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NPL Friction Measurement Methods :

Data assessment techniques and a sample database.

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Data assessment techniques and a sample database.

By

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ABSTRACT

Reliable materials property data obtained under conditions relevant to the metal working and forming industry are essential for software modelling packages used by such industries to optimise production processes. Over the past six years, under the auspices of DTI funded projects as part of the Materials Measurement which affect Processability (MMP) Programme, considerable effort has been devoted at NPL to the development of two techniques for the measurement of friction ; namely the Big Friction Rig and the Pin on Disc Friction Rig. A significant number of tests have been performed using both measurement techniques, primarily with a view to evaluating and validifying the techniques but also producing useful friction data relevant to the metal forming industry.

As part of an interim project on the metrology of friction and oxide strength, these data have been re-evaluated, developing a classification system designed to express confidence in friction results, and additional tests performed to infill gaps in the existing data sets. An industrial consultation exercise was performed, involving software houses and a representative selection of end users to ascertain the preferred format of a friction database.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Materials Centre, NPL.

CONTENTS

	Page No
Abstract	2
Contents	4
1. INTRODUCTION	6
2. NPL FRICTION MEASUREMENT TECHNIQUES	6
2.1 The NPL Big Friction Rig	6
2.2 The NPL Pin-on-Disc Friction Rig	8
2.3 Uncertainty of Measurement	10
3. MATERIALS AND TEST CONDITONS	10
4. DATA ANALYSIS	11
5. CONSULTATION EXERCISE	13
6. FRICTION DATA AND DATABASE	15
7. DISCUSSION	19
8. REFERENCES	21
APPENDIX 1 : EXAMPLES OF FRICTION DATA CLASSIFICATION	22
APPENDIX 2 : FRICTION DATABASE (PRINTOUT)	29
APPENDIX 3 : FRICTION SUMMARY PLOTS FOR PIN ON DISC FRICTION RIG	47
APPENDIX 4 : FRICTION SUMMARY PLOTS FOR BIG FRICTION RIG	55
APPENDIX 5 : INTERCOMPARRISON OF RESULTS	63

1. INTRODUCTION

Increasingly, the implementation of code to deal with the effects of friction in computer software models requires the user to choose an appropriate friction law. The basic choice is between the Coulomb friction law, that relates friction coefficient to applied stress, and the Tresca expression that is a constant function of stress, with the proportionality constant potentially being influenced by parameters such as tool material, surface condition, lubrication, temperature etc. These can be combined, Figure 1, and plotted against normalised stress.

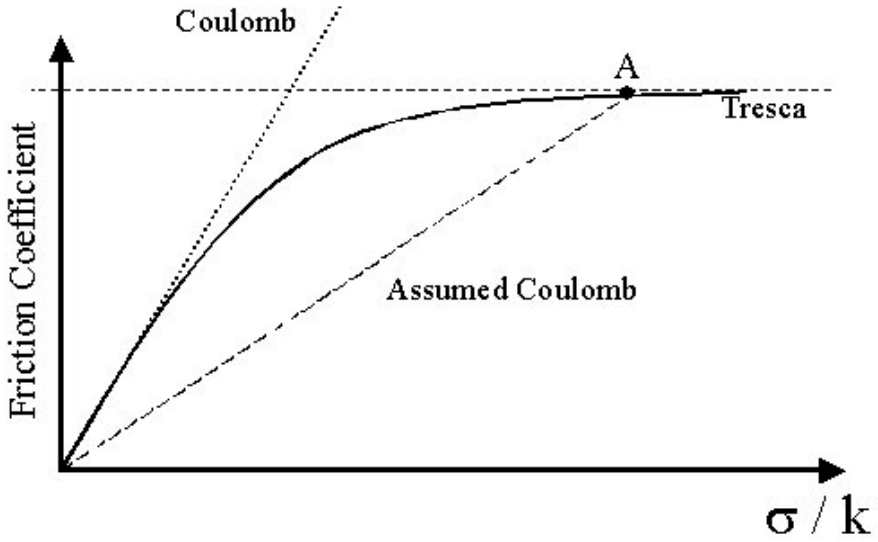


Figure 1 : Variation of friction coefficient as a function of normalised stress, for the Coulomb and Tresca friction laws

Clearly, if the friction coefficient is measured at point A and Coulomb's law assumed then the assumptions give rise to erroneous predictions. A more appropriate rationale is to combine the two laws. For this purpose, experimental data are required, especially for the proportionality constants in the Tresca law to be evaluated or mapped for the effects of variation in the properties affected by surface condition, lubrication, temperature etc.

This requirement provides the underpinning rationale for the development of validated methods for the measurement of friction described in this report.

2. NPL FRICTION MEASUREMENT TECHNIQUES

2.1 The Big Friction Rig.

The technique incorporates a 250kN Instron servo hydraulic high rate actuator mounted on a NPL designed rig, used in conjunction with a 7MN (~700ton) press, Figure 2. The rig can be used with two sizes of cylindrical billets, of 30 mm and 50 mm nominal diameter and 55 mm in height. Test billets are heated in a furnace at temperatures of up to 1000°C and are manually transferred into the grabber on the friction test rig for testing (Figure 3).

An axial load is applied using the press, and the load is monitored using a three column 7500 kN load cell designed and built at NPL. As the billets are compressed between two tool steel platens, they are dragged horizontally a nominal 90mm displacement between the platens, at rates of up to 100 mm/s, using the 250kN actuator controlled by an Instron 8500 Series controller.



Figure 2 : The NPL Big Friction Rig along side the 7MN Press

The test billets have small holes, ~1mm in diameter drilled into the sides approximately one third of the distance from the top surface to accommodate support wires which protrude by ~10mm. These wires rest on the top of the grabber arm, thereby supporting the hot billet clear of the lower platen. As the vertical ram is lowered, the top platen comes into contact with the billet, forcing it down, shearing off the support wires, until the lower face of the billet is in contact with the lower platen. Thus both the upper and lower platens come into contact with the billet at virtually the same time, hence asymmetric cooling of the billet is minimised.



Figure 3. Hot billet being transferred from a furnace to the grabber arm on the Big Friction Rig.

