1.3mm (upper sample in Figure 1 – c). It is loaded against a semi-cylindrical sintered steel specimen, internal diameter of 32mm (lower sample in Figure 1 – c), by a constant normal load. The torsional spring and the cylinder are the brake components of the investigated brake system [29]. The applied load, the sliding velocity and the temperature are maintained constant during each frictional test.

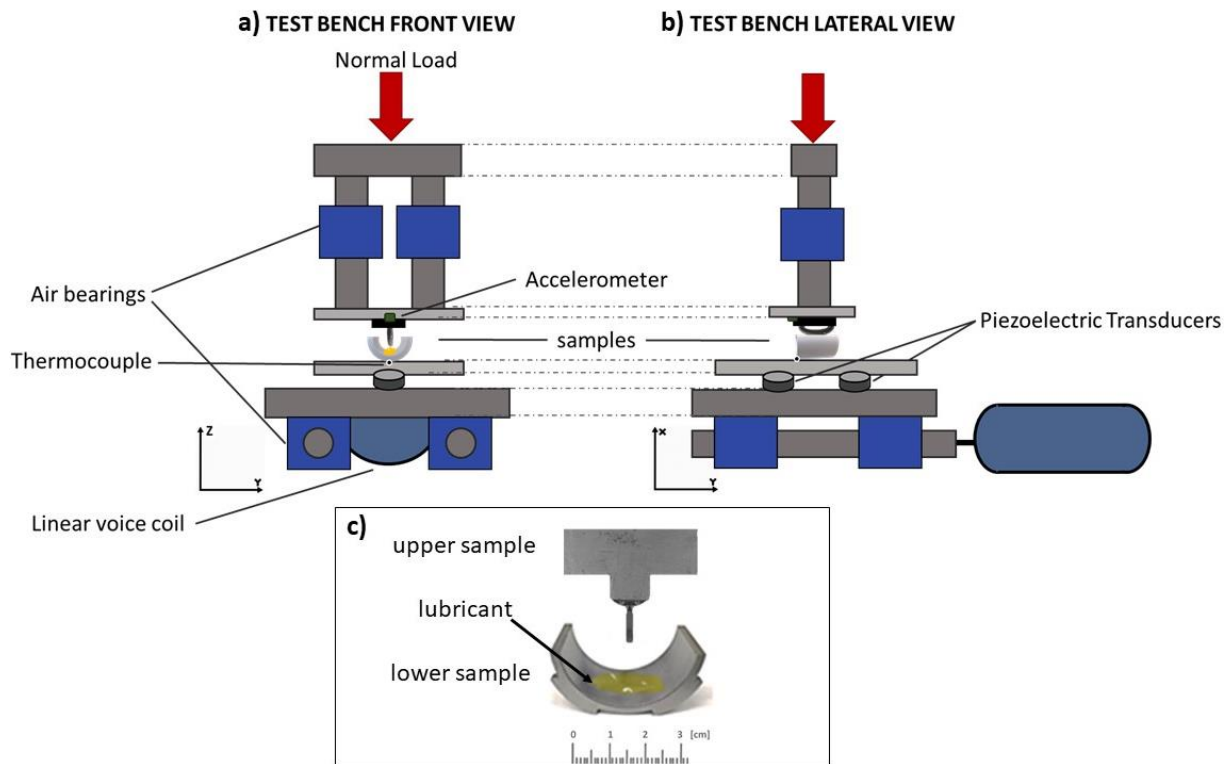


Figure 1: Test bench scheme. a) front view. b) lateral view. c) detail of the samples in contact.

The driving velocity ranges from 0.1 to 20 mm/s and is imposed by a linear voice coil (BEI KIMCO LA30-75-001A). The speed profile is regulated by a controller (ELMO Gold DC Whistle) and a linear optical encoder (MicroE OPS-200-1-1), which measures the instantaneous position with a resolution of 0.1 $\mu$ m. The normal force is applied by death weights along the z-axis and supported by a two air bearings system. The air bearings allow for avoiding frictional forces in the vertical direction, assuring a constant normal load. The tangential motion of the lower sample is allowed as well by air bushings. The contact forces are measured with two 3-axial piezoelectric transducers (Kistler 9017C). The signals are acquired synchronously by an analogue-to-digital data acquisition card (NI4472) at the sampling frequency of 5120 Hz and then post-processed using Matlab ©. Infrared lamps have been used to regulate the temperature of the specimens, which is monitored by thermocouples positioned on the samples, close to the contact surfaces. More details on the used test bench are available in [24].

## 2.2. Tested conditions and procedures

As showed in previous works [14, 24], the appearance of stick-slip can be promoted by drops in the friction coefficient with respect to velocity, i.e. an high difference between static and dynamic friction coefficient and negative slope of the friction-velocity characteristic. Aim of the experimental tests is the evaluation of such stick-slip promoters, by analysing the frictional response of the greased contact under analysis at low velocities, focusing the attention on the different role played by the grease components.

### 2.2.1. Boundary conditions and test protocol

Table 1 shows the different tested boundary conditions. Tests at constant imposed velocity have been performed, with velocity ranging between 0.1 mm/s and 20 mm/s. The test at 0.1 mm/s has been used to determine the static friction coefficient as well, at the onset of the sliding. Two loads have been tested for each velocity, 10 N and 20 N respectively. The tests have been then repeated at both ambient (25 °C) and high (80 °C) temperature.

Sliding speed range	Temperature	Load	Lubrication conditions
from 0 to 20mm/s	25°C and 80°C	10N and 20N	Grease & DLC coating; Grease; Base oil; Dry

Table 1: List of experimental test boundary conditions

The lower specimen is a sintered steel half cylinder. The reference length of the specimen is equal to 15 mm and, for all the experiments reported in this paper, the imposed sliding distance is set to 10mm. The upper sample is the semi-circular section of the spring, with and without DLC coating, as a function of the tested lubrication condition.

In case of lubrication with presence of DLC, the upper sample is coated with a DLC coating. Such films are generated by tribologically activated reactions between lubricant additives and the metallic surface [31, 32]. DLC films cover a wide range of coatings with different compositions and structures and therefore they also behave differently in tribological contacts. These coatings can be divided into two major groups, as function of their hydrogen content: amorphous hydrogenated (a-C:H) and hydrogen-free carbon films (a-C). The two coating families have different mechanical properties and thermal stabilities. The a-C films have considerably higher hardness and higher elastic modulus compared to a-C:H films [32, 33]. This difference in the structure and mechanical properties influences then the tribological performance of the coatings [32]. The DLC coating used here in the experimental tests is a multilayer amorphous hydrogenated coating. Extreme hardness, high elastic modulus, excellent wear and corrosion resistance, high thermal and chemical stability, and low-friction characteristics makes them suitable for a wide range of tribological applications [34, 35].

