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Wet clutch friction characteristics obtained from simplified pin on disc test

Pär Marklund*, Roland Larsson

Division of Machine Elements, Department of Applied Physics and Mechanical Engineering, Luleå University of Technology, Luleå, SE-97187, Sweden

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Abstract

The frictional behavior of wet clutches in vehicle drivetrains is critical for their overall behavior. During the development of new wet clutch systems there is a need to know this friction behavior. The transferred torque is normally investigated in test rigs where the friction in a sliding interface between a friction disc and separator disc is investigated. These test rigs can be designed differently, depending on the working conditions of the investigated clutch. However, it is possible today to simulate the clutch behavior and not limit ourselves to only using measurements from test rigs for the design of the wet clutch. The torque transferred by the clutch during engagement can be roughly divided into full film torque and boundary lubrication torque. The full film regime is possible to simulate quite well, whereas the friction in the boundary regime is much more difficult to simulate due to its strong additive dependency. To obtain a good prediction of the total engagement, friction measurements in the boundary lubrication regime are still needed. These measurements should be easy to perform and fast tests are preferable. Friction coefficients for the whole range of sliding speed, interface temperature and nominal surface pressure should be measured. To use these measurements in simulations and get a better understanding of the friction behavior, it is also preferable to conduct these measurements on a small test sample, for which the temperature and sliding speed can be regarded as constant.

Here, the friction of a small sample of a wet clutch friction disc is investigated in a pin on disc test and the temperature is measured in the sample during the tests. Measurements are compared with measurements from a test rig for whole friction discs. A good correspondence between the frictional behaviors of the different measurement methods is achieved.

Keywords: Wet clutch; Friction measurement; Pin on disc

1. Introduction

Wet clutches are often used in vehicle drivetrains. The working conditions of different clutches in the transmission greatly vary depending on the application. Wet clutches in automatic transmissions are often used as lock-up clutches between different rotating parts in the gearbox, where the initial sliding velocity of the clutch interface can be quite high. Other parts of the drivetrain can have wet clutches that work with much lower sliding speeds and higher surface pressures. This is the case in limited slip differentials, which normally have a rather low surface sliding speed, and seldom reach the state of lock up. For the drivetrain to work smoothly without any unnecessary noise and vibrations, the friction characteristics of the wet clutches have to be thoroughly investigated. Depending on the working conditions some clutches will work in full film, mixed and boundary lubrication, whereas others will work mainly in boundary lubrication regime. To get a better understanding of the frictional behavior of wet clutches, several simulation models have been developed as a complement to traditional measurement methods [1–6]. Most investigations include simulations of clutches in automatic transmissions that start the engagement at a high difference in rotational speed and then reach a state of lock up. The high speed in these cases implies that the clutch will work in full film lubrication, the largest part of the engagement. Such an engagement process is possible to simulate with good results. There will be a torque

*Corresponding author.
E-mail address: par.marklund@ltu.se (P. Marklund).

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contribution from the boundary friction at the end of the engagement. This friction is much more difficult to simulate, since it is very additive dependent. For this part of the engagement there is still a need to do frictional measurements that can be used in simulations. For clutches working mainly in boundary lubrication, during longer periods, the simulations will be very dependent on measurements. Examples of simulation models for this kind of application are temperature simulations used to predict changes in torque transfer during a long engagement with high surface pressure and a small limited slip torque as in Marklund et al. [6]. For these kinds of semi-empirical simulation models, we encounter a need for a more local friction measurement than what is possible to measure in a test rig that measures torque transfer from one whole friction disc [3,7], or larger parts of a friction disc, including grooves [8]. A measurement method to do these local measurements should measure on a quite small sample of the friction disc, to get the local effects. It should also be possible to measure the temperature inside this small sample close to the sliding interface, since it is shown in [6,7], that the temperature will affect the friction. If the test sample has no grooves, the measured friction will not be geometry dependent. This is not the case when measuring torque transfer from a whole friction disc, where grooves and other surface patterns also can affect the torque. A measurement method based on a pin on disc test can fulfill all these demands. A special pin is designed with a holder for a small sample of the friction disc where a thermocouple is mounted to monitor the temperature during friction measurements. This method can also give a better understanding about the friction phenomena than what is possible in whole friction disc test rigs. The friction coefficient and its variation with temperature, sliding velocity and surface pressure is measured in this paper in a pin on disc test. The test is relatively fast and the normal range of operational parameters are covered within 2 h. Another advantage of the proposed test is the possibility to measure the local friction effect, which is of great interest when using measurements in simulations.