Billet temperature is monitored during the test via a 1mm diameter Type N (Nicro-Nisil) sheathed thermocouple, which is inserted into a 1.2mm diameter radial hole drilled with its centreline 1.5mm below the top surface of the billet. Applied axial load is measured via the 7500kN load cell situated directly below the lower platen in the press and horizontal load by an integral loadcell built into the grabber arm. Displacement of the test billet is measured by a transducer incorporated into the 250 kN horizontal actuator.

The coefficient of friction for the material under test can then be determined from the ratio of the horizontal force required to drag the heated billet to the axial load applied by the 7MN press, an allowance being made for the fact that both the upper and lower platens are in contact with tool steel platens. The loads, displacement and temperature of the billet are recorded using a PC based data logger, written using National Instruments™ LabView software. Further details of the design and calibration of the Big Friction Rig are given elsewhere (Loveday *et al*, 2001)

The initial design for the Big Friction Rig incorporated room temperature, H13 tool steel platens. The platens have since been re-designed to incorporate removable inserts with a structural substrate heated by cartridge heaters, allowing different tool steels to be tested at platen temperatures up to 400 °C, bringing the range of test conditions available using the measurement technique closer to the conditions seen in industry.

2.2 The NPL Pin-on-Disc Friction Rig

A DC heated pin assembly that clamps a testpiece in place is mounted below a loadcell at one end of a lever arm, which is pivoted about the horizontal axis. An electric servo actuator is connected to the other end, enabling the DC heated pin assembly to be forced down into a rotating disc. The lever arm assembly is mounted on a second bearing with a vertical axis, rotation of which is prevented by the frictional loadcell. A schematic of the test system is shown in Figure 4, below.

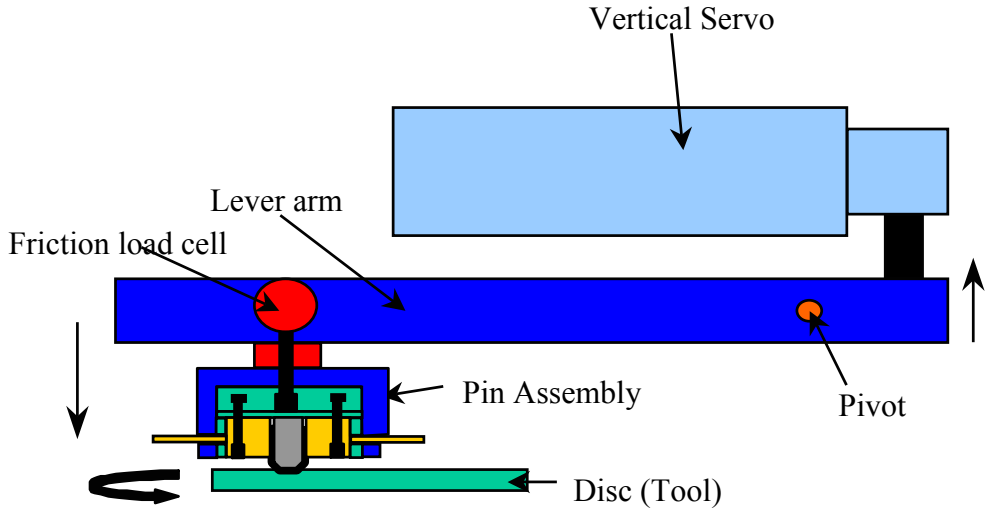


Figure 4 : Schematic layout of Pin on Disc Rig.

The testpiece is a U shaped piece of metal, machined to give a nominal 5mm x 5mm contact area during testing. The nominal thickness of the pin at point of contact is approximately 1mm.

The pin is supported on a zirconia block that acts as both a structural support and a thermal break, concentrating the heat within the testpiece and protecting the remainder of the assembly. The zirconia element has a groove machined into it, such that a sheathed thermocouple can be 'sandwiched' between it and the pin ensuring good thermal contact during testing, Figure 5.

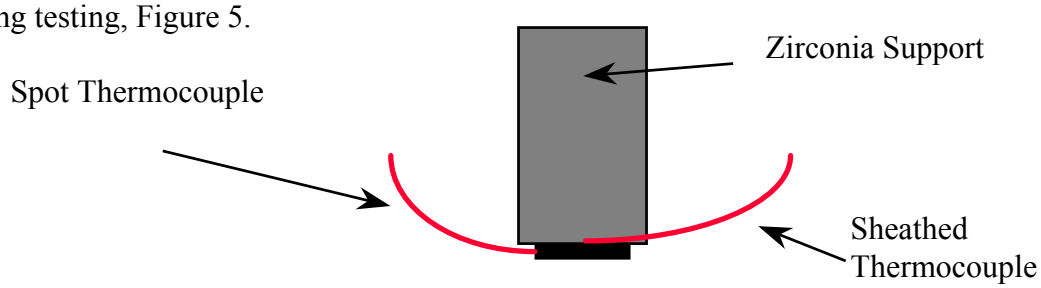


Figure 5 : Cross Section Through Instrumented Testpiece and Zirconia Support

The U shaped testpiece and zirconia block are clamped into position by water cooled brass blocks. These conduct the DC current into the testpiece and are insulated from the rest of the test system by means of tufnol inserts. The brass 'clamps' fit closely inside a stainless steel structural element, which provides lateral strength to the whole heated pin assembly.

The tool disc is mounted in a tufnol support, electrically and thermally insulating it from the rest of the test system. A heating current can then be applied to the testpiece while in contact with the tool disc. By continuing to pass current through the pin during testing, a higher pin temperature can be maintained than would be possible without post contact heating. The tool disc is rotated by a large motor drive system.

The applied normal load is measured in the axial plane by a high resolution piezoelectric loadcell located between the pin assembly and the lever arm. The horizontal frictional force is measured by a strain gauge loadcell mounted on the side of the lever arm, located on the centreline of the loading axis of the testpiece, Figure 6.

