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Influence of surface topography on friction characteristics in wet clutch applications

Pär Nyman[a], Rikard Mäki[a,*], Richard Olsson[b], Bager Ganemi[c]

[a] *Luleå University of Technology, Division of Machine Elements, SE-971 87 Luleå, Sweden*
[b] *Haldex Traction Systems AB, Box 501, SE-261 24 Landskrona, Sweden*
[c] *Statoil Lubricants R&D, Box 194, SE-149 22 Nynäshamn, Sweden*

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Abstract

In heavily loaded wet clutches, such as in limited slip differentials, sintered friction materials are sometimes used due to their resilience at high loads and high temperatures as well as their competitive cost in comparison to alternative friction materials.

During the lifetime of the clutch, changes in the friction materials' topography occur. These changes will influence the friction characteristics of the clutch, and therefore affect the anti-shudder performance of the transmission system. This paper investigates the influence of, and classifies, changes in the topography of the sintered friction material.

The topography is measured by utilizing vertical scanning interferometry. Different parameters are investigated in order to find relevant parameters correlating to the wear of the material.

Results show that changes in the topography of the friction material do indeed influence the friction characteristics of the clutch and that it is possible to calculate relevant topography parameters that describe the amount of wear the material has been subjected to.

Keywords: Wear; Topography; Wet clutch; Stick-slip; Sintered friction materials

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1. Introduction

The Haldex LSC AWD system features a multiple disc wet clutch that consist of clutch plates covered with a sintered friction material running against separator plates made from hardened steel. The clutch pack distributes drive torque to the rear axle of the vehicle. By electronically controlling the wet clutch, controllability of the torque transfer is gained. Hence it is possible to electronically control the drive train in order to optimize the function of different electronic driving aid systems.

Characteristic operating conditions for wet clutches in this type of application include low sliding velocities and high clutch disc pressure, typically up to 0.5 m/s and 10 MPa. Under these conditions it is common that stick-slip or shudder arise. This behaviour has been investigated and described in a number of papers, both experimentally [1–5] and theoretically [6–8].

The general opinion on this matter states that in order to avoid vibrations, the friction–velocity ($\mu - v$) relationship should present a low static coefficient of friction (μ_s) and a dynamic coefficient of friction (μ_d) that increases as the sliding velocity increases.

The friction characteristics will not be constant throughout the life of the clutch, generally the anti-shudder properties will deteriorate, and at some point cause audible shudder to occur which will determine the end of life of the clutch system. The changed properties can be attributed to degradation of the lubricating oil as well as wear or degradation of the friction material [9]. A number of different articles dealing with the degradation of organic (or paper-based) friction materials have been presented [10–12], but on the degradation of sintered sinter material less effort has been made so far.

The aim of this paper is to investigate whether the change in frictional behaviour can be explained by changes in the topography of the sintered fiction material and, if that is the case, try

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[*] Corresponding author.
E-mail addresses: Rikard.Maki@ltu.se (R. Mäki), Richard.Olsson@haldex.com (R. Olsson), sbga@statoil.se (B. Ganemi).

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to find relevant surface parameters that can be used as a measurement of the wear or degradation.

1.1. Approach

The problem has been approached by first running tests in a clutch test equipment in order to investigate whether the change in friction is caused by fluid degradation or by a change in the friction material properties.

The next step is to run a number of clutch plates for different sliding distances, ranging from only a short running-in up to the occurrence of shudder, i.e. end of life. After the tests, each friction disc is cleaned and then the topography is measured in three dimensions using vertical scanning interferometry.

After that, the topography has been evaluated by calculating many different surface parameters in order to find parameters that give reasonable values and describe the functional surface in a proper way. One source that causes a lot of complications in this work is the porous nature of the friction materials which makes many standardized surface parameters unstable or cut-off dependent, and therefore unusable in this investigation.

The final step is then to correlate the identified surface parameters to the sliding distance in order to find parameters that describe the wear of the friction material. Ultimately this should yield a method that enables the engineer to predict the residual life of the friction disc by only performing a few topography measurements.