2. Method

A measurement of boundary lubrication is needed to be able to simulate torque transfer in wet clutches working in boundary lubrication regime. This friction is very additive dependent, and is therefore a function of the additives adsorption and reaction on the surfaces. Adsorption, desorption and reactions depend critically on the operating conditions temperature, sliding velocity and contact pressure. To obtain a friction coefficient for the whole working range of temperature, velocity and pressure, many measurements are required to describe the friction. The friction in the sliding interface of a wet clutch is often measured as output torque for one whole friction disc in contact with one steel separator disc. This is a good method to measure the final output from an existing wet clutch design, but if only the output torque is measured, the friction coefficient that can be computed for the clutch is simply the mean friction coefficient. Temperature and velocity are not constant in the interface, meaning that the friction is also not constant, see [2,6].

To get a better understanding of how the friction can be described in terms of temperature, velocity and surface pressure, a testing method that measures more local effects has been developed.

2.1. Pin on disc

A special holder is developed for a pin on disc test to enable these local friction measurements for the material combinations used in wet clutch systems. In a pin on disc test, a stationary pin is loaded axially in contact with a rotating disc, as in the schematic sketch shown in Fig. 1. The friction force on the pin can be measured, thus making it easy to compute the friction coefficient. The pin on disc machine used in these tests is a Phoenix Tribology TE67.

In these measurements, a special pin, Fig. 2, is made which has a holder for a small specimen made of a friction disc, Fig. 3.

A thermocouple that measures the temperature at about 0.3 mm from the contact surface is inserted in the specimen. Since the specimen only has a diameter of 3.0 mm, a constant velocity and temperature can be assumed over the whole test specimen contact area. This makes the measured friction suitable to use in wet clutch simulations and gives a better understanding of the boundary friction. The friction material on the friction discs used in this investigation is made of sintered bronze.

The disc is designed as a holder for a piece of the steel separator disc used in the real wet clutch system. This means that the test specimen will have the same properties as the separator disc used in the clutch. The lubricant used in these experiments is a semi-synthetic oil tailor-made for the Haldex Limited Slip Coupling, which is a limited slip differential manufactured by Haldex Traction AB. This application is further described in [9].

The friction measurements are in this case made to correspond with the working conditions of a wet clutch in a limited slip differential, meaning that the sliding velocities

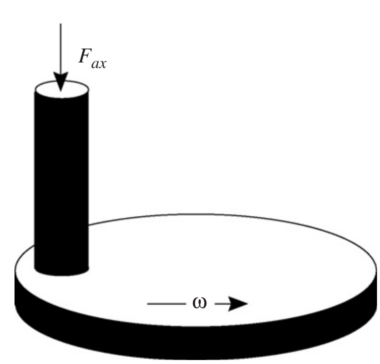

Fig. 1. Schematic sketch of a pin on disc apparatus.

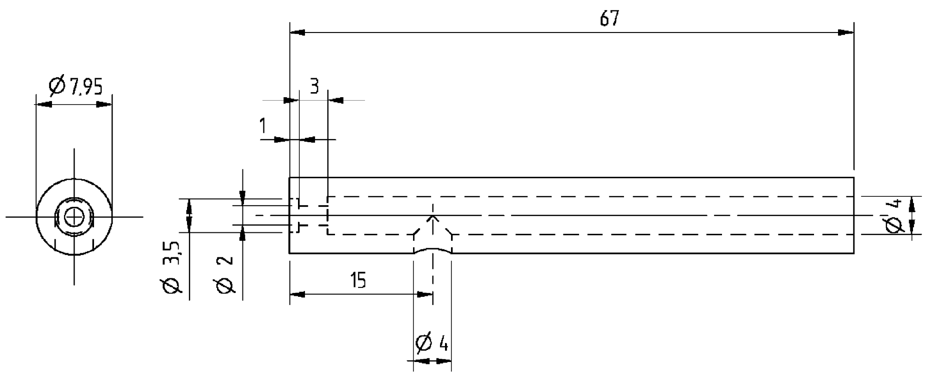

Fig. 2. Pin with holder for test specimen.

