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Humphrey, Edward, Theofilos Gkinis, Nicholas J. Morris, Michael Leighton, Ramin Rahmani, and Homer Rahnejat. 2019. “Clutch Lining Frictional Characteristics Under Thermal Tribodynamic Conditions”. figshare. https://hdl.handle.net/2134/22656.

3rd Biennial International Conference on Powertrain Modelling and Control (PMC 2016)
Testing, Mapping and Calibration
7th-9th September 2016, Loughborough University, UK

Clutch Lining Frictional Characteristics under Thermal Tribodynamic Conditions

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Abstract

The frictional performance of the clutch mating surfaces varies transiently during clutch engagement. The friction characteristics depend on the clamp load, relative slip speed of the mating surfaces and the generated contact temperature. These operating conditions affect the characteristics and lead to clutch take-up judder during engagement. To study this phenomenon as well as issues relating to clutch wear, it is essential to evaluate the friction lining characteristics. This paper replicates the clutch conditions through careful experimentation with a fully instrumented pin-on-disc tribometer. It is shown that the kinetic coefficient of friction for the clutch friction lining material in contact with the sinusoidal wavy and rough surface of pressure plate decreases with rising contact temperature and increasing slip speed.

Keywords: *Clutch friction lining, coefficient of friction, pin-on-disc tribometry, stick-slip oscillations, micro-slip creep*

1. Introduction

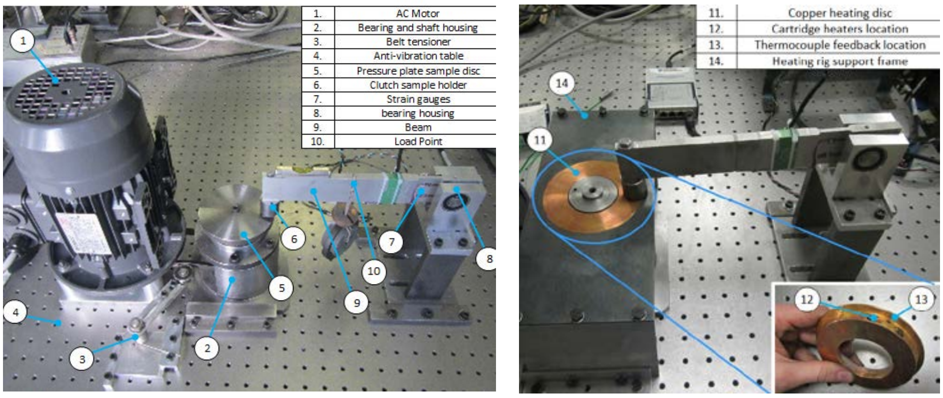
The interfacial friction generated between the automotive clutch lining and the flywheel and pressure plate is responsible for transfer of engine torque to the drive train system, thus determining the drivability of the vehicle. During the engagement process the engine supplied torque reduces as that of the driven inertia (the remainder of the powertrain system) is increased, achieving equilibrium. The transmission of power is thus achieved. However, during the process of engagement the transient response occurs as the result of relative interfacial slip condition. This leads to stick-slip conditions, known as clutch take-up judder. The stick-slip oscillatory behaviour continues thereafter as well, but with significantly reduced amplitude (as a micro-stick slip, which is not very discernible). Therefore, clutch Judder is characterised by the torsional oscillation of the clutch, particularly during the engagement process. Judder is the first rigid natural frequency response of the clutch system, which is accompanied by a fore and aft motion of the vehicle. The propensity of the vehicle to undergo judder has been found to be as the result of two main underlying causes. These are loss of clamp load, which can occur as the result of rapid release of the clutch pedal, providing insufficient time for the proper clamp load to be generated [1-3]. Another contributing factor is the friction characteristics of the clutch lining material, specifically a negative slope in the variation of coefficient of the coefficient of friction with relative interfacial slip speed.