For the configurations without DLC, the same spring specimen is tested. Nevertheless, after few sliding tests, the uncoated spring surface wears quickly, modifying the contact area and requiring the use of a new spring specimen. Even if the configuration without DLC coating is not suitable for applications, as in the case of spring brake systems, the tests are here performed for investigating the role of the DLC into the overall trend of the friction coefficient as a function of the sliding speed.

Each lubrication condition has been tested following the protocol reported below:

- The tested specimens are first cut from the real brake components and cleaned with ethanol by ultrasonic cleaning;
- The samples are mounted on the Tribometer, as shown in Figure 1;
- The lubricant (grease or base oil) is placed on the contact area;
- The temperature is settled (25°C or 80°C) and maintained constant through two infrared lamps;
- The normal load (10N or 20N) is applied on the upper specimen;
- A running-in of the contact surfaces is first performed with 15 cycles;
- The samples are brought into contact again, the normal load is applied and the reciprocating motion is imposed;
- The upper sample covers a distance equal to 10mm on the counter surface (i.e. lower sample) at the imposed velocity; 4 cycles are performed.
- The test is then repeated changing the sliding velocity each time.
- At the end of each set of tests at different velocities the first test is repeated to verify the stability of the measurements (surface wear, lubricant leaking, ...). The tests are retained only if the initial value in terms of the friction coefficient is retrieved.

### 2.2.2. Lubrication conditions

In the following, the different tested lubrication conditions are presented, in order to decouple the influence of the DLC coating and the grease components (thickener and oil) on the overall lubricated frictional response. The tested lubrication conditions are summarized in Table 2.

Lubrication conditions	Composition	Base oil viscosity at 40°C	Quantity
<b>Grease LiCPAO &amp; DLC</b>	Lithium Complex, PAO and additives & DLC	460 cSt	5 ml introduced by a pipette on the contact zone & DLC coating on the upper specimen
<b>Grease LiCPAO</b>	Lithium Complex, PAO and additives	460 cSt	5 ml introduced by a pipette on the contact zone.
<b>Dry</b>	-	-	-
<b>Base oil PAO</b>	PAO	460 cSt	fully flooded conditions.
<b>Base oil PAO with additives</b>	PAO and additives	460 cSt	fully flooded conditions.

Table 2: List of tested lubrication conditions

First, the applicative condition on the real spring brake system is tested, when both solid (DLC) and fluid (grease) lubrication contribute to the overall measured friction coefficient. Then, the

same contact boundary conditions have been tested on the grease lubricated contact, excluding the DLC solid lubrication. Comparison between the frictional responses, with and without DLC, are discussed for both dry and greased contacts. Finally, the contribution of the base oil has been investigated by comparing the results from the greased contact, the contact lubricated with the base oil (with and without additives) and the dry contact.

### 2.2.3. Grease preliminary rheological analysis

The grease used for the experimental tests is a commercial synthetic lithium complex grease. It is based on a synthetic base oil (PAO), a Lithium Complex thickener and additive package designed to guarantee low and high temperature performances, improve the mechanical efficiency and ensure a longer service life. It is one of the most used grease in mechanical applications nowadays. The PAO base oil has a definite and consistent composition [9]. The Lithium and, in particular, Lithium Complex thickeners have excellent worked stability, low temperature pumpability, high temperature performance, and good water resistance [4, 36, 37]. When a stress is applied, the grease response depends on the elastic and viscous properties of both the thickener fibers and the base oil respectively. The elastic response is described by the storage modulus, and the viscous response is described by the loss modulus. With increasing thickener concentration, both the storage and the loss moduli increase, until at a certain point, where the storage modulus demonstrates a rapid increase by a few orders of magnitude. At this point the grease starts to lose its ability to flow freely. However, when the applied stress exceeds the yield stress, the internal structure of grease is broken and the grease acquires fluidity [37]. Shear tests of the used grease have been here performed, both at ambient (25°C) and high temperature (80°C), to characterize its viscosity and the yield stress. The grease has been characterized using both continuous shear and oscillatory shear measurements.

Figure 2 shows the obtained results.

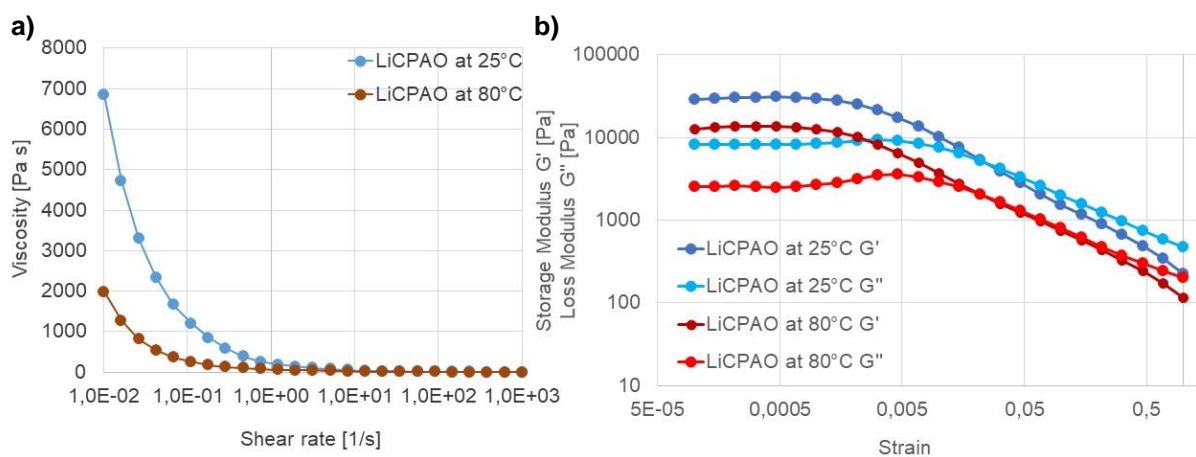


Figure 2: a) Viscosity versus shear rate and b) Storage Modulus  $G'$  and Loss Modulus  $G''$  versus strain at a frequency of 1 Hz, both at  $T=25^\circ\text{C}$  and  $T=80^\circ\text{C}$  for the tested LiCPAO grease.

The flow curve (Figure 2-a) shows a high-viscosity region at lowest shear rates, followed by a sudden decrease and a stabilization region, with a consequent strong decrease of the viscosity at room temperature. This behaviour is much less pronounced for higher temperature and the difference in viscosity between low and high shear rate is markedly lower. The viscoelastic



properties (i.e. the elastic modulus  $G'$  and the loss modulus  $G''$ ) were measured by oscillating shear at a frequency of 1 Hz (Figure 2-b). The storage modulus decreases, while the loss modulus stays almost stable, until a crossover point is reached. The crossover point is where  $G'$  is equal to  $G''$  [38]. Beyond this point,  $G'$  starts to faster decrease respect to  $G''$ , indicating a structural breakdown within the grease microstructure.