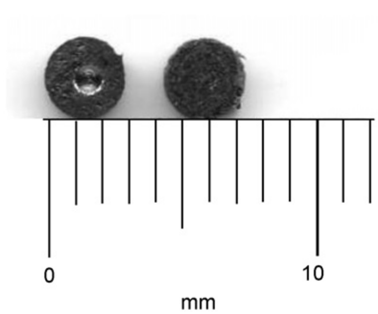

Fig. 3. Test specimens from bronze friction disc. Specimen to the left with drilled hole for thermocouple.

Table 1
Working range and resolution

	Working range	Resolution
Nominal surface pressure, p (MPa)	4.0–8.0	
Temperature, T (°C)	22–100	0.2
Rotational speed (rpm)	0–318	1.0
⇒ Sliding speed, v (m/s)	0–0.5	0.0016
Friction force, F_{fric} (N)	0–49	0.015
⇒ Friction coefficient, μ (–)		$<5.3\times10^{-4}$

will be fairly low while there will be quite high temperatures and surface pressures. The ranges for temperature, velocity and surface pressure and the resolution of the measurements are shown in Table 1.The sampling rate during the measurements is 10 Hz.

2.2. Test procedure

The tests start at an ambient temperature, 22 °C, and the equipment is gradually heated during the measurements.

Before the test starts, the surfaces are run in with the test lubricant. The disc rotates at a speed of 100 revolutions per minute for 10 min with an applied load, corresponding to a sliding speed of 0.15 m/s.

During the test, the velocity is increased from 0 to 0.5 m/s, followed by a decrease in speed to a standstill. The whole measurement takes about 30 s. When the test is finished, a heater is engaged to warm up the test equipment to the next temperature level and a new measurement is conducted. There is a temperature difference of 5 °C between the temperature levels. The total temperature range for which the friction is measured is 22–100 °C. The whole test series is therefore performed for 16 different measurements with different start temperatures.

3. Results and discussion

During each test the velocity is increased from standstill to 0.5 m/s and then decreased back to standstill. This variation in speed is not linear, and a typical velocity plot for the tests is shown in Fig. 4(a).

3.1. Temperature variation during test

The temperature in the test specimen increases due to frictional heating during the velocity increase. When the velocity is decreased, the temperature will decrease. This temperature behavior during the test is visualized in Fig. 4(b) for a start temperature of 25 °C. It is obvious from this figure that there is no significant delay in the temperature measurement, indicating that the measured temperature is a good measure of the mean temperature in the sliding interface. The sliding interface is located about 0.3 mm from the thermocouple. The temperature measurement is also a good indicator that the temperature is very dependent on the surface heat flux, since the temperature will immediately start to decrease when the velocity is decreased, see Fig. 4. The measured temperature in this point, 0.3 mm from the surface, will in this paper be referred to as interface temperature.

3.2. Friction measurements

To use the value of the friction coefficient in wet clutch simulations, or for a wet clutch control software, the most important is to describe the friction coefficient as a function of sliding speed, v, interface temperature, T, and nominal surface pressure, p. One test cycle in this pin on disc test will give this frictional behavior for one combination of friction material, lubricant and load. Results from the measurements can be visualized in differently. One way