The clutch lining friction characteristics alters with clamp load and contact temperature as well as with the interfacial slip speed. This shows the interactions between the clamp load and contact kinematics. Therefore, the determination of the frictional characteristics is a prelude to the prediction of system dynamics as well as the thermal performance of the lining. To obtain these characteristics a set of controlled test is carried out using an in-house built fully instrumented precision pin-on-disc tribometer. Realistic contact pressures, based on clamp load variation during the engagement process, representative of a light truck clutch system is maintained during the tribometric studies, also applying a range of practical slip speeds and clutch operating temperatures. The experimental procedure also comprises measurement of surface topography of the counter face surfaces pre and post testing using an infinite focus white light interferometer to take into account the state of wear of surfaces.

2. Method

2.1. Test rig

A unidirectional pin-on-disc tribometer is used to simulate the contact conditions found during clutch engagement (figure 1). The tribometer comprises an AC motor (1) driven disc (5) with the same material and surface topography as the pressure plate of the clutch system under investigation. A loaded beam (9) supports the vertically loaded pin of rectangular cross-section, to the contacting surface of which a piece of clutch lining sample is firmly attached (6). This sample makes a flat contact with the rotating disc (5). A recess in the beam allows for its bending to be predominately confined to a single section of the beam which can be measured using a strain gauge rosette (7). The addition of a copper heating disc (11), shown in figure 1(b), allows for the bulk surface temperature of the disc to be controlled though a feedback loop. The close proximity of the disc (5) to the copper plate (11) allows for a significant amount of heat transfer, raising the bulk temperature of disc to $80^{\circ}C$ in 15 minutes.

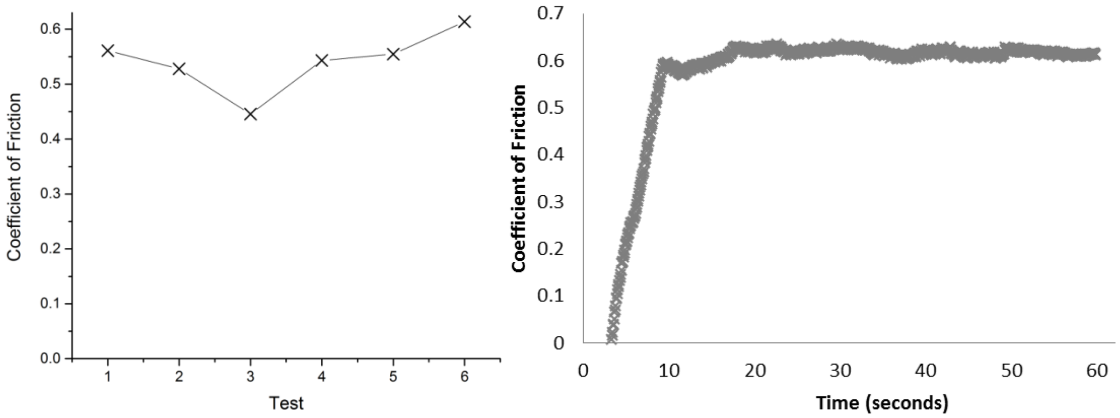


(a) (b)

Figure 1: (a) The pin-on-disc tribometer (b) the heating system

A measurement frequency of 1000Hz is used in line with the ATSM G163-10 which recommends that the sampling rate must be 10 times the highest frequency present in the signal.

To quantify the measurement error with the tribometer a well-documented material pair is initially tested, comprising a mild steel disc and a chrome-steel ball, both of specified surface topography. The published coefficient of friction for such a pair is between 0.4 and 0.6 [4]. A series of six tests were performed at 300 rpm and a contact pressure of 792MPa, assuming a flat rectangular contact. By taking the coefficient of friction from the steady state portion of the graph and discounting the initial transient period, the standard deviation can be calculated. The results of are shown in figure 2.