In order to account for the variability of the results due to the lubricated condition, which greatly affects the repeatability of experiments, the tests in lubricated conditions were carried out in fully flooded conditions and each test has been repeated three times. The results showed a variability less than 6%, allowing to assert the reliability of the recovered results and trends. For confidential issues, in the following figures, the friction coefficient values have been normalized on a scale from 0 to 1, with respect to the maximum recorded value.

### 3. Friction tests and Stribeck-like curves

In the following, first the experimental results on the reference configurations are reported. The friction curves, obtained in the reference lubrication conditions (i.e. grease and DLC coating), are shown and compared, as a function of the imposed sliding velocity.

Figure 3 shows an example of a recorded test signals when imposing a normal load equal to 20N and 0.1mm/s of sliding velocity at low temperature (25°C). From the time evolution of the friction coefficient, it is possible to retrieve both the static friction coefficient (onset of the sliding) and the dynamic friction coefficient, as a mean of the curve within the sliding phase at constant velocity.

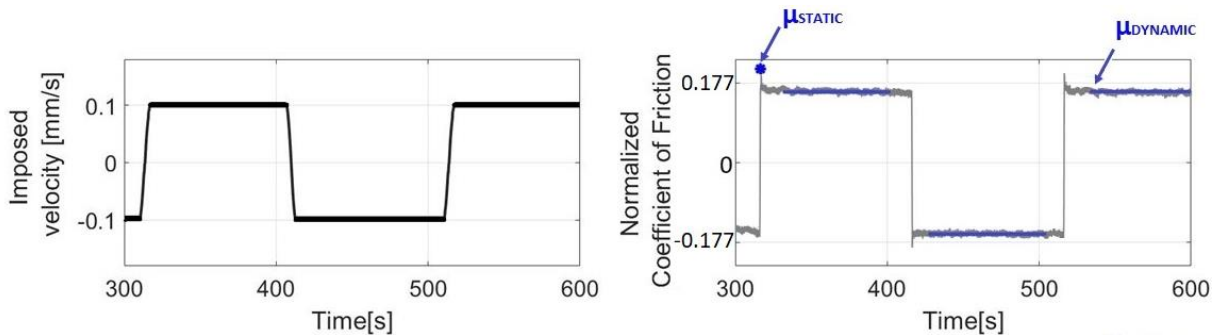


Figure 3: Recorded test signals in greased condition (LiCPAO) with DLC, imposing a normal load equal to 20N, room temperature and sliding velocity equal to 0.1mm/s.

The dynamic friction coefficient has been then retrieved for all the tested sliding velocities. The overall results, as a function of sliding velocity, obtained for the applied normal loads and temperatures are shown in Figure 4.

After the first sudden drop between static and dynamic friction coefficients, the dynamic friction grows rapidly as the sliding velocity increases, up to a maximum value at around 2mm/s, after which it starts stabilizing.

This behaviour is emphasized increasing the operating temperature (80°C). In fact, when the temperature increases, the grease viscosity decreases, as shown in Figure 2, decreasing the overall friction resistance (red curves in Figure 4).

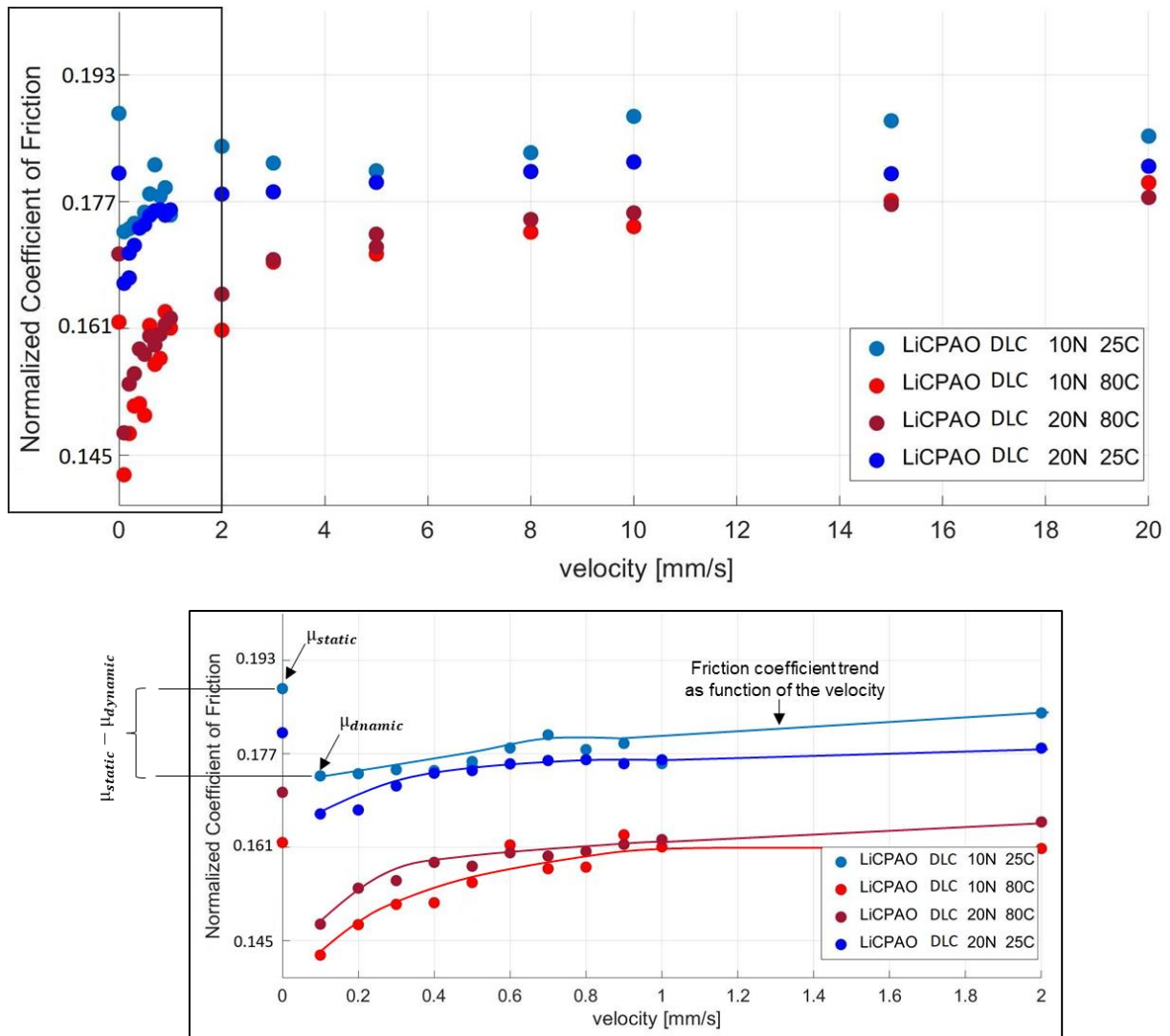


Figure 4: DLC/Steel experimental results - normalized friction coefficient trend in function of the sliding velocity for the tests performed both at  $T=25^{\circ}\text{C}$  and  $T=80^{\circ}\text{C}$  and imposing two different normal load equal to 10N and 20.N. The lower inset shows a zoom in the velocity range from 0 to 2mm/s, with the static and dynamic friction identification.