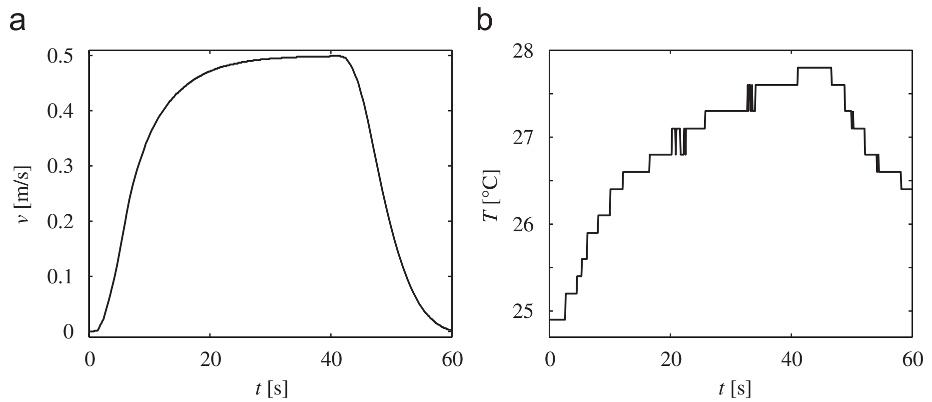

Fig. 4. Temperature variation and sliding speed during one test cycle: (a) sliding speed; (b) temperature.

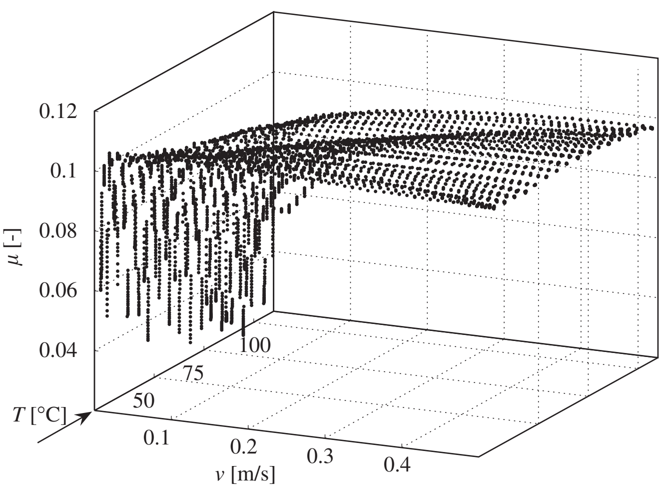

Fig. 5. Friction coefficient as function of sliding speed and interface temperature. Nominal pressure = 8.0 MPa.

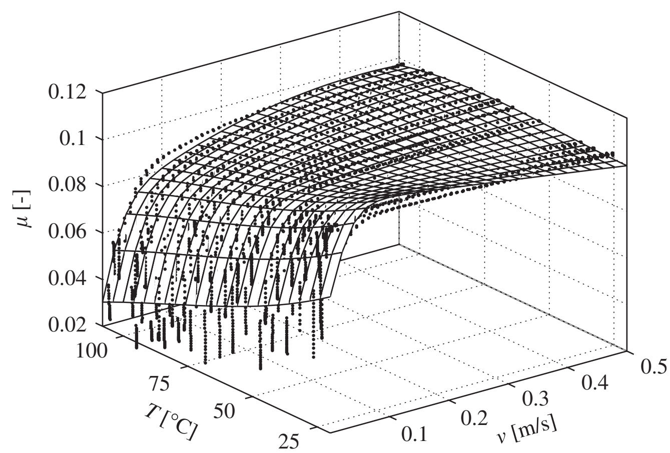

Fig. 6. Friction coefficient versus sliding speed and interface temperature. Measured data and approximative mathematical surface. Nominal pressure = 8.0 MPa. The mesh is the approximation according to Eq. (1).

is to plot the friction coefficient as a function of sliding speed and interface temperature, as in Fig. 5. The measurements are statistically very good with little spread between the measurements.