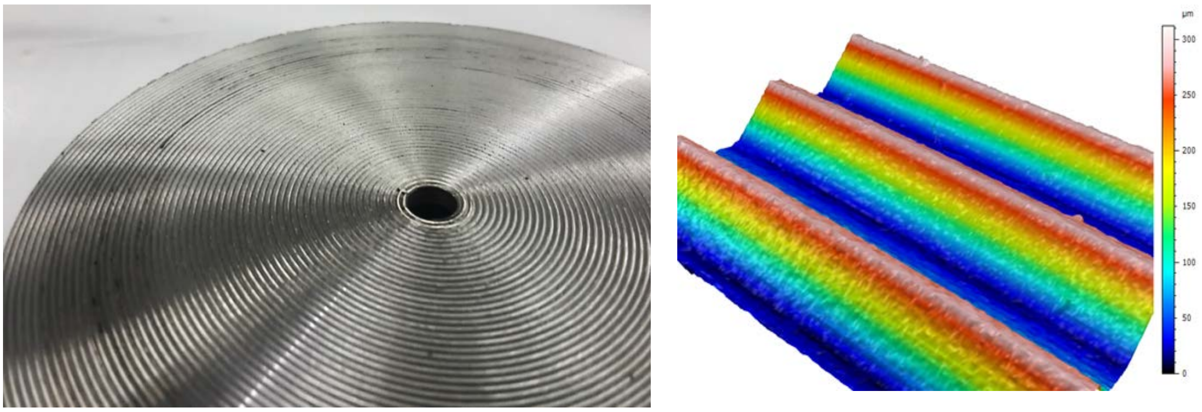
(a) (b)

Figure 2: A chrome-steel ball on steel disc pair: (a) A graph showing the variations in repeated measurements, (b) variation of coefficient of friction in a single experiment

The results in figure 2(a) show the variation between tests, which has a mean value of 0.541 and a standard deviation of 0.055. Figure 2(b) shows the variation of the coefficient of friction with time during a single experiment. A transient region can be observed within the first 10 seconds after which a steady state condition is reached. The representative coefficient of friction is taken from the steady state conditions, and it conforms well with those reported for the same counter face surfaces in the literature [4]. This procedure imparts a good degree of confidence with respect to the measurement devices and procedures, as well as serving as a robust method of system calibration.

2.2. Sample preparation

Both the disc sample and the clutch lining samples are prepared in such a way as to replicate the contact conditions in clutch engagement. For the friction lining a sample is cut from the clutch friction disc of suitable area to create representative clutch contact pressures during clutch engagement. A chamfer is made on all the edges of the sample in order to remove any burred and sharp edges and achieve nominally flat contact with the sample disc. The particular friction plate used in the current study is a composite composing of an organic resin, copper particles and reinforcing fibres. The rotating disc shown in figure 3 was made from mild steel. The disc was finished in such a manner as to match the radially sinusoidal form of the pressure plate surface. The wave pattern imparted to the surface has peak-to-trough amplitude of approximately 325μm and wavelength of approximately 1mm. Surface measurement was undertaken to act as baseline to monitor surface wear and ensure all samples' topography use in multitude of tests remain consistent.



(a) (b)

Figure 3: (a) Images of disk representing pressure plate (b) Measured surface at x5 magnfication showing an area of approimately 6 mm^2

2.3. Test Procedure

The challenging nature of determining the coefficient of friction requires a detailed test procedure to control the error and enable comparison of results. The procedure consists of a number of steps to clean and prepare the samples and monitor any changes to the surfaces of the clutch lining and pressure plate samples.

Firstly, the pressure plate sample is cleaned using a three stage chemical cleaning process. ASTM G99-05 recommends cleaning the contacting surfaces before testing as: grease, cutting fluid residue, debris and other contaminants can affect the measurements. The surfaces are cleaned by covering them in a series of solutions, and dabbing away the excess with a lint free cloth to avoid the cloth leaving any fibres on the surface. The three solutions used to clean the surface were firstly petroleum ether, secondly methanol and finally acetone. The pressure plate sample is then allowed to air dry in-between each chemical cleaning process. After cleaning, the sample surface must avoid contact with skin to avoid contamination. The surface typography of the pressure plate is then scanned using an optical interferometry, applying the focus variation technique at 4 different circumferential positions. ASTM G115-10 suggests each condition is run for a predetermined distance to allow for comparison of results. In the current study a distance of 300m is chosen.