Analysing the performed tests and focusing the attention on the low speed velocity range (zoom in Figure 4), it is possible to underline that the friction coefficient shows the same trend, with respect to velocity, for both the normal loads and both temperatures. Focusing the attention on the difference between static (reported as dots at 0 mm/s in Figure 4) and dynamic friction coefficient (value of the friction coefficient at the lowest sliding velocity, i.e. 0.1mm/s), this difference is higher at higher temperature. This trend is related to the difference in the rheological response of both the matrix of the grease and its base oil [39]. This difference, between static and dynamic friction, is one of the main parameters leading to the conditions for which the propensity to stick-slip increases, i.e. the higher is the difference, the higher is the propensity of the brake system to promote stick-slip vibrations [24].

The purpose of this work is therefore to investigate the different contribution of the lubrication components in the obtained trends of the frictional response.

## 4. Effect of lubrication components on the friction-velocity characteristics

### 4.1. Effect of DLC coating in greased contact condition

The first element to be considered in the investigated lubrication process is the presence of DLC coating, which plays the role of solid lubricant and can affect the frictional response both directly, by modifying the contact rheology, and indirectly, by reacting with the grease components. Tests have been performed on the same samples in contact, but without DLC coating. Figure 5 shows the results of the tests performed on the Steel/Steel specimens under the greased lubrication condition (LiCPAO); same normal loads, sliding velocities and temperature conditions are applied, as in the DLC/Steel case, previously investigated.

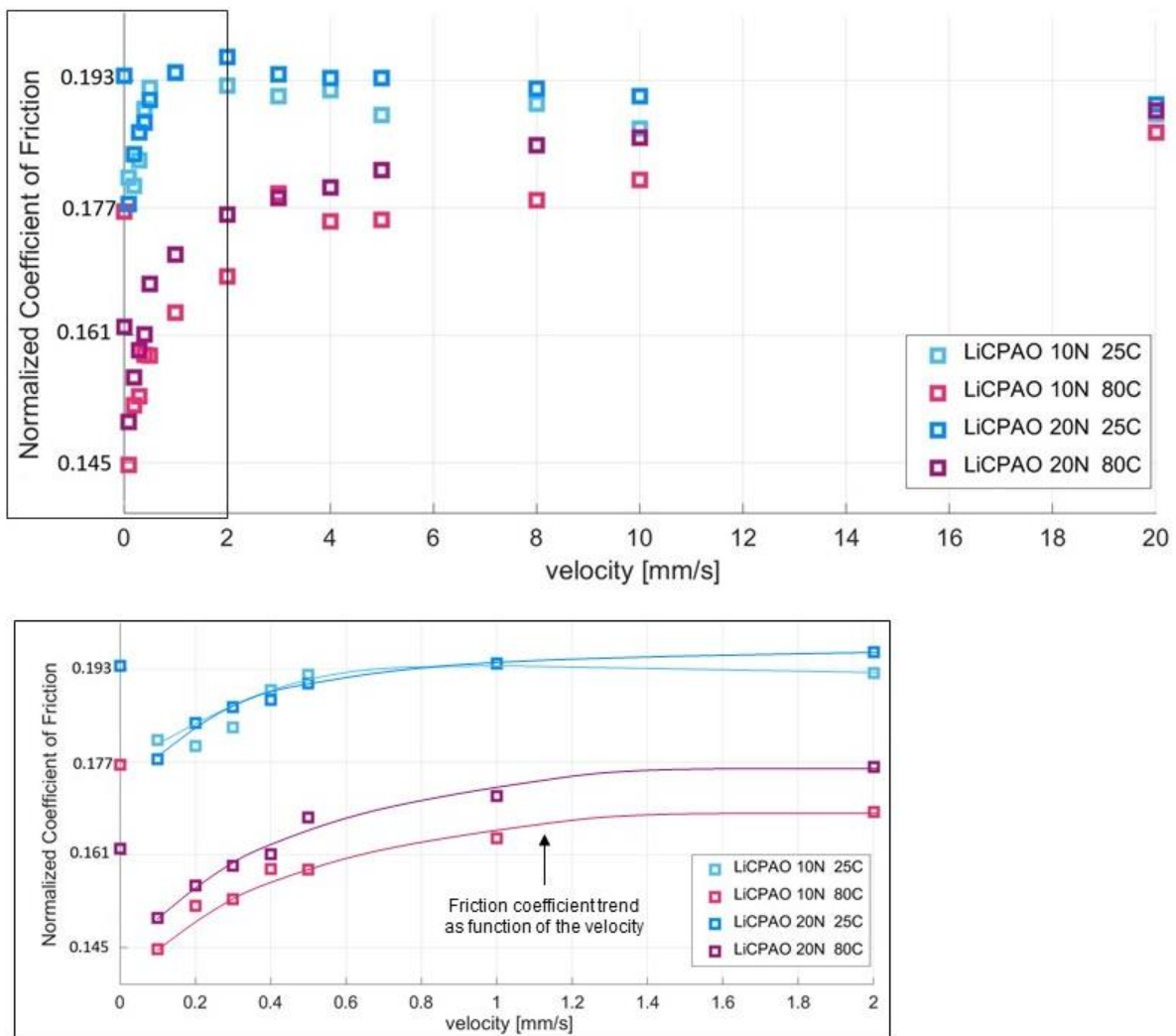


Figure 5: Frictional tests without DLC coating - normalized friction coefficient trend in function of the sliding velocity for the tests performed both at  $T=25^{\circ}\text{C}$  and  $T=80^{\circ}\text{C}$  and imposing two different normal loads, equal to 10N and 20 N. The lower inset shows a zoom in the velocity range from 0 to 2mm/s.

The friction coefficient shows a similar trend, with respect to velocity, to the one observed with DLC. As before, a higher static coefficient of friction is retrieved. Then, in sliding condition at the lowest velocity, there is a sudden fall of the coefficient of friction, which rises then again until it reaches the stability for higher velocities. Increasing the load, the trends remain the same. Increasing the temperature, the friction coefficient presents lower values. When

comparing the experimental results obtained in greased conditions (LiCPAO grease), both with and without DLC coating (Figure 6), the shape of the friction curves, with respect to velocity, does not follow the classic Stribeck-like curve, where an exponential decrease of friction with velocity would be expected.