1.2. Limitations

The sintered fiction material is much softer as compared to the opposing hardened steel separator plates, as revealed by much larger deformations in the sinter material. Therefore, this study has primarily investigated the change in topography of the friction discs and not that of the separator plates.

The topography has been studied at micron scale, i.e. the oil grooves, as can be seen in Fig. 2, have not been included in the study. The surface parameters are only calculated using the part of the surface actually influencing the friction characteristics, i.e. typically the fraction of the surface within 8 μm below the highest summits.

All tests have been performed using the same type of transmission fluid, i.e. the commercially used Statoil LSC fluid. The study covers two different generations of one commercially available sintered friction material (see Section 2.2).

2. Method

2.1. Equipment

The investigated clutch plates have been tested utilizing the Limited slip clutch test rig, with the exception of a number of clutch plates originating from full-scale vehicle tests. This equipment is described below.

The surface topography has been measured using a vertical scanning interferometer called NT1100 from Wyko; this method has also been briefly described below.

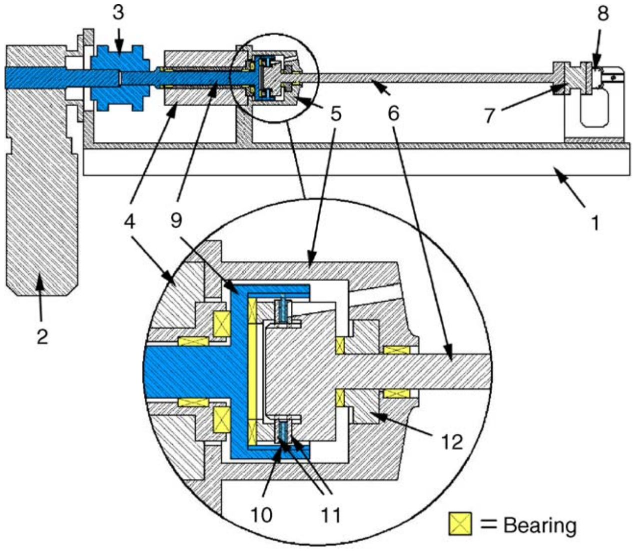

Fig. 1. Simplified cross-section of the Limited slip clutch test rig.

2.1.1. The Limited slip clutch test rig

The friction measurements have been carried out using the LSC test rig (Fig. 1) [13].

The speed can be varied between 0.5 and 125 rpm (2.5–600 mm/s on the mean radius). The normal force on the test clutch is applied by a double acting hollow piston cylinder (4). In this case the normal force was limited to 30 kN by a pressure limiting valve.

In the magnified view of the clutch housing in Fig. 1, the friction disc (10) and the separator discs (11) can be seen. The friction disc is connected to the driving shaft (9), and the separator discs are connected to the torsion bar (6). During operation, the shaded parts in Fig. 1 are rotating.

When a normal force is applied to the clutch by the hydraulic cylinder (4), torque is transmitted from the driving shaft (9) to the torsion bar (6). The transmitted torque is then measured by the torque transducer (7). The applied normal force is measured by the load cell (12). This is possible due to the slider system (8) which allows the torsion bar and torque cell to move freely in the axial direction. Both the force and torque transducers are full bridge, strain gauge type with built-in amplifiers. The accuracy of the measurements from this rig is well within ±1% [13].

During this investigation thermocouples have been installed in the oil sump to measure oil bulk temperature, and in the separator disc to measure friction surface temperature.

2.1.2. Wyko NT1100

The Wyko NT1100 utilizes vertical scanning/white light interferometry. The technique uses the bright and dark pattern which is the result of the splitting of a light beam where one part is reflected against an internal smooth reference surface and the other off the sample. After reflection the beams recombine in the interferometer and a pattern of constructive and destructive interference occurs. The pattern is photographed by a CCD-camera analyzed by using a computer. A piezoelectric transducer moves the focus down and another picture is taken continuing until the specified scanning depth is reached. Then the pictures are ana-

Fig. 2. Investigated clutch discs. Separator disk of hardened steel to the left and friction disc with sintered brass friction material to the right.

lyzed in the computer which store the height data and create a three-dimensional picture. After this the measurement data can be analyzed. The software used for the analysis was Vision32.