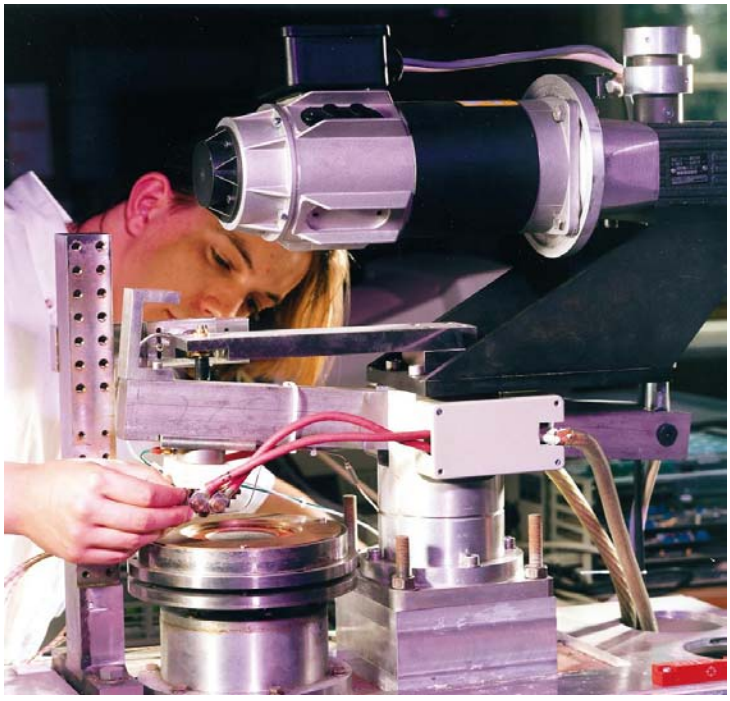


Figure 6 : Pin on Disc Friction Measurement Rig.

The testpiece temperature is measured by one of two thermocouples. A floating earth sheathed type N thermocouple can be used as mentioned earlier, or a thermocouple can be spot welded directly to the body of the testpiece. For the spot welded thermocouples, type R thermocouple wires (Pt / 13%RhPt) with a thickness of 0.1mm are fused together to form a thermocouple bead which is then spot welded to the edge of the testpiece.

The data acquisition / control system is built around a standard PII Pentium, running MS Windows '95, and LABVIEW 5.1 . Measurement signals from all the transducers are typically logged by this system at an acquisition rate of 50Hz. The duration of a typical test is 10 seconds.

2.3 Uncertainty of Measurement

A simplified approach to estimating the uncertainty of measurement for three friction test methods, including the two described above has been performed using the ISO TAG4 '*Guide to the expression of uncertainty in measurement*' as the basis. Table 1 below gives the expanded uncertainty of measurement at the 95% confidence level for both the Big Friction and the Pin on Disc Friction test methods. Further information on the approach taken to calculate these uncertainties can be found elsewhere (Loveday & Brooks, 2001).

Test Method	**Measured Parameter**	**Uncertainty * + /- %**
Big Friction Rig	μ	7
Pin on Disc Friction Rig	μ	15

* at the 95% confidence level

3. MATERIALS AND TEST CONDITIONS

Early on during the lifetime of the DTI funded projects, a consensus of opinion was formed on the materials to be tested within the projects Industrial Advisory Group (IAG) meeting. The materials selected were Commercial Purity Copper, Commercial Purity Aluminium, Mild Steel and IN718. These currently form the basis for the friction data sets available.

The friction coefficients for these materials have been evaluated over a wide range of conditions, dependent on the capabilities of the test measurement system in question, see Table 2.

Note : The data sets do not include a comprehensive set of results for all the below conditions.

In both the case of the Pin on Disc Rig, and the Big Friction Rig, testpieces were oxidised in air. In the case of the Big Friction Rig, testpieces with a thick oxide were those that were tested after being heated in the furnace for a nominal 30 minutes at soak temperature. Those with thin oxide were either tested at Room Temperature, with no soaking, or were 'de-scaled' after removing from the furnace.

Table 2 : Summary of Friction Test conditions

	Temperature °C	Displacement Rate (mm/s)	Axial Stress (MPa)	Oxide	Lubricant
Big Friction Rig	RT – 1200	0.2 – 100	0 – 120	Thick / Thin	None Oil DAG 580 AQUADAG DAG 2543
Pin on Disc Rig	RT - 1200	30 – 200	0 – 200*	Thin, 100 – 400 μm	None DAG 2543 AQUADAG

* Nominal applied load, not accounting for contact area, see section 4.

In the case of the Pin on Disc Rig, due to the rapid heating time of the testpieces, typically in the order of one minute, it was assumed that without a soaking period at temperature, the testpiece would have a thin oxide layer at time of testing. The soaking period required to grow an oxide layer on Mild Steel testpieces was calculated using the following equation :

$$d = \sqrt{A \exp[-Bt/T]}$$ (Kubaschewski and Hopkins)…….Eqn.1

where d is the thickness of the oxide layer,
A = 5.75 and B = 2250,
T is the temperature in Kelvin,
t is the time in Seconds.

4. Friction Data Analysis.

Friction coefficients for both the Pin on Disc and the Big Friction Rig are calculated from the ratio of the horizontal forces measured, to the axial loading force measured while a testpiece is moving across a tool steel platen. As mentioned in section 2.1, a factor of two is used with the Big Friction Rig to take into account that the test billet is being dragged between two platens. This assumes that the friction coefficient is the same for both contact surfaces. A typical friction curve for the Pin on Disc rig is shown on the next page, in Figure 7.