For each test a new clutch sample is used to ensure consistent and repeatable conditions. After testing, the disc is scanned to monitor any changes to its surface as recommended in ATSM G163-10. This procedure is repeated for each test. The same procedure is also applied to clutch lining samples. ASTM G115-10 also gives further guidance on a number of potential sources of errors/inconsistencies, which are fully complied with in this study. All instrumentations are calibrated.

2.4. Test Conditions

To accurately replicate the clutch engagement process, equivalent conditions are calculated from information on the clutch plate movement in relation to the applied clamp load. The representative test conditions are listed in table 1. For clutch clamp load representation the average contact pressure of disc-pin contact equates the Pascal pressure of the clutch contact which is the clamp load over the total friction disc pad area. The interfacial clutch surface sliding speed is achieved by variation of disc speed.

Table 1: Comparison of clutch engagement conditions with the equivalent pin-on-disc tests

Equivalent pin-on-disc condition			Clutch condition	
Time (seconds)	Speed (m/s) / (Rpm)	Load (kg)	Clamp load (N)	Fly wheel speed (m/s)
30	10.1 / 2412	0.21	400	10.1
34	9.0 / 2149	0.27	500	9.0
37	8.3 / 1972	0.48	900	8.3
41	7.4 / 1756	0.66	1250	7.4
47	6.4 / 1534	0.93	1750	6.4
55	5.5 / 1311	1.12	2250	5.5
67	4.5 / 1083	1.60	3010	4.5
82	3.7 / 878	2.00	3750	3.7
110	2.7 / 656	2.66	5000	2.7
164	1.8 / 439	3.26	6125	1.8
210	1.4 / 342	3.72	7000	1.4
502	0.6 / 143	4.52	8500	0.6
662	0.5 / 109	4.65	8750	0.5
1257	0.2 / 57	5.32	10000	0.2

3. Results and Discussion

Through monitoring of the surface of the disc it is possible to establish when running-in wear has occurred. During this process any manufacturing defects, such as burs are removed. Post running-in wear, only gradual wear occurs (figure 4). The initial wear of the pressure plate sample can be attributed to the formation of small debris from repeated sliding over the same track pin track on the disc surface. The particles are formed through transfer of material from the friction lining counter face as well as plastic deformation of surface asperities, extruded laterally at their sides perpendicular to the direction of sliding. This process, due to its cyclic and progressive nature as well as the unidirectional plastic strain of the material, would appear to be an example of plastic ratchetting [5]. After initial wear the disc surface is shown to achieve a steady cyclic state. This is due to three mechanisms; the residual stresses from the initial deformation make any subsequent yielding harder, strain hardening acts to improve the material's elastic limit and also the local geometrical changes make the surface to better conform, reducing the applied stresses [6]. This implies that after the initial wear the disc surface does not experience loads over the elastic shakedown limit.