Moreover, as shown in Figure 6, the trend is similar for both the tested conditions, with and without DLC coating. The first friction drop, due to the shift between static and dynamic friction, is followed by an increase and stabilization with respect to the velocity. The main effect provided by the DLC coating is an overall lower value of the coefficient of friction, more evident with the decrease of the velocity. This agrees with the role of DLC, which provide further solid lubrication at lower velocities, when the contact moves toward more severe boundary lubrication conditions.

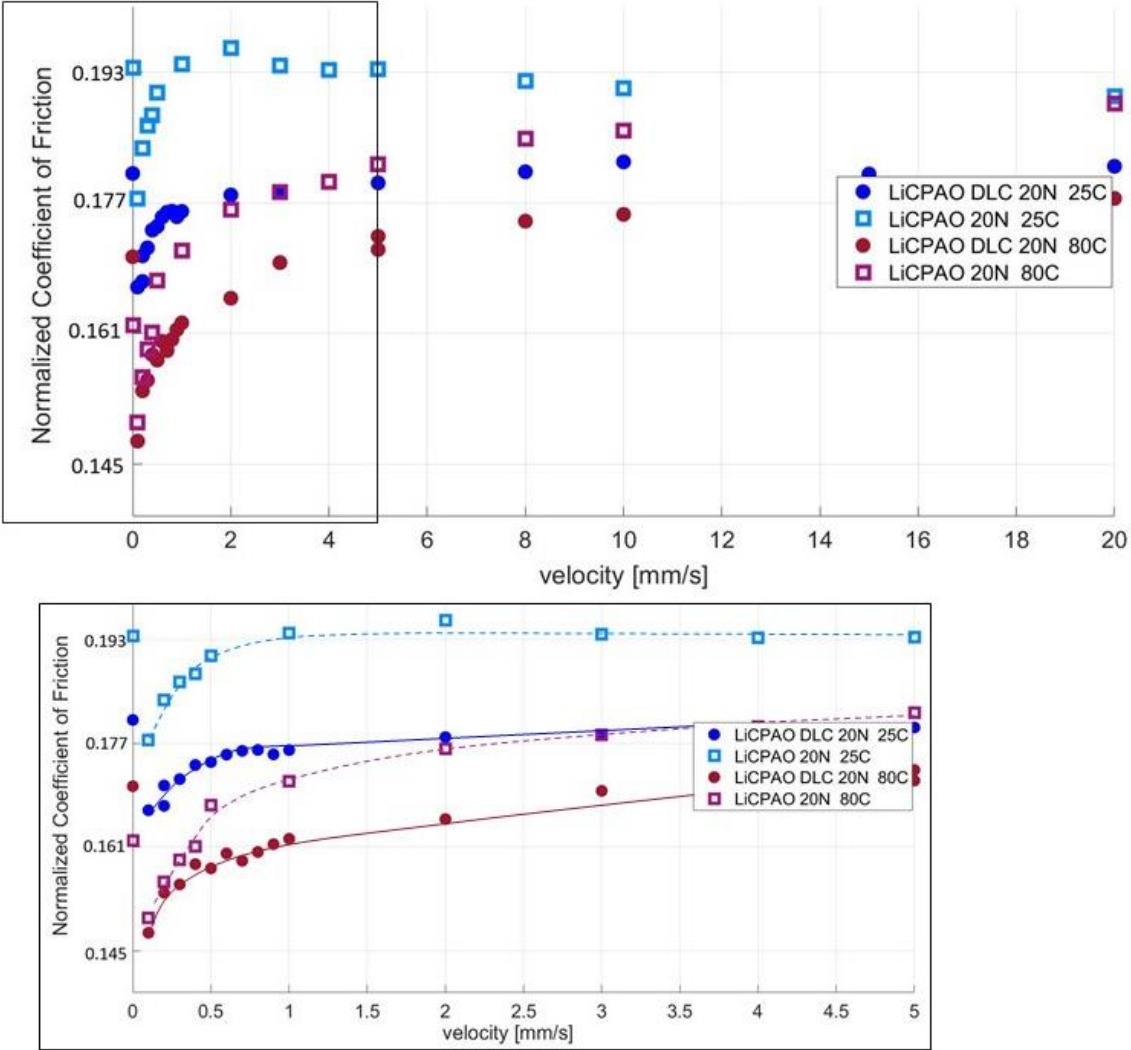


Figure 6: Comparison between the friction coefficient trend as function of the sliding velocity for the DLC/Steel samples and the Steel/Steel sample in greased condition at room temperature condition (25°C) and higher temperature condition (80°C) imposing a normal load equal to 20N.

Figure 7 shows the contact surfaces, of both the drum and spring in contact, for both the tested conditions, with and without the DLC coating. The surfaces have been cleaned with ethanol, by ultrasonic cleaning, and the images have been obtained using an electron microscopy.

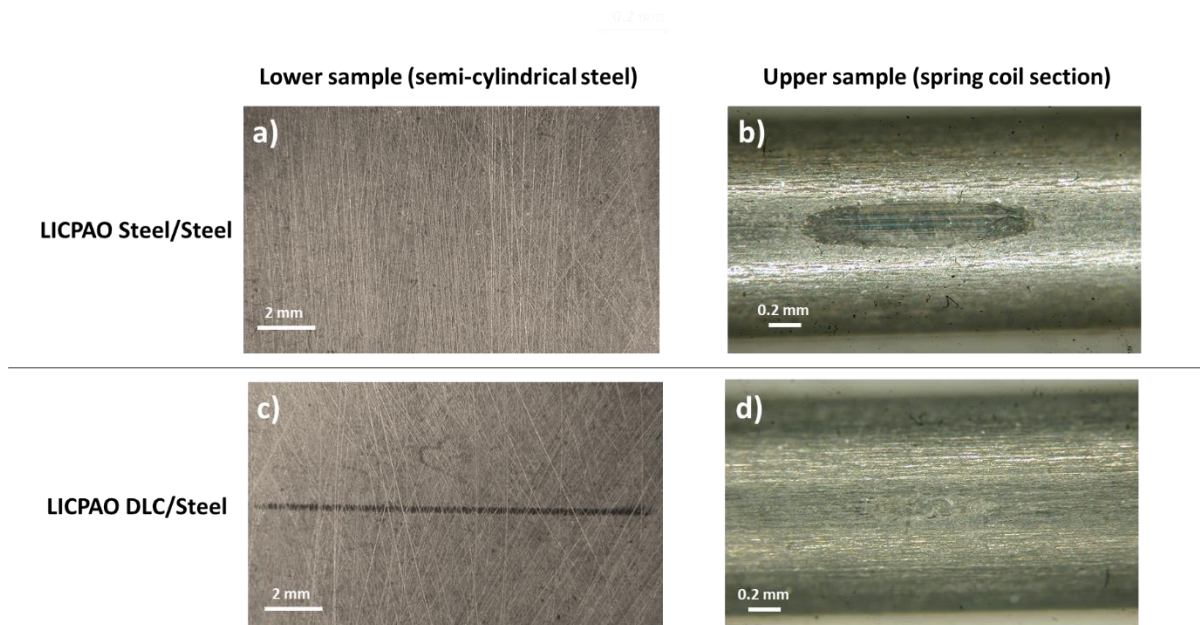


Figure 7: Electron microscope images of the lower and upper sample contact surfaces. Both have been tested, imposing a normal load equal to 20N and in greased (LiCPAO) conditions. a) and b) lower and upper sample respectively of the test without DLC. c) and d) lower and upper sample respectively of the test with DLC.