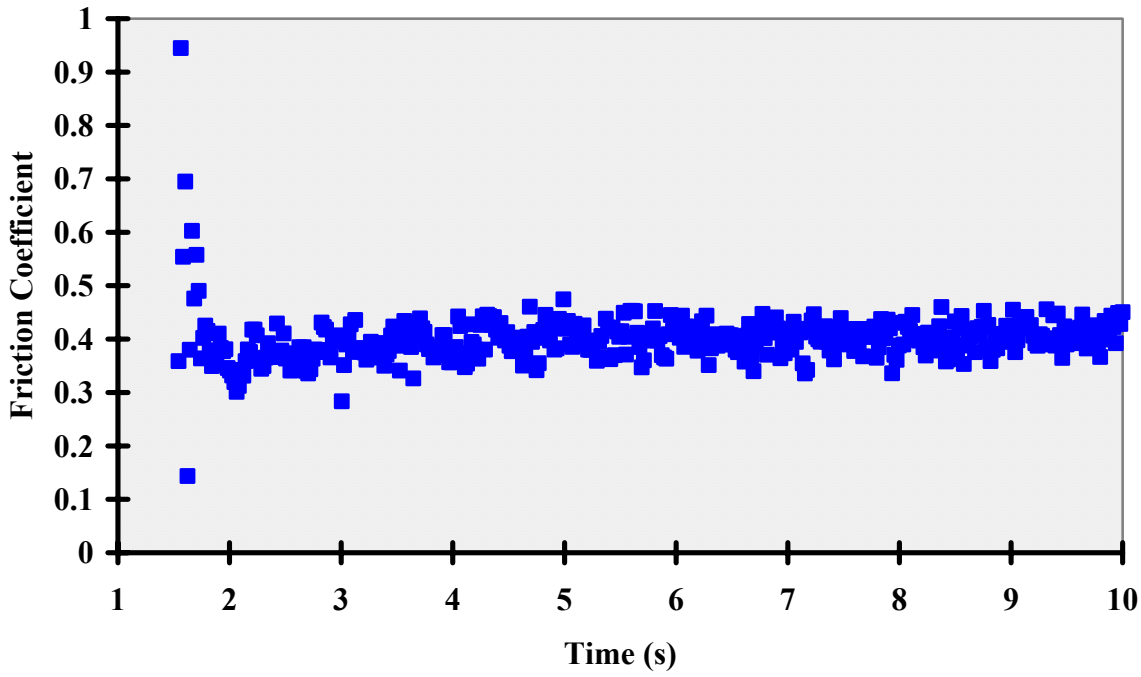


Figure 7 : Typical friction curve measured using Pin on Disc Rig ; IN718 ; No Lubricant ; 80MPa Axial Stress ; 250 ℃ average test temperature ; 114 mm/s displacement rate.

A data classification system has been introduced, as a means by which to express confidence in the friction coefficient for any given material and test condition. This system uses three classes, as described below :

Class 1 Data : The friction coefficient rapidly attains a steady state value, which is maintained for the duration of the test.

Class 2 Data : This is essentially the same as Class 1 Data, with the friction coefficient rapidly attaining an approximate steady state value, though there is a slight variation over the duration of the test.

Class 3 Data : The friction coefficient for the material under test varies continually throughout the duration of the test.

Examples of the relevant data classes can be found in Appendix 1.

Each Friction curve is visually examined and classified using the above criteria.

Having defined the Data Class of a particular test, the average friction coefficient, the standard deviation of the friction coefficient and the average temperature of the testpiece over the duration of the test is determined. The exact start point and endpoint of the data, over which the analysis is carried out is dependant on the Data Class which is summarised in Table 3, on the next page.

Table 3 : Summary of regions over which friction analyses carried out.

	Test Temperature	Average Friction*	Standard Deviation*
Class 1 Data	Average temperature over period testpiece in sliding contact with platen.	Over period friction coefficient at steady state value.	Over period friction coefficient at steady state value
Class 2 Data	Average temperature over period testpiece in sliding contact with platen.	Over period friction coefficient at approx steady state value.	Over period friction coefficient at approx steady state value.
Class 3 Data	Average temperature over period testpiece in sliding contact with platen.	Over period of entire test	Over period of entire test

* The initial rise in friction coefficient (or fall as is frequently the case with the Pin on Disc Rig) at the start of a test and drop off at the end of the test is not included in these calculations.

Applied axial stress calculations are based on the average of the steady state axial load applied over the period of the test. In the case of the Big Friction Rig, the initial diameter of the test billet is used to calculate contact area. The Pin on Disc Rig testpieces have a nominal contact area of 25 mm^2 . The actual contact area for a test is assessed once the test is complete, to take into account of any testpiece misalignment that might occur. This often means that the actual contact area for a given test is less than 25 mm^2, resulting in a higher axial stress for the region of the testpiece in contact with the tool steel disc.

5. Consultation Exercise

In order to enhance the usefulness of the friction data sets, the data from both test measurement methods has been compiled into a user friendly, searchable database. The preferred format of this database was ascertained through consultation with those to whom such a database would prove useful. A representative selection was taken from :

- Modellers and modelling software houses
- Process machine manufacturers
- Primary processors
- End product manufacturers

Views were sought on whether such a database would be useful, the preferred format of such a database, desired workpiece and tool steel materials, and die / platen temperatures. The results are tabulated in Table 4, on the next page.

All who responded to the consultation document expressed an interest and potential use for a friction database, were it available. After considering the views expressed regarding the preferred format of the friction data, it was decided to produce a tabulated summary of all the friction tests to date, with summary plots examining trends in the data. A table providing 'best estimate' values for friction coefficients of materials tested under certain conditions has also been provided. A CD-ROM containing a searchable spreadsheet of the data and the

Table 4 : Summary of Responses resulting from consultation exercise

Industrial Sector	Preferred Format of Friction Data	Materials of interest	Other Materials	Tool Steels	Die Temperatures
Academic / Industrial Advice	Spreadsheet / Summary Graphs	Mild Steel, Aluminium, Copper, IN718	Titanium		300, 400 °C
Industrial	Spreadsheet / Summary Graphs, Raw Data				
Academic	Friction Graphs	Mild Steel, Copper	Titanium Alloys		
Academic	Spreadsheet, Summary Graphs	Mild Steel, Copper, IN718	Alloy / Stainless Steels, Al Alloys, Titanium Alloys		100 °C
Industrial	Spreadsheet / Summary Graphs	Mild Steel, IN718	Waspalloy, UDIMET 720		200 C, 400 °C
Academic	Spreadsheet / Summary graphs / Raw Friction data / Plots of individual tests / Constitutive equations.	Mild Steel, Aluminium, Copper, IN718	Ti-6-4, Brasses	Moly Coated	RT – 400 °C
Academic	Spreadsheets / representative curves				
Industrial	Spreadsheet / single data value				
Industrial	Constitutive Equations	IN718	Stainless Steels, Ti Alloys, Udimet Alloys	Eronite	200, >800 °C
Academic	Spreadsheet / Summary graphs / Raw Friction data / Plots of individual tests / Constitutive equations.	Mild Steel, Aluminium	AISI 316 Stainless Steel, Aluminium Alloys, Titanium Alloys	Coated Tool Steels	200 – 300 °C, Superplastic forming temperatures.

individual friction curves for all the tests tabulated in the summary table can be made available on request.

6. Friction data and database.

A set of summary plots for the friction data and tables listing the results of friction coefficients for the materials tested for both friction test methods are given in Appendices 2, 3, 4 and 5. The error bars on the summary plots represent the standard deviation of a data set, as mentioned in section 4.

6.1 Variation of friction coefficient with applied axial stress

Figures 8 and 9, below, illustrate the effect the assessment of contact area has on the distribution of the friction data within the summary plots for Mild Steel tested on the Pin on Disc rig. As can be seen, correcting for contact area has a significant effect when the data is viewed as a function of applied stress.