There are basically two ways to describe the relationship between friction coefficient, sliding speed and interface temperature. A mathematical expression can be fitted to the measured friction data, or the data could be stored in a large matrix from which friction coefficients could be interpolated from nearby cases. A mix between these two methods can also be used [6]. The advantage with an approximated function is that it will not need a large storage space, and that is vital for control softwares with small memory capacities. Another advantage with this method is that the friction coefficient will be easy to compute. The disadvantage is the limited flexibility of the chosen expression that can only be applied for a specific frictional behavior. For this case, the expression

$$\mu = a_1 + a_2 \cdot \tanh(v \cdot a_3) + a_4 \cdot T + a_5 \cdot T^2 + a_6 \cdot T^3 + a_7 \cdot v + a_8 \cdot vT + a_9 \cdot (vT)^2 \quad (1)$$

gives a good approximation to the measured frictional data, see Fig. 6.

In this equation μ is the friction coefficient, v is the sliding velocity and T is the interface temperature.

Another way to visualize frictional behavior is to use this expression and plot the friction coefficient as function of sliding speed for different interface temperatures, see Fig. 7.

3.3. Comparison with other test rig

Traditional friction measurements of wet clutches are performed in test rigs with one whole pair of friction discs [3,10]. In [8], larger parts of a friction disc, including grooves, have also been tested in a pin on disc test. With this test method, where a small sample of the friction disc is tested, it is important to investigate the correlation with other performed tests. Fig. 8 shows a comparison between curve fits from the measured friction coefficient in the pin on disc and a wet clutch test rig [10] with nominal pressures of 8.0 MPa.

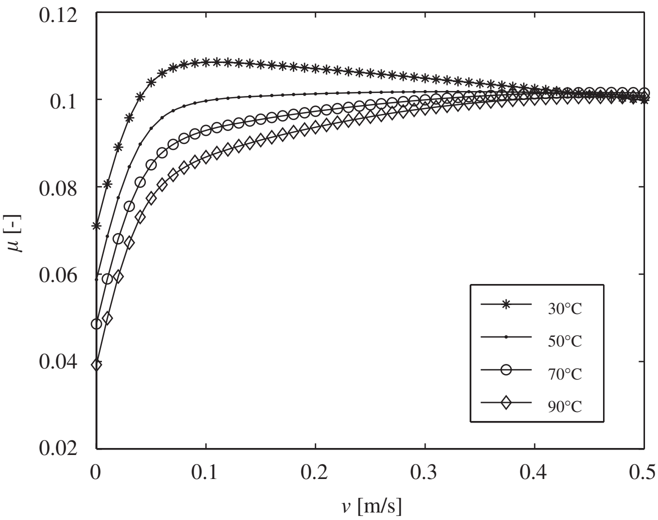

Fig. 7. Friction coefficient as function of sliding speed at different interface temperatures. Based on curve fitted mathematical surface. Nominal pressure = 8.0 MPa.

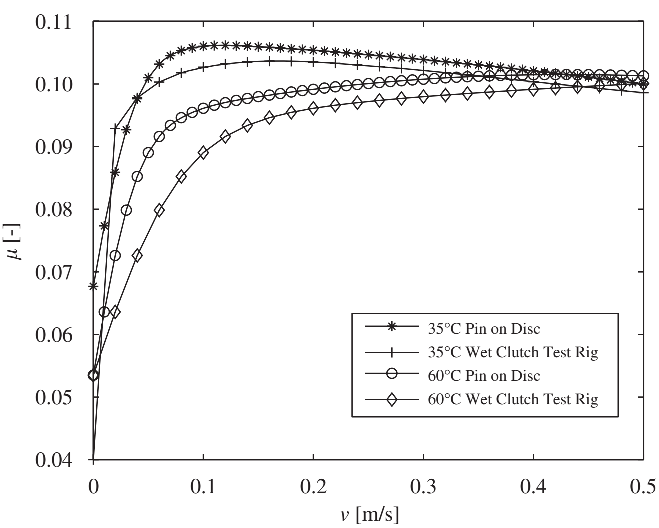

Fig. 8. Comparison between friction measurements in pin on disc and wet clutch test rig [10]. Nominal pressure = 8.0 MPa.

Friction coefficients from the different measurements show the same trends in variation of friction coefficient throughout the whole range of speed and temperature. However, the friction coefficient is consistently slightly smaller in the wet clutch test rig measurements. The measured friction coefficient should not be exactly the same for the different test rigs, since grooves are not included in the pin on disc test.