In the case of tests performed with the DLC/Steel contact pair, the lower sample shows the presence of solid 3<sup>rd</sup> body on the drum surface (Figure 7, c), due to the transfer of material from the DLC coating on the spring. This 3<sup>rd</sup> body layer remains on the surface of the drum even after the cleaning protocol, due to a material transfer from the spring to the drum surfaces. In agreement with previous studies [32, 35], DLC coatings strongly contribute to the tribological performances at the contact, due to the establishment of a DLC - DLC contact, or more correctly, DLC- DLC plus lithium complex grease contact and DLC solid third body, able to assure a more stable frictional response. Moreover, the DLC layer protects the spring surface, which does not show remarkable wear. In fact, focusing the attention on the spring contact surface (image d) in Figure 7), the surface coating does not appear to be significantly damaged.

On the contrary, when observing the contact surfaces without DLC coating, signs of wear are evident at the end of few test cycles (Figure 7 **Erreur ! Source du renvoi introuvable.**-b). A premature wear of the upper specimen (spring) is observed, despite the small number of performed cycles, due to the removal of the spring material by abrasive wear. The fast wear of the spring surface brought to the need for a frequent replacement of the sample during the friction tests.

The absence of solid lubricant resulted thus in a contact area of the spring strongly worn, showing a flattened zone. On the contrary, the counterpart (drum in sintered steel) surface does not show remarkable surface wear, due to its high hardness.

#### 4.2. Effect of DLC coating in dry conditions

Specific tests in dry conditions have been carried out with the aim of observing the role of the DLC coating on the frictional response of the investigated contact without the presence of the grease. Figure 8 shows the results of the tests in dry condition, with and without DLC coating, at 20N of normal load. The overall friction behaviour is almost constant with respect to the sliding velocity.

Nevertheless, the DLC coating decreases drastically the friction coefficient, with respect to the uncoated samples. Again, the formation of a deposit of solid lubrication, on the contact surfaces, has been observed. The hydrogenated amorphous DLC, on the coated surface sample, creates a third body (DLC particles), which deposits on the counterpart sintered steel during the sliding, protecting the surface from a premature wear. The same behaviour has been observed both in dry conditions and with grease lubrication (LiCPAO).

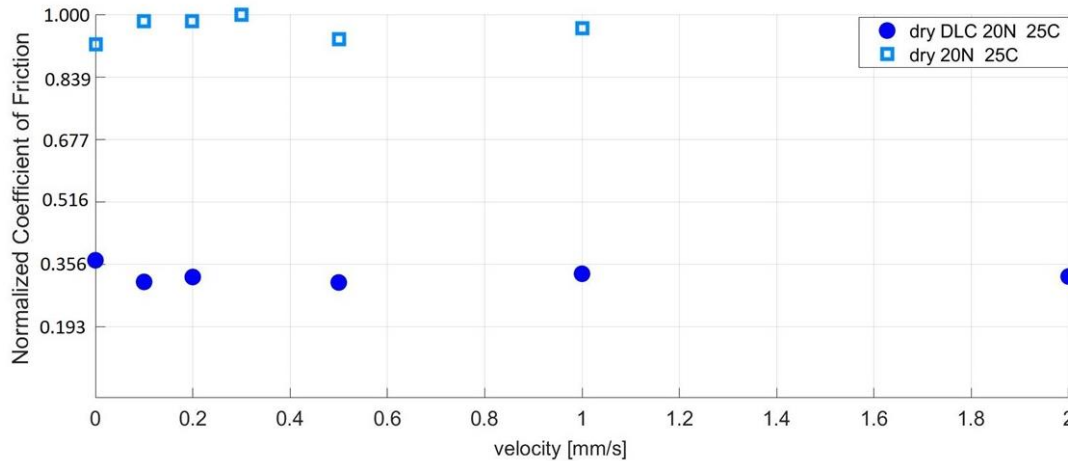


Figure 8: Comparison between the trend of the friction coefficient as function of the sliding velocity, with and without DLC coating, in dry condition.

Overall, the tests with DLC coating showed a faster running-in process, with less wear and lower steady-state friction, compared to the same tests performed on the same specimens without coating. The results are consistent with previous works in literature [32, 35, 33].

In conclusion, analysing the effect of the DLC coating on the overall frictional response of the contact pair, both in greased and dry conditions, the solid lubricant doesn't affect the frictional trend (as a function of the imposed sliding velocity), but only the overall value of the friction coefficient. In fact, the presence of DLC leads to a lowering of all the values of friction, compared to the case of a Steel/Steel contact, under the same boundary conditions, leaving the overall trend of the curves unchanged. All these observations let assume that the retrieved trend of the friction coefficient, with respect to the sliding velocity (Figure 4), is not determined by the presence of the DLC, which has an overall effect of decreasing friction.

### 4.3. Base oil lubrication VS grease lubrication

The performance of the base oil (PAO) without additives has been investigated too, aiming to isolate the influence of the oil, which composes the lithium complex grease analysed in this work, in the observed trends of the friction curves. The results are here compared with the ones obtained by the greased tests (Figure 9).