The trend in the corrected friction data, apparent in Figure 9, can be seen in all the materials tested on the Pin on Disc rig, i.e. mild steel, aluminium and IN718. The friction coefficient, as viewed in Figure 9, can be seen to asymptotically approach a steady state value at the higher applied stress of 0.25 ± 0.04. This point is considered further in the Section 7. It is interesting to note that the class 3 friction data still adheres to the same trend.

It is expected that a similar trend will be discernable from data produced using the Big Friction Rig. However, the press that is currently used to apply axial loads does not have the capability to apply controlled loads, and is hence more commonly used as dead weight loading device, typically resulting in axial stresses of approximately 110 MPa. It is expected that this issue will be addressed in a future project.

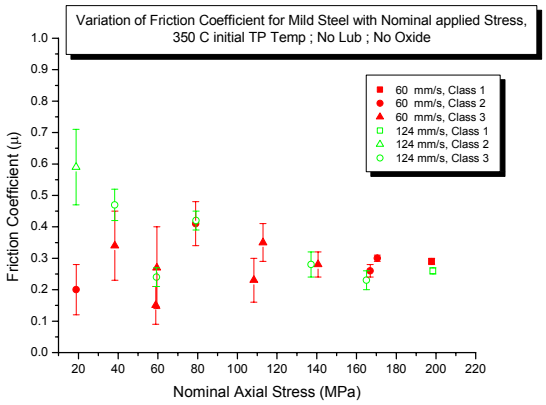


Figure 8 : Variation in Friction coefficient for Mild Steel as a function of nominal applied stress, Pin on Disc Rig.

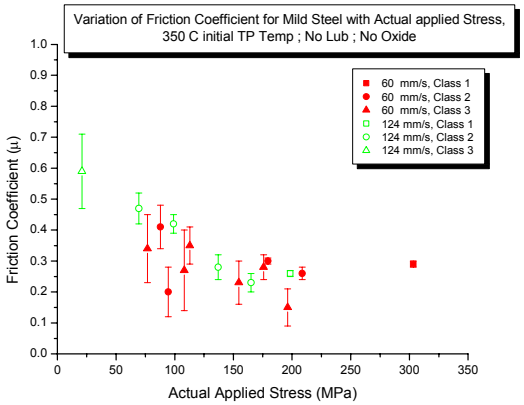


Figure 9 : Variation in Friction Coefficient for Mild Steel as a function of actual applied stress, accounting for contact area, Pin on Disc Rig.

6.2 Variation of friction coefficient with temperature

With both the Big Friction and the Pin on Disc rigs, the temperature of a heated testpiece can vary significantly during the duration of a test, due to the relative thermal masses of the testpiece to the cold tool steel platen. This is particularly apparent with high temperature tests carried out on the Pin on Disc rig, where the testpiece can cool from an initial test temperature of 1050 °C to an average temperature of ~ 400°C in one or two seconds. The cooling of heated billets on the Big Friction Rig is dependent on the displacement rate, and therefore the duration of the test. However, typically billets cool in the region of 200 °C to 400 °C during the lifetime of a single test.

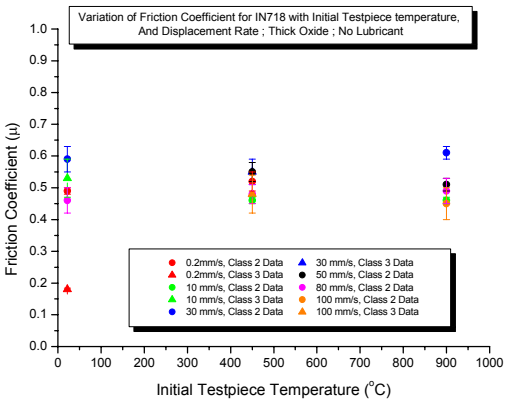


Figure 10 : Variation in Friction coefficient for IN718 as a function of initial testpiece temperature, Big Friction Rig

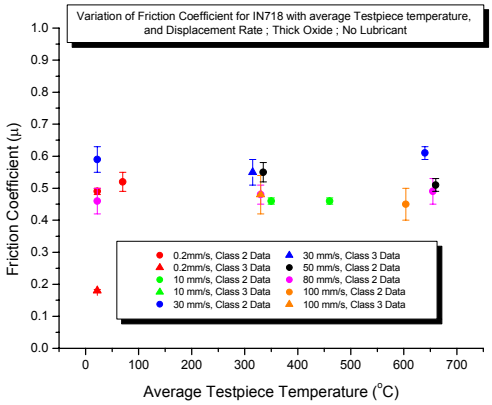


Figure 11 : Variation in Friction Coefficient for IN718 as a function of average testpiece temperature, Big Friction Rig

Figures 10 and 11, above, illustrate the typical spread of temperatures that can result during high temperature testing. In general, variation in temperature appears to have a minimal effect on the friction coefficient for the materials tested, when in an unlubricated stated.

An exception to this statement is Aluminium. Although exhibiting a large degree of scatter, it is possible to discern from Figure 12 that an increase in testpiece temperature results in a progressive increase in the friction coefficient. Comparative data from the Pin on Disc rig is unavailable. This is due to the electrical resistance of aluminium being so low that the current DC power supply used to resistance heat the testpieces has insufficient power to significantly increase the temperature of an aluminium testpiece.

6.3 Effect of material hardness on friction coefficient

Although, as stated in section 3, Aluminium testpieces were specified to be manufactured from Commercial Purity Aluminium, it became apparent during testing that the first, second and third batches of testpieces were producing different friction coefficients. This prompted an investigation into the hardness of the materials being tested.

Figure 13, on the next page, illustrates a series of repeat tests performed on a testpiece from the first and second batch of testpieces, varying the displacement rate. The data at the top of the plot (testpiece 1, second batch of testpieces) was repeatedly tested while decreasing the displacement rate and was found to have a Vickers hardness of 105, whereas the data at the bottom (testpiece 2, first batch of testpieces) was repeatedly tested while increasing the displacement rate and was found to have a Vickers hardness of 77. This would seem to indicate that material hardness can have an effect on the coefficient of friction.