The nominal pressure on the friction discs used in the wet clutch test rig is calculated for the net surfaced area in contact in the interface, i.e. the groove area subtracted from the total disc area. A smaller difference in this area from the manufacturing process of the discs, could affect the geometry of the friction material and therefore the net surface area and nominal pressure for a given axial load, which would then influence the friction coefficient's variation with pressure.

3.4. Load dependence

The normal load does not greatly influence on the friction coefficient in these measurements. The fact that the friction coefficient is not very load dependent has also been earlier observed in other experiments, such as Mäki [11]. Fig. 9 shows the friction coefficient for three different loads in the whole range of sliding velocity. Here, the largest difference in friction coefficient is about 5% at 30 °C, Fig. 9(a). At 50 °C, Fig. 9(b), the difference in friction coefficient at different loads is not very large; hence, at these temperatures and higher it is possible to describe friction coefficient as only a function of sliding velocity and temperature without loosing much precision. At higher temperatures, Fig. 9(c) and (d), the difference in friction coefficient for different loads is even smaller. The lowest friction coefficient is achieved for the medium pressure of the three investigated pressures. This makes the difference in friction coefficient to be dependent on the load less plausible. It is possible that the difference in friction coefficient is instead dependent of other variables, such as surface structure and friction material composition, indicating that the friction coefficient could be described just as a function of sliding velocity and temperature for the whole temperature range. Fig. 9 also shows that for sliding velocities about 0.5 m/s, the friction coefficient, μ, will be about 0.1 for all investigated loads and temperatures.

3.5. Error analysis

As described in Section 3.4 the difference in friction coefficient for different surface pressures is not large. The friction coefficient could therefore be described as a function of only interface temperature and sliding velocity without loosing much precision. As a measure of the deviation of the measured data for the maximum and minimum load, the maximum deviation from mean friction coefficient computed for maximum and minimum loads is visualized in Fig. 10.

Here, six subsequent measurements at two different loads are investigated. These measurements will contain over 60,000 measurement points over the measured region described in Table 1. Fig. 10(a) shows plots from the curve fit expression (1) for each measurement at an interface temperature of 60 °C. From these functions the mean friction coefficient for 60 °C is computed. Fig. 10(b) shows the largest absolute deviation from the mean friction coefficient for each sliding velocity. This illustrates that the maximum absolute deviation in friction coefficient for these measurements in the velocity interval 0.05–0.4 m/s is less than 0.004.