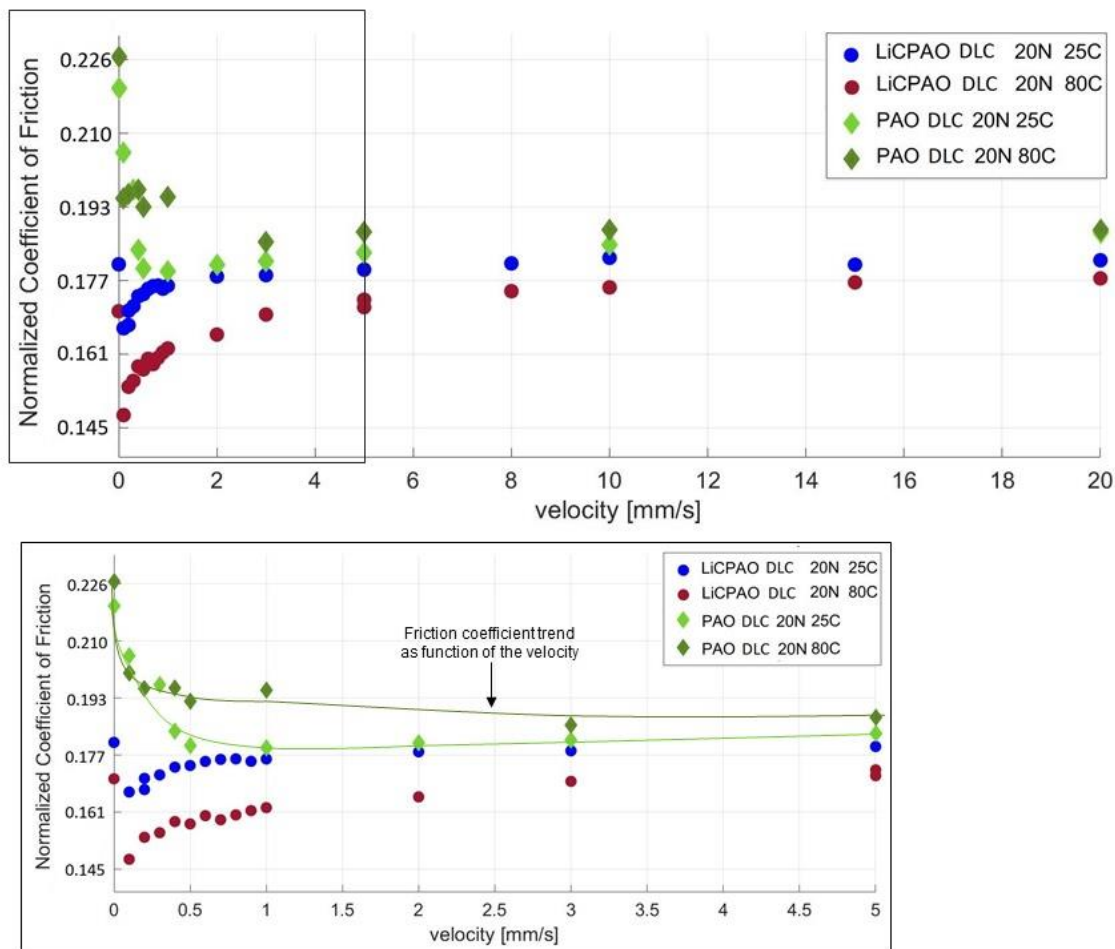


Figure 9: PAO and LiCPAO frictional behavior as function of the sliding velocity, at both room (25°C) and high temperature (80°C). The lower inset shows a zoom in the velocity range from 0 to 5mm/s.

As reported in the previous cases, also in the case of oil lubrication, there were no significant variations with the normal load. For sake of clarity, Figure 9 shows only the tests carried out with a normal load of 20N, at both room and high temperatures.

Looking at the curves of the base oil (PAO) lubrication, the maximum friction coefficient, which is the static friction coefficient, is following by an exponential decrease as the speed increases, producing a Stribeck-like curve, typical of a lubricating oil [5, 9]. Increasing the sliding velocity, the coefficient of friction becomes stable.

On the contrary, in the higher speed region, the friction coefficient measured in the greased tests converges with the one obtained by the base oil alone, letting assert that in this region friction is mainly governed by base oil viscosity, as expected when full oil lubrication regime is reached [9].

#### 4.4. Role of the Additives

The performance of the PAO base oil with additives, without thickener, has been investigated aiming to examine the influence of the additives, included in the lithium complex grease, on the trends of the friction-velocity curves. The results are shown in Figure 10 and here compared with the ones obtained by the tests performed with the grease (LiCPAO) and the base oil alone (PAO) (Figure 9).

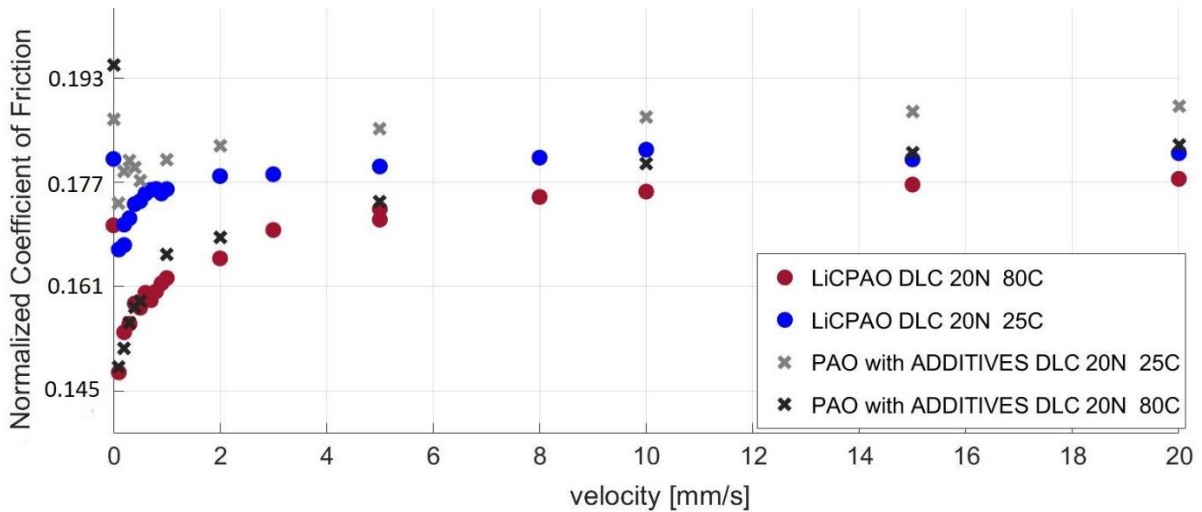


Figure 10: Frictional response, as function of the sliding velocity, of the contact with LiCPAO grease and PAO base oil with Additives, at both room (25°C) and high temperature (80°C).

The friction coefficient of the tests performed by the PAO oil with Additives (crosses in Figure 10) shows values close to the ones observed with the lithium complex grease (LiCPAO), except for the static friction, which results higher.

While in the high-speed region the friction reaches the values obtained with the base oil tests (PAO), in the low-speed region the friction follows the same trend observed for the greased contact.

Consequently, the lower values of friction observed at the lowest velocities, with the following increasing trend, can be ascribed mainly to the presence of additives, together with the thickener, which play the main role of maintaining the lubricant at the contact interface and decrease friction in boundary regime. The lower dynamic friction increases then the initial drop between the static and dynamic one, observed in oil lubrication, promoting stick-slip instability.