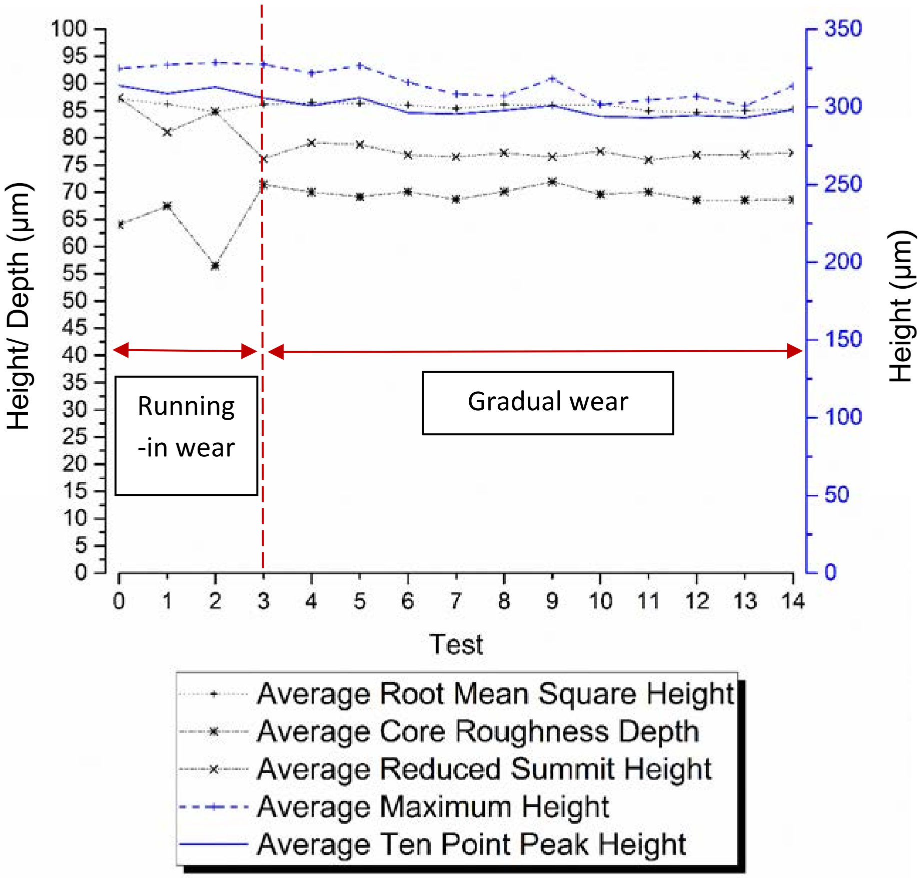


Figure 4: Variations in the peak asperity heights due to wear over the course of a number of test runs

Figure 5 shows the variation in the coefficient of friction across the clutch engagement from high relative sliding speed and low clamp load conditions at the initial stages of engagement to little relative sliding speed and high clamp loads at the latter stages of engagement. It can be seen that the coefficient of friction is constantly changing throughout the engagement process, across the range of sliding speeds and clamp loads. A closely linear relationship between the clutch engagement process and the coefficient of friction can be observed. However, it is observed that there is a more significant change to the coefficient of friction at the beginning and end of engagement.