The optics in use has a large influence on the accuracy of the topometer. In this investigation a magnification of 1.25 have been used. As a result of this the smallest measurable area is 6.57 μm × 6.57 μm. Height resolution is set to 1 nm. Additionally there is a built-in uncertainty due to problems with the reflection properties of some surfaces. The total area of measurement is 3.8 mm × 5.0 mm and covers more than a full square of the groove pattern of a sintered lining friction disc (see Fig. 2).

A measurement uncertainty analysis was performed which showed that 10 measurements on each friction disc is sufficient in order to obtain an interval of confidence level of about 90%.

2.2. *Friction and separator discs*

In this study two different sintered friction materials have been investigated, one is an older composition and the other a newer modified material. The investigated friction materials consist of a dispersion sintered lining with a brass base applied to a hardened steel disc. These materials are able to withstand higher stresses and temperatures compared to paper-based materials and are fairly cheap to manufacture contrary to carbon-fibre materials. The separator disks are manufactured of hardened steel.

A friction pair can be seen in Fig. 2. The outer diameter of the friction lining is 108 mm, and the inner diameter is 76 mm. The area of contact when the oil grooves have been accounted for is approximately 2250 mm^2. The grooves facilitate oil distribution to the area of contact, and help in lowering the temperature in the clutch by enhanced oil flow.

The friction materials consist of a brass base containing a small amount of solid carbon-based lubricants. In addition to this, they also contain solid friction increasing fractions such as silicon oxides. Their heat conductivity is ∼15.7 W/m °K, their heat capacity is ∼471 J/kg °K and their E-module is 2000–5000 MPa (porosity-dependant).

The older type of friction material appears darker in colour compared to the newer material. More importantly, the life of the material differs by a factor 4 in favour of the new composition under the test conditions chosen in this study. The older material managed to sustain its frictional properties for about 8 h compared to 32 h for the new material. The test is accelerated and these values should therefore not be regarded as actual values but rather serve as an indication of the performance of the materials under very high load conditions. The older material, in comparison with the newer material, contains less copper and tin, and a larger fraction of zinc and solid carbon-based lubricants.

The topography of the sintered face of the friction disc is very porous; this enables the lubricant to reach to and flow through the contact zone providing lubrication and transporting the frictional heat away.

When measuring the topography, the high porosity makes the measurement complicated due to the fact that at the bottom of the pores, if there is one, the material doesn not reflect light; this means that the ratio of measured data points to actual points usually is about 50–70% compared to about 99% for a homogenous steel plate. The problem was solved by normalizing the measurement data to contain only height information 3 μm above and 5 μm below the most frequent height of each measured surface. Another advantage of this is that most of the points left in the dataset have participated in the contact between the surfaces, i.e. points that actually experience a change in topography. The topography of a new friction disc is too rough to be characterized using the topometer.

2.3. *Lubricant*

In this study a commercially used semi-synthetic Statoil LSC fluid designed for this application have been used. This fluid has a viscosity of 35cST at 40 °C and 6.7cST at 100 °C, and meets the requirements for a fill-for-life service in the vehicles. The lubricant is further described in [5].

3. Friction

3.1. *Test cycle*

Each tested clutch disc is run at a different number of load cycles. A load cycle consists of two parts, unloaded and loaded. The unloaded part lasts 30 s and the loaded 30 s, i.e. one load cycle/min. During the loaded part, a normal force of 15 kN, a