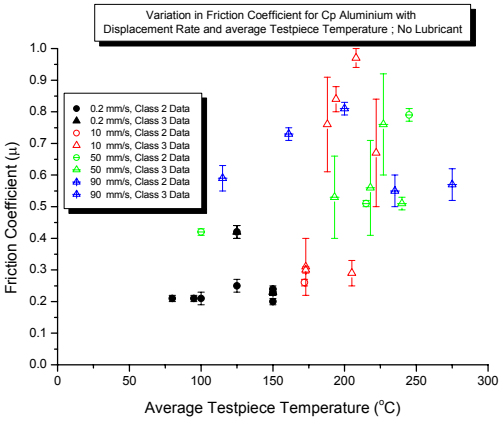


Figure 12 : Variation in Friction coefficient for Aluminium with displacement rate and temperature, Big Friction Rig.

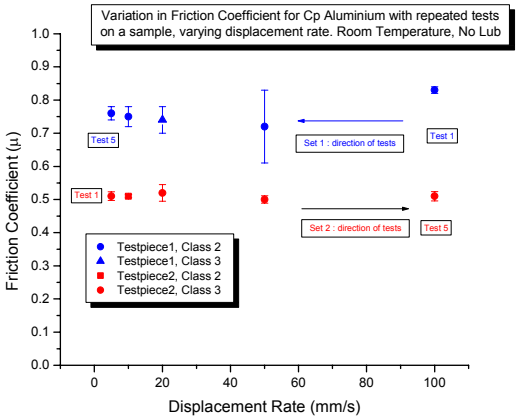


Figure 13 : Variation in Friction coefficient for Aluminium from batch1 and 2, with displacement rate.

6.4 Effect of surface finish on Friction coefficient

The testpieces used for testing on both test rigs were manufactured from a variety of sources, using different manufacturing techniques, resulting in different surface finishes. Specifically, for the Big Friction Rig, the earlier testpieces manufactured for a previous project had a ground surface finish, whereas the testpieces manufactured for the latest project had a turned finish. The data plotted in Figures 13 and 14, on the next page, for the Big Friction Rig, resulted from testpieces with a mixture of these surface finishes. Overall, the data matches very well, indicating that surface finish and or machining route was unimportant under these test conditions.

6.5 Variation in Friction Coefficient with displacement rate.

Both Test rigs provide the ability to test materials over a range of displacement rates. Aside from having an effect on the average temperature of billets tested on the Big Friction Rig, Figures 14 and 15, below, illustrate that displacement rate has a minimal effect on the friction coefficient for the materials tested. This can also be seen in Figure 8, for the Pin on Disc rig.

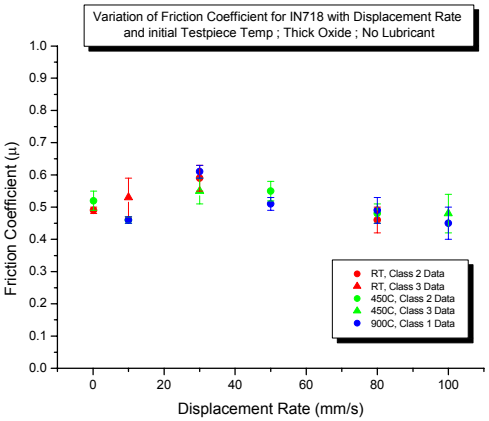


Figure 14 : Variation in Friction coefficient for IN718 with displacement rate and temperature, Big Friction Rig.

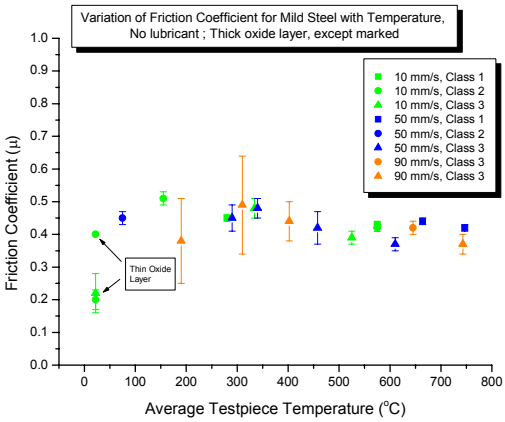


Figure 15 : Variation in Friction coefficient for Mild Steel with displacement rate and temperature, Big Friction Rig.

6.6 Inter-comparison of Data From Pin on Disc and Big Friction Rigs.

Although a significant number of tests have been carried out using both the Pin on Disc and Big Friction rigs (233 and 291 respectively), some of the issues raised above, such as cooling of testpieces and applying a controlled load on the Big Friction Rig have limited the number of results available for a comparison of the two techniques.

A set of inter-comparison summary plots for Mild Steel and IN718 can be found in Appendix 5. Figures 16 and 17, below, compare friction coefficients from the two friction rigs for Mild Steel. As can be seen, there is variable agreement between the friction coefficients produced from the two test techniques. This is discussed further in section 7.

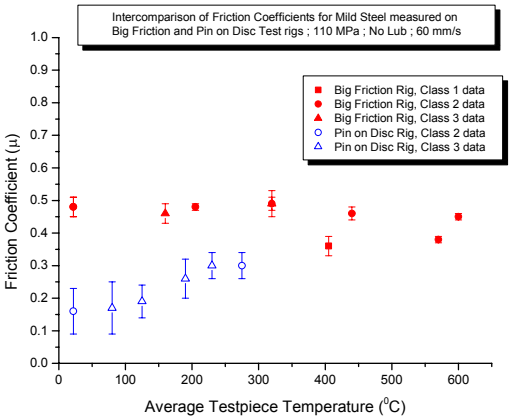


Figure 16 : Comparison of friction coefficients for Mild Steel, generated from the Big Friction and Pin on Disc Rigs, data taken from 'interim' data sets

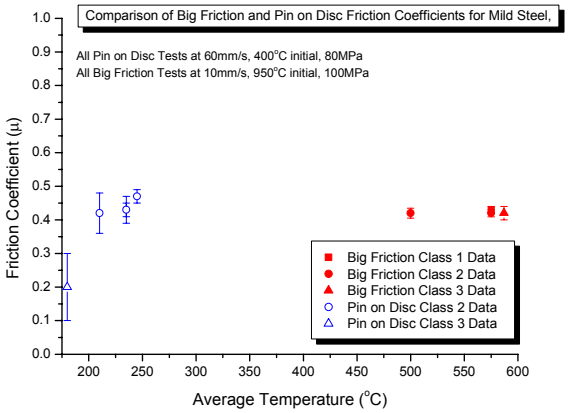


Figure 17 : Comparison of friction coefficients for Mild Steel, generated from the Big Friction and Pin on Disc Rigs, data taken from 'repeatability' data sets

7. Discussion of Results.

Although at first, the variation of friction coefficient with applied stress for materials tested using the Pin on Disc rig appears to be at odds with a conventional interpretation (Figure 1). Closer inspection reveals that this is not necessarily the case. Figures 18 and 19, below, (Schey, 1984), illustrate the variation of shear stress and friction coefficient at various interface pressures.