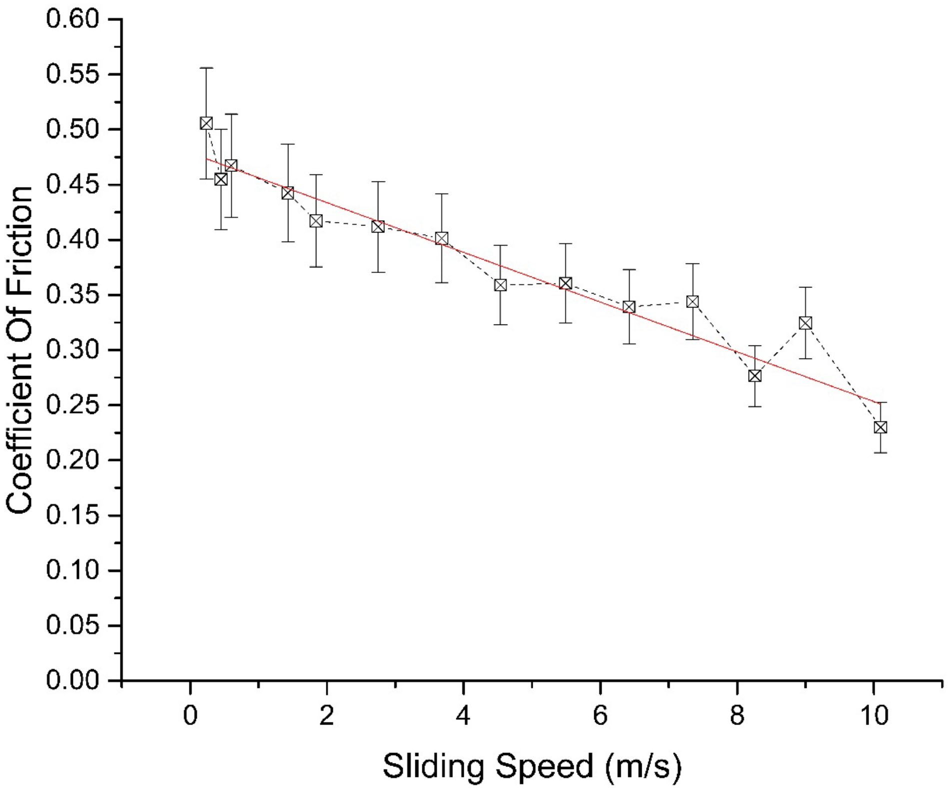


Figure 5: Variation of the coefficient of friction over the clutch engagement process

A series of tests performed to analyse the effect of bulk temperature change on the coefficient of friction. This shows the effect of bulk surface temperature from ambient to 90^{O}C is rather small. This is evident by the shallow gradients of coefficient of friction characteristics. Although this still affects the value of coefficient of friction, its effect is unlikely to significantly affect the clutch material performance as shown in table 2 and figure 6.

Table 2: The variation of coefficient of friction at various clamp loads with bulk disc surface temperature

Clamp Load (N)	Coefficient of friction (μ)
400	$0.183 + 0.00145$ T
900	$0.313 – 01.096\times10^{-4}$ T
2250	$0.379 + 6.586 \times 10^{-4}$ T
3750	$0.431 – 3.654 \times 10^{-4}$ T
5000	$0.386 + 7.150 \times 10^{-4}$ T
7000	$0.414 + 3.957 \times 10^{-4}$ T