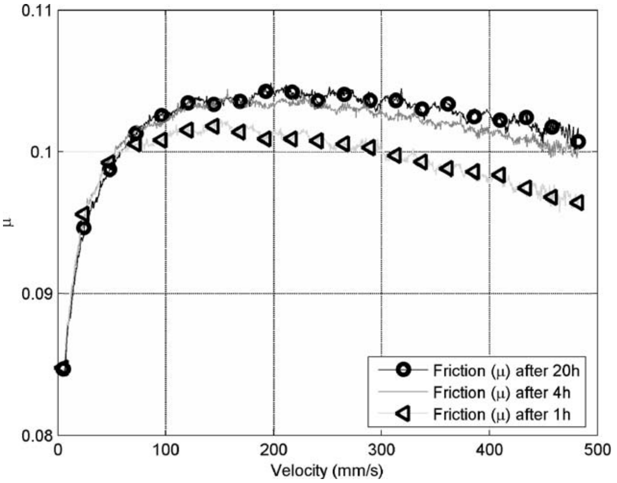

Fig. 3. The change in friction characteristics during clutch life.

force that accelerates the testing without exceeding the maximum force in road application, is applied to the clutch. As the clutch engages an overshoot of the force is present yielding around 20 kN for the first 1–2 s before levelling out at 15 kN. The sliding velocity is always held constant at 25 rpm and the cooling oil flow between the friction surfaces is 200 ml/min.

Some of the discs have also been tested in order to determine the friction characteristics. In this test the load is 20 kN, and same oil flow as before. The velocity is first held constant at 1 rpm, and then the velocity is linearly increased from 1 to 100 rpm in 10 s while the friction is monitored yielding the friction–velocity characteristics. This speed ramp is run five times each at temperatures 50, 40 and 30 °C.

3.2. *Changes in friction characteristics during clutch life*

The friction characteristics change during the life of the clutch. After run-in, as seen in Fig. 3, the friction characteristics stabilizes and changes very little over sliding distance.

In order to verify that the friction discs play an important part in the clutch performance, a set of fresh friction discs and fresh lubricants were driven until shudder occurred. The friction characteristics were measured, and after this the oil was changed. The clutch was run for another hour and the friction characteristics were measured once again. As the result in Fig. 4 shows, the curves are quite similar, indicating that the friction material rather than the fluid is responsible for the change in friction during clutch life. Thus the friction material has a severe impact on clutch life. A friction disc of the newer type lasted typically about 32 h in the test rig compared to about 8 h for the older material (see Figs. 9 and 10).

4. Topography

4.1. *Measurement method*

Before measurement every disc has to be cleaned. This is performed by ultrasonic cleaning. A magnification of 1.25 allows measurement over a full square of the groove pattern on the friction disc while maintaining high accuracy. The scanning depth is set to well cover the 8 μm depth required for data analysis.

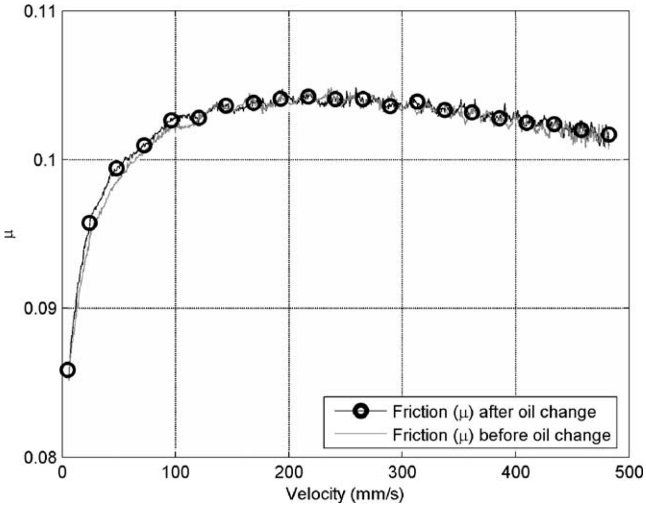

Fig. 4. Friction characteristics before and after oil change.

4.2. *Method for recognizing the contact area*

If the histogram curve describing the height distribution of an unworn surface of a sintered friction disc is known, it is possible to find the lowest height that has been in contact with the counter surface. This is of great interest since every point higher than that actually has been subjected to wear. Still the measurements in this work are normalized to contain data points below the lowest contact height since it is believed that they affect friction characteristics.