## 5. Conclusions

The present work addresses a greased contact of a real industrial case, a mechanical brake used in tubular electric actuators [29], which can generate stick-slip instabilities due to the frictional response between the two main brake components. Root causes of stick-slip instabilities are either a large difference between static and dynamic friction and/or a negative friction-velocity slope within the low sliding velocity range. Then, within this range, critical for such dynamic instabilities, the local frictional contact response has been here reproduced and analysed on a dedicated test bench, in order to evaluate the trends of friction as a function of the imposed boundary conditions. First, the influence of the DLC coating, present in the real brake system, has been analysed and compared to the uncoated case. Then, results with the base oil alone (PAO) and the thickener (Lithium Complex) have been compared too. Markedly different friction behaviours have been observed under the same operating conditions. It has been possible to identify the overall trend of friction within the investigated velocity range, and some of the relative influences of the lubrication components on the friction trends with respect to the velocity. The following conclusions can be drawn:



- All the investigated conditions under greased lubrication (i.e. different coating, normal load and temperatures) do not follow the typical Stribeck-like curve.
- While the well know effect of the additives and thickener, i.e. lowering friction at mixed and boundary conditions, has been retrieved, the main new finding of this work is the observation of a non-trivial trend of the overall friction, within the extremely low velocity range. Two regions have been identified in case of greased lubrication: the extremely low-speed range and the relatively high-speed range. First, the friction coefficient shows a drastic drop at the lowest velocities, showing frictional resistance much lower than the static one and the one due to the base oil lubrication. Then, it increases progressively up to values slightly higher than the one with the oil alone. Such trend of the frictional response of a greased contact, within the investigated range of sliding velocities, has not been previously observed in literature, even if the greased contacts often work in such extremely low velocity conditions.
- In the high-speed region, friction seems to be governed by the base oil. Increasing the sliding speed, the friction coefficient of the grease tends in fact to reach the oil behaviour, which follows a Stribeck-like curve. On the contrary, the frictional behaviour in the low-speed region seems to be mainly affected by the presence of the additives and the thickener. The friction coefficient of the greased contact, as well as the one of the oil with additives, shows values, at the lowest velocities, much lower than ones of the base oil alone. Afterwards, the friction increases again with the velocity.
- Consequently, while the grease reduces the static friction coefficient, the difference between static and dynamic friction coefficient (relevant for stick-slip propensity) stays high for both the oil and grease lubrication, because of the friction drop at low speeds. A schematic representation of the main trends discussed above is shown in Figure 11.
- In general, in all cases the difference between the static and the dynamic friction coefficient is significantly larger at high temperature, compared to ambient temperature, increasing the possible occurrence of stick-slip. This increasing in the difference between static and dynamic CoF is due to an overall decreasing of the dynamic friction coefficient values, as the temperature increases. This behaviour is independent of the tested loads and configurations.

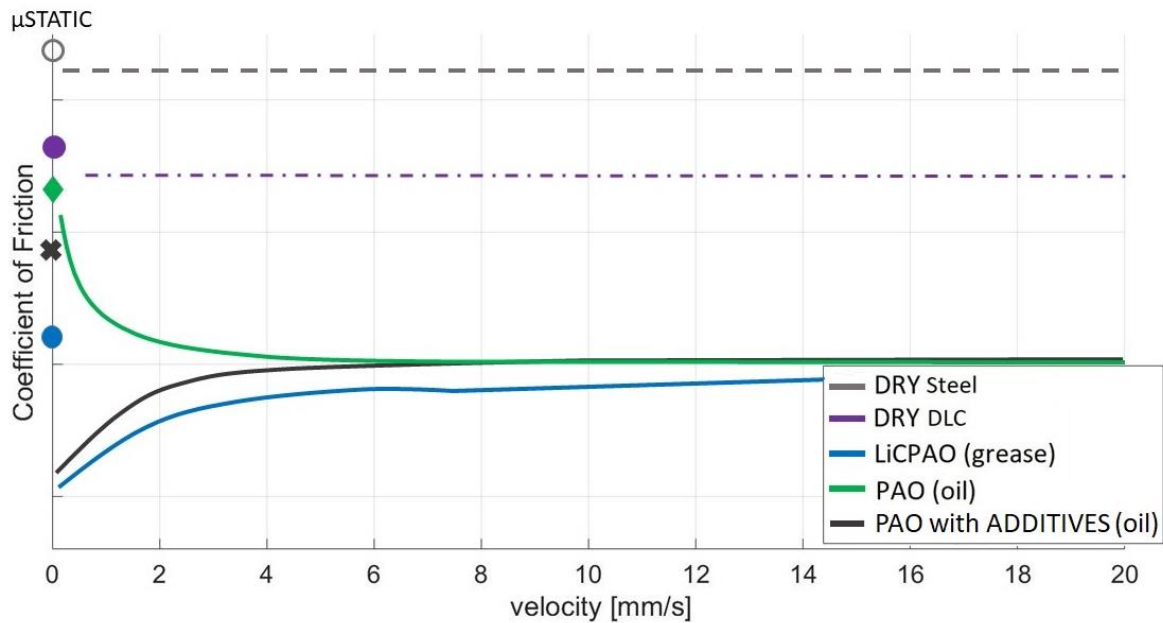


Figure 11: Generalized friction coefficient trends for the dry cases (Steel/steel and DLC/Steel), Lithium Complex grease (LiCPAO) and Synthetic base oil (PAO).

- Increasing the temperature, the greased friction coefficient behaviour (LiCPAO) shows lower values, independently of the tested loads and coatings. This decrease of friction at higher temperature could be associated to both a decrease in oil viscosity and an increase of oil release by the grease matrix, when the temperature increases.
- The hydrogenated amorphous DLC coating provide an overall decrease of friction coefficient, compared to the Steel/Steel contact, both in dry and greased conditions. In the case of the dry experimental tests, this difference is notable. In all cases (i.e. dry, LiCPAO, PAO and PAO plus Additives), the formation of a deposit of DLC on the contact countersurface is observed. Then, the DLC creates a third body layer on the counterpart surface, which decreases friction and prevents a premature wear.

In general, the thickener and additives contribution affect mainly the frictional response in static conditions and within the low-velocity range. The different observed frictional trends are a macroscopic result of the rheological and physiochemical interactions between the thickener, the additives and the base oil of the grease. With respect to stick-slip propensity, while the grease has a positive effect in lowering the static friction coefficient, the decrease of the dynamic friction coefficient in the lower-velocity range can promote stick-slip, by maintaining a large static-dynamic friction drop. In future works, rheological analyses will be addressed to investigate the rheological and chemical roles of the thickener and the additives in the lower-velocity range, with the aim of reducing the static-dynamic friction drop.

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