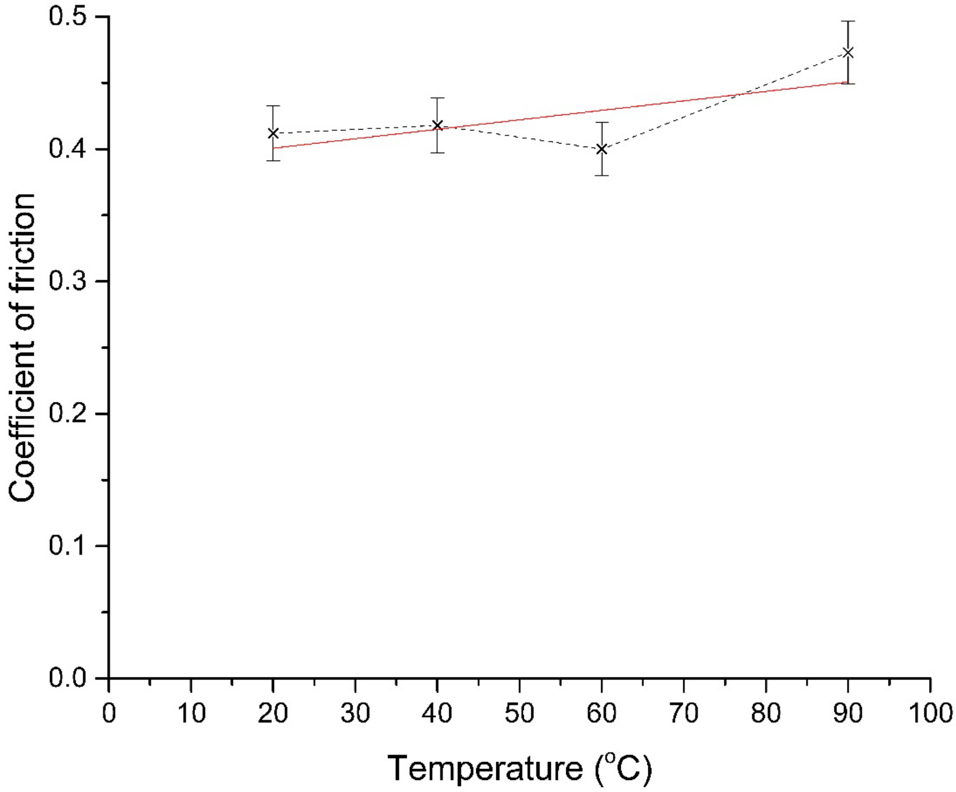


Figure 6: Effect of temperature on friction characteristics at a constant clamp load

Figure 7 shows the effect of interfacial slip speed on the coefficient of friction for various clamp loads. There is a clear trend of increasing coefficient of friction with an increasing clamp load. This is a clear indication that loss of designed clamp load due to hurried release of clutch pedal would increase the propensity to judder, a point that has been demonstrated in literature with numerical analysis [1, 7]. Furthermore, a decreasing coefficient of friction with interfacial slip speed is noted. This decrease leads to a general trend of –ve slope for $\mu - v$ characteristics, which according to numerical analyses results in take-up judder, particularly at low clamp loads [1, 2, 7, 8]. At low slip speeds, a higher proportion of the contact remains in stick region, which is also true of higher clamp loads. Thus, a Karnopp-type characteristic is observed [9]. In practice it is difficult to obtain repeatable measurements at low sliding velocities in the vicinity of the ordinate of the figure 7. This is because of sticking and sudden releasing in the contact, particularly of softer materials. These materials, including the friction lining can be subject to creep at low sliding speeds. Creep occurs as the result of a difference in tangential strain between the contacting sliding pairs. Sticking takes place in some region of the contact in which the material tends to stretch. The length of the friction lining test piece, fixed to the pin, is therefore becomes longer than its nominal length by a fraction, known as the creep ratio, γ [10, 11]:

$$\frac{\gamma R}{\mu a} = 1 - \left(1 - \frac{f}{\mu W}\right)^{1/2} \qquad (1)$$

where, f is friction, W is the normal applied load on the pin, a is the length of contact (along the sliding direction) and R is the radius of the pin/test piece. Of course, it is assumed that R is large, but not infinite. Under these conditions, the following relationship holds:

$$\frac{f}{\mu W} = 1 - \left(\frac{s}{a}\right)^2 \qquad (2)$$

where, s is the length of stick region in the contact. When: $s = 0$, $f = \mu W$, which is the case for pure sliding. On the other hand, when: $\frac{s}{a} = 1$, then $f = 0$, which corresponds to stiction (perfect engagement in the case of the clutch system) [10].

Now substituting (2) in (1) and re-arranging:

$$\mu = \gamma \frac{R}{d}, \text{ where: } d = a - s \qquad (3)$$

where, d is the length of test piece in slip motion.

One can see that as d decreases, coefficient of friction increases as there is a greater stick region. The same can also be observed as the creep ratio, γ is increased. All the characteristics in figure 7 show the relationship of the form below, which is also reported by Centea et al [1, 3]*:*

$$\mu = C + mv \qquad (3)$$

where, v is the slip speed, C a constant and m is the gradient of the $(\mu - v)$ characteristic curves in figure 7.

Clearly, C is the static coefficient of friction at $v = 0$, which should be nearly the same for all the characteristic curves, apart from the fact that plastic deformation of surfaces at different clamp loads as well as generated heat alter this value somewhat. The gradient m is nearly always negative. A larger negative slope would increase the propensity to judder according to Centea et al [1, 3] and others [7, 9]. With higher clamp load friction is increased due to greater region of stick, s. Theoretically, as $s = a, f = 0$ as already described, but this never occurs in practice, because there would be no traction. So, in fact with higher clamp load the characteristics occur at higher coefficients of friction.