The method is performed by trying to find a point in the right hand side of the histogram curve which contains height information from at least three data points, everything higher than that can be considered noise and should not be taken into account. The next step is to find a point in the histogram curve where the negative slope suddenly increase, this point is denoted 'decreasing negative slope' in Fig. 5, and a point close to it where the negative slope decrease, this point is denoted 'Increasing negative slope', going from right to left in Fig. 5. The heights

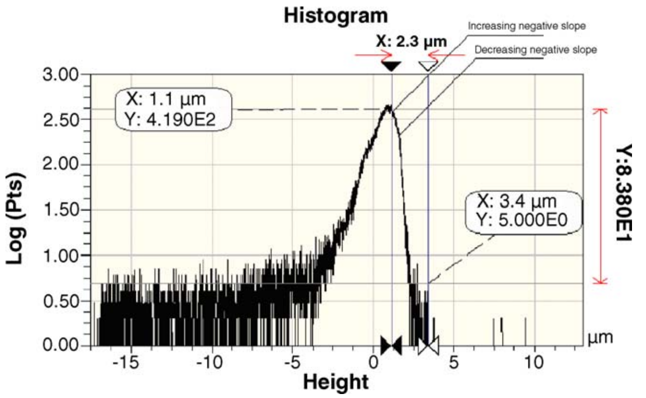

Fig. 5. Histogram curve with cursors enclosing the points that has been subjected to wear.

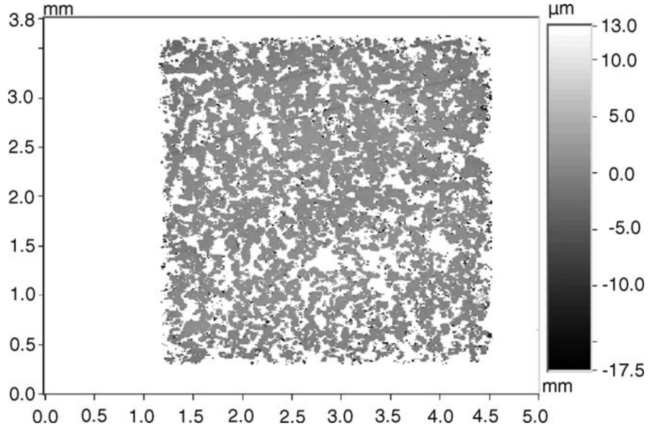

Fig. 6. The surface described in Fig. 5 before removal of data points. White spots contain no height information.

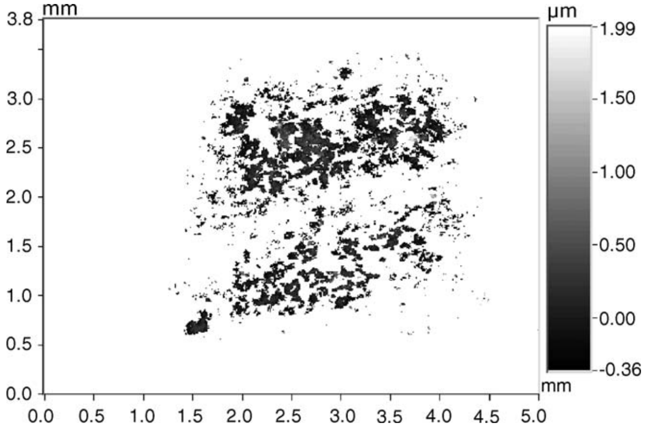

Fig. 7. The same surface as in Fig. 6 after removal of surface points which have not been subjected to wear. White spots contain no height information.

between these two points represent the points on the surface that has only partly participated in the contact between the friction surfaces. The increasing slope is caused by the fact that all the summits higher than this point has been worn down and by that has been moved to this area in the histogram curve. The area where the slope decreases represents the points on the surfaces that has been subjected to the most wear. The slope decrease because the points that used to be in this area has been worn down and thus been moved to a lower level in the histogram curve, i.e. the area between the two described points. Summarized the method assumes that the points to the right in the histogram curve when the disc is new moves to the left in the histogram curve when they are subjected to wear; this in turn causes the slope in the curve to change in two distinct points as described. Figs. 6 and 7 display a measured surface before and after use of the method described.