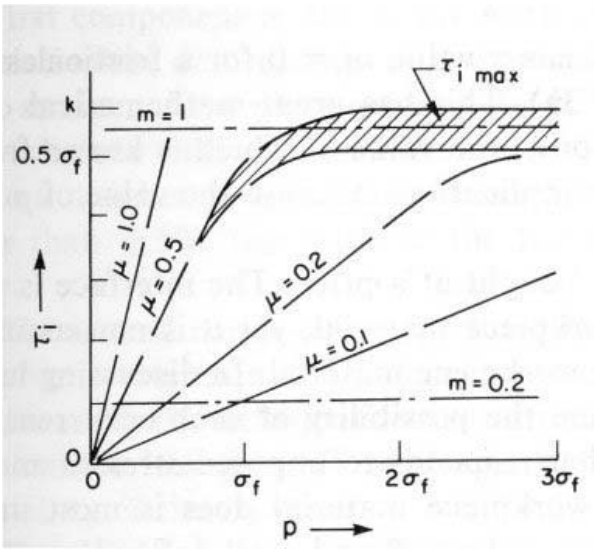


Figure 18 : Variation of average frictional shear stress in sliding with various interface pressures

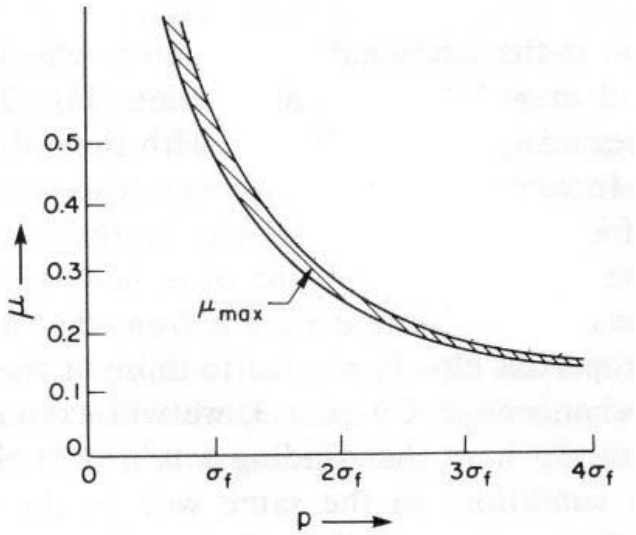


Figure 19 : Variation of maximum Friction coefficient in sliding with various interface pressures.

From the equation $\mu = \tau_i / p = F / P$, for a constant friction Coefficient, μ, τ_i must increase inline with increasing axial stress, which is known as Coulomb Friction, as illustrated by the broken lines in figure 18. However, when τ_i exceeds the material property k, defined as 0.577 σ_f by Von Mises or 0.5 σ_f by Tresca where σ_f is the flowstress of the material, it takes less energy for the material to shear inside the body than slide at the interface and sticking friction occurs ($\tau_i = \mu p > k$).

For metals, k remains constant. Therefore, for increasing axial stress, μ_{max} (the maximum friction coefficient before sticking occurs) must decrease, as illustrated by figure 19. This decreasing friction coefficient with increasing applied axial stress is what has been observed in the data from the Pin on Disc Friction rig. This implies that the friction coefficients measured are not those of sliding friction, but rather those of sticking friction.

As can be seen from Figures 16 and 17 comparing friction coefficients for Mild Steel generated from both the Pin on Disc and the Big Friction Rig, discrepancies can arise depending on which data are chosen from the overall database.

These discrepancies could arise from a range of sources. The Pin on Disc rig, in its current design, does not have the same degree of stiffness as the Big Friction Rig. Indeed, at applied axial stresses of greater than 100 MPa (2.5kN applied axial Load), the Pin on Disc Rig can be seen to flex laterally and vertically. Further, a decision was made on financial

grounds to use the discs on the Pin on Disc Rig for up to five tests. Figures 20 and 21 illustrate the effect this can have on the friction coefficient, which can increase with the number of tests performed, depending on the materials under test. This latter effect is more noticeable for tests performed using either Mild Steel or IN718 testpieces, but did not hold true for tests using aluminium testpieces on the same tool steel disc, Figure 21.

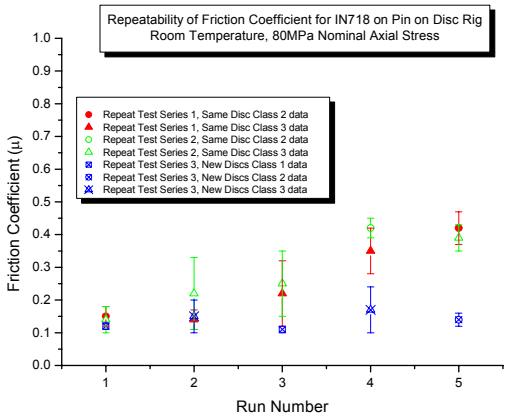


Figure 20 : Repeatability of friction coefficient for IN718 with repeated and individual tests on a tool steel disc.

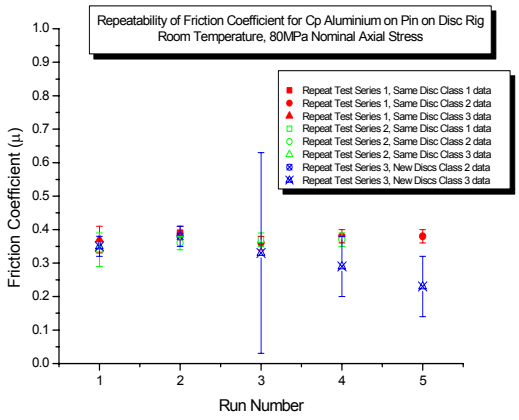


Figure 21 : Repeatability of friction coefficient for Aluminium with repeated and individual tests on a tool steel disc.