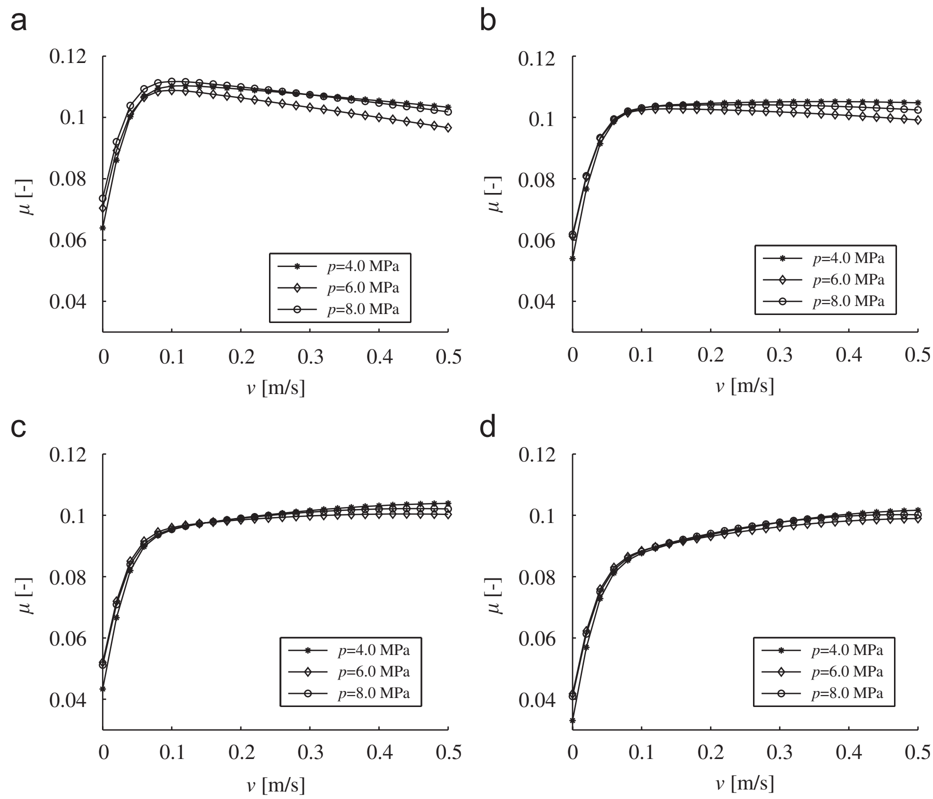

Fig. 9. The curve fitted mean friction coefficient, μ, from three measurements at each load is visualized for four different temperatures: (a) 30 °C; (b) 50 °C; (c) 70 °C; (d) 90 °C.

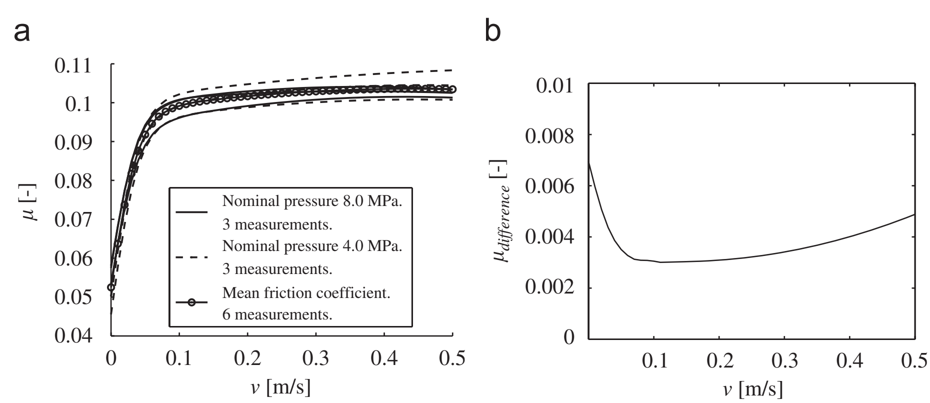

Fig. 10. Error analysis for six measurements with nominal pressures 4.0 and 8.0 MPa. Temperature 60 °C: (a) six measurements at two different loads; (b) maximum difference of six measurements to mean friction coefficient.

4. Conclusions

A simplified experiment is developed where the boundary friction behavior of a wet clutch can be investigated in a pin on disc test. The advantages with this method are that it is inexpensive and time saving to test different combinations of friction materials and lubricants. This makes the method suitable for screening-tests where a large number of different combinations can be investigated. Another advantage is that the pin on disc test measures more local friction than what is possible with torque measurements from a test rig where whole friction discs are investigated. This local behavior is preferable when using measured friction coefficients in simulations, such as [6].

The fact that this test method is rather geometry independent can be an advantage. The hydrodynamic effects can be considered in a simulation of the clutch disc friction behavior, thus providing a possibility to study the effects of not only different materials, but also different groove geometry that otherwise could be quite expensive to investigate.

The results from the pin on disc test were compared with tests in whole friction disc test rigs. A good correlation between the different tests was achieved. Since this method does not test the complete friction disc it should be regarded as a complement of ordinary wet clutch test rigs and not a total replacement of those rigs.

The friction coefficient is not greatly affected by load at temperatures above about 50 °C. Even for lower temperatures the load dependence is not substantial. At 30 °C, the maximum difference in friction coefficient is about 5% between different loads, indicating an opportunity to simplify the friction coefficient function because a sufficiently accurate friction coefficient can be described as only a function of sliding velocity and interface temperature for many cases at a normal working temperature.

Acknowledgments

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