The above observations and simple analysis conform to the findings in figure 7.

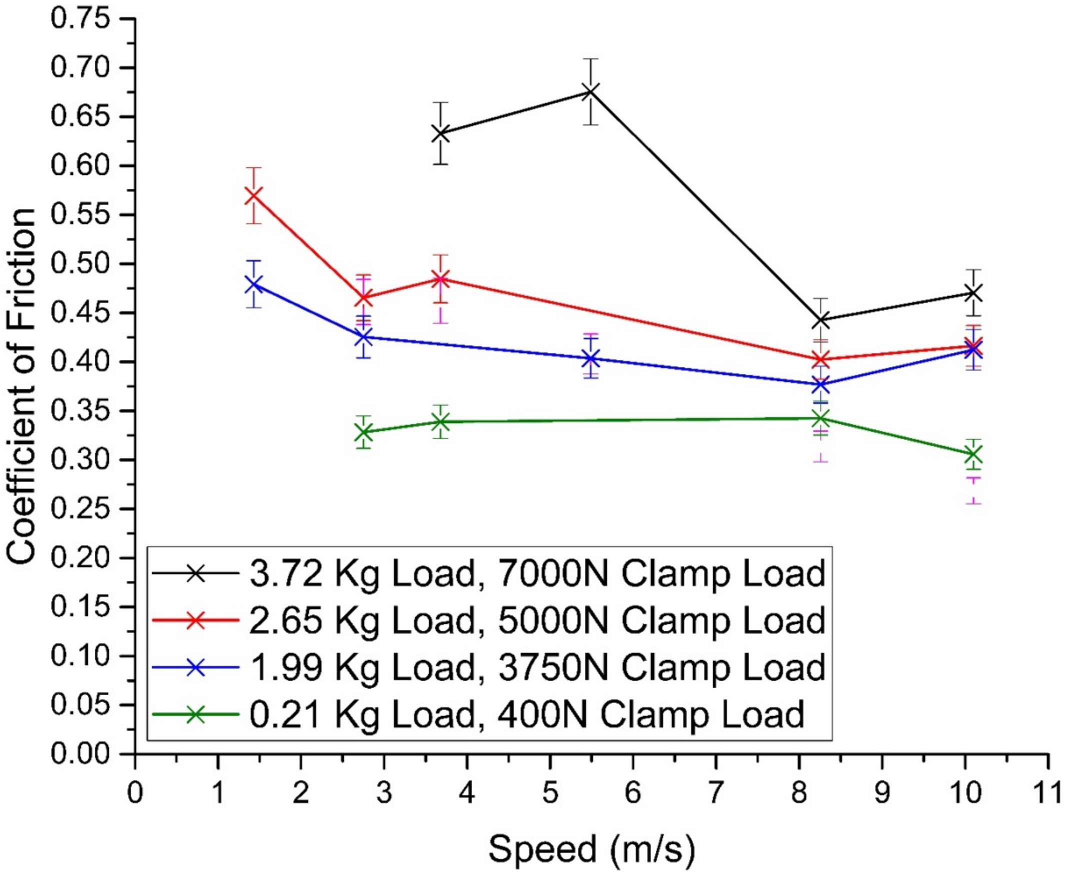


Figure 7: Variation coefficient of friction with slip speed at various clamp loads

4. Concluding Remarks

The results of pin-on-disc experiments show that the kinetic coefficient of friction for the clutch friction lining material in contact with the sinusoidal wavy and rough surface of pressure plate decreases with rising contact temperatures and increasing slip speeds. The coefficient of friction increases with the clamp load to better conform the rough surfaces through deformation, but traction requires certain degree of micro-slip due to creep of the lining material. These characteristics of the contact are all observed in the experimental results and conform well to the tractive contact mechanics with creep under slip conditions.

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