4.3. Investigated parameters

All of the parameters investigated are included in the Birmingham 14 parameters, a proposition of standardization of surface topography measurement. The parameters chosen are S_{sk}, surface skewness which describes the skew of the height distribution of the surface and is usually referred to as an amplitude parameter. This parameter describes the distribution of heights but it contains no information of where on the surface a certain height is located. The next parameter is S_{dq} or $S_{\Delta d}$, as it is referred to sometimes. It describes the average slope of the surface, i.e. in a way it relates a specific height to its closest neighbours, and thereby it is dependant of lateral resolution since this determines the distance to the neighbours and the height resolution since this determines the smallest measurable height difference. In that manner it is similar to the next parameter S_{sc}, the arithmetic mean summit curvature of a surface. S_{sc} is highly resolution sensitive since it is only calculated for summits. Both S_{dq} and S_{sc} are often referred to as hybrid parameters. The final parameter of this study is S_{bi}, the surface bearing index, it is included in the investigation because it claims to describe the load-bearing capacity of the surface, something that is considered important. S_{bi} is a so-called functional parameter.

4.4. Changes in topography during clutch life

The topography of the sintered friction lining changes during its life time, as shown in Fig. 8. When new, it is very porous and rough as a result of the manufacturing method. The run-in process is characterized by its high wear rate, which is a result of a number of processes, one of which is the high contact pressure applied to the highest summits. This results in wearing down of the high summits and fresh material coming into contact from below. The wear rate then decreases with the decreasing pressure applied to the summits caused by an increase of the real area of contact. This eventually leads to a state of constant wear rate, which is referred to as steady state. Both on the sintered face

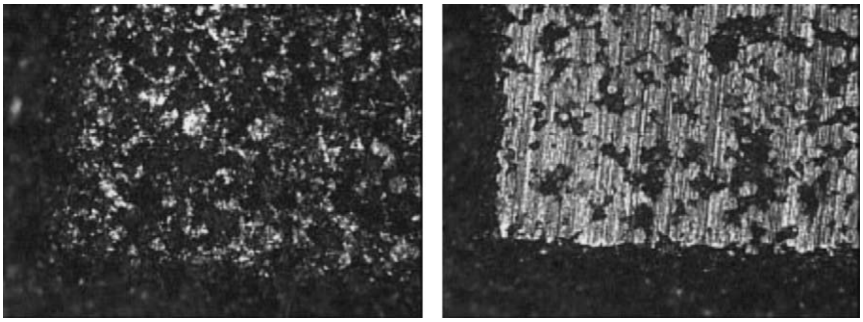

Fig. 8. New surface to the left and a worn surface to the right.

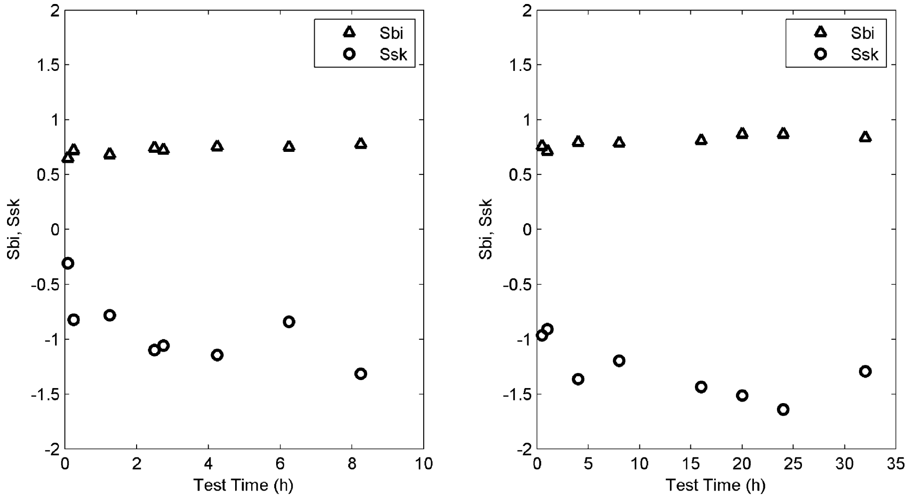

Fig. 9. S_{bi}/S_{sk} older friction material to the left, newer to the right.

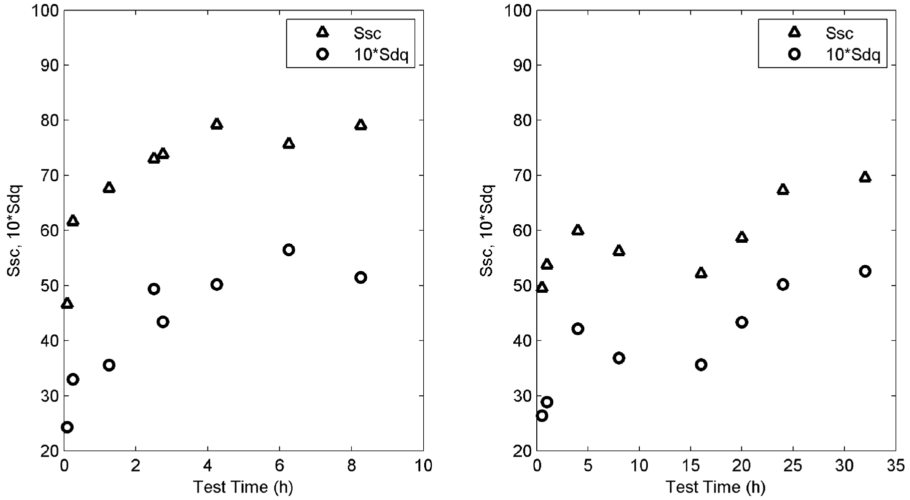

Fig. 10. $S_{sc}/S_{dq} \times 10$ older friction material to the left, newer to the right.

and on the steel face of the friction discs, traces of abrasive wear were found, probably caused by strain-hardened debris.

The results of the parameter investigation, shown in Fig. 9, indicate that S_{sk}, since it is decreasing with sliding distance, can be used for characterization of a change in topography. However, the parameter is much too uncertain, for one of the discs measured, the standard deviation was 75% of the average value. S_{bi} does not indicate the change in topography since it remains practically constant over sliding length. A closer study of the parameter reveals that it is almost linearly dependent on cut-off length and inversely proportional to S_q, the RMS average roughness. S_{dq} and S_{sc}, however display a trend towards increasing with wear and have a steep slope during run-in, indicating a high wear rate, as a suitable parameter is expected to have. Since the two parameters are quite similar in their way of describing the surface, they also display similar curves. There is a small difference though, probably caused by the fact that S_{sc} is calculated only for summits while S_{dq} is calculated for the entire measurement data set. When comparing S_{sc} and S_{dq} for the newer and the older type of friction disc, they appear to have about the same trend although different wear rates.

As seen in Fig. 10, the parameters S_{dq} and S_{sc} increase with increasing sliding length; however, the figures show spurious points. This is probably caused by small differences in the manufacture of the friction discs. Since each point in the figure represents the average value of 10 measurements on a single friction disc, the result is sensitive to differences in porosity and composition of the friction material in the measured friction discs. If a friction disc from a car or a test is measured and the composition is known, it is possible to get an indication of the remaining life of the wet clutch by looking in the graphs shown in Fig. 10.

5. Conclusions

(1) The friction discs in a wet clutch play an important part in the anti-shudder performance of the clutch.

(2) It is possible, by characterizing the topography and calculating the parameters S_{sc} and S_{dq}, to predict the remaining lifetime of a sintered friction material in a wet clutch.
(3) Due to the uncertain nature of the parameter S_{sk} it is not recommended to be used for characterization of rough and porous surfaces.
(4) The parameter S_{bi} is not suitable for characterization of the topography of the friction material of a wet clutch since it does not change over sliding distance.

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