Bearing these issues in mind, and the fact that the Big Friction Rig is of a significantly larger scale, representing more closely the conditions found in industry, it is felt that the data produced from the Big Friction Rig is of more value and represents more accurate friction coefficients for the materials tested. Table 5 below tabulates the recommended friction coefficients for Copper, Mild Steel and IN718.

Table 5 : Recommended Friction Coefficients

Material	Test Condition	Friction Coefficient, μ
Mild Steel	No Lubricant, Thick Oxide, Room Temperature	0.45 ± 0.03
Commercial Purity Copper	Thin Oxide, No Lubricant	0.35 ± 0.02
IN718	Thick Oxide, No Lubricant	0.50 ± 0.04

Note : The use of thick and thin oxide here is subjective, relating to the definitions given in section 3. Thin oxide refers to testpieces tested at room temperature or those that were de-scaled after heating, Thick oxide refers to testpieces soaked at 30 minutes at temperature.

8. References

1. Brooks, M.R. and Loveday, M.S. (2000) '*Friction and Oxide Strength Data for Forging & Rolling Process Modelling'* CMMT (MN) 0??, Pub: National Physical Laboratory.

2. Loveday, M.S., Brooks, M.R., Custance, P.J., Gee, M.G., Grombridge, C., Gunn, D.A., Jenkins, R.F., Knott, A.J., Parfitt, M.J., Prince, D.J, Stammers, G., Varma, R.K., *'The Design, Calibration and Operation of a Big Friction Rig'* NPL Report CMMT(A)112, Pub : National Physical Laboratory.

3. Loveday, M.S., Gee, M.G. and Brooks, M.R. (2000) '*Measurement of Friction, Heat Transfer and Strength of Oxides for Rolling and Forging Process Control Models.',* NPL Report CMMT(A) 210, Pub : National Physical Laboratory.

4. Loveday, M.S., Brooks, M.R., (2001) '*High Temperature Friction : a simplified approach for estimating uncertainty of measurement'*, NPL Report CMMT(A)305

5. Kubaschewski, and Hopkins, (1962), '*Oxidation of Metals and Alloys…Second edition*', Butterworths: London.

6. Schey, J. (1984) '*Tribology in Metalworking, Friction, lubrication and wear*', American Society for Metals.

Appendix 1 : Examples of Friction Data classification

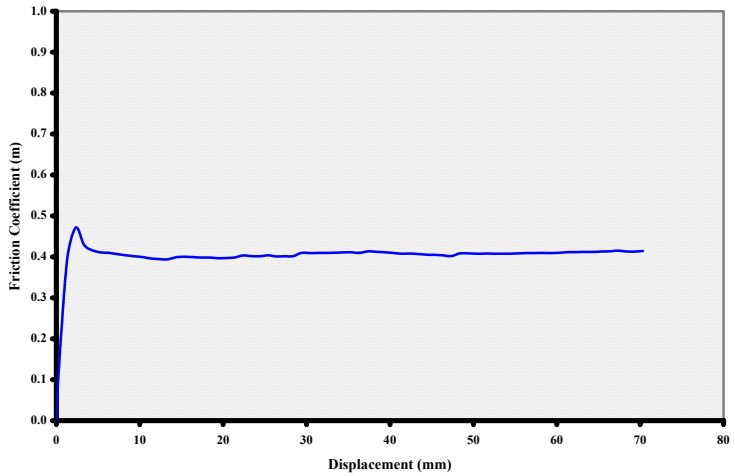
A data classification system has been introduced, as a means by which to express confidence in the friction coefficient for any given material and test condition. This system uses three classes, as described below and can be applied to both the Big Friction and The Pin on Disc Friction test rigs.

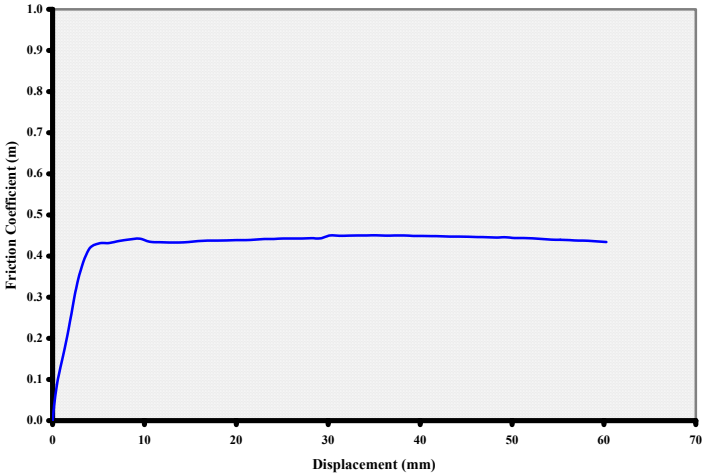
Class 1 Data : The friction coefficient rapidly attains a steady state value, which is maintained for the duration of the test.

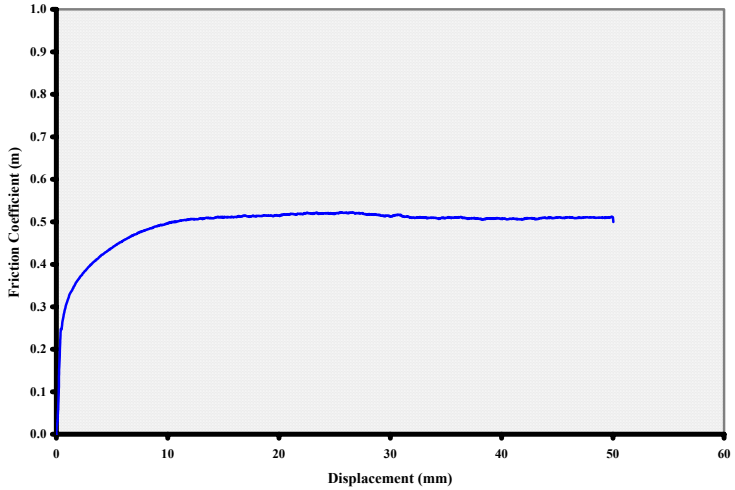
Class 2 Data : This is essentially the same as Class 1 Data, with the friction coefficient rapidly attaining an approximate steady state value, though there is a slight variation over the duration of the test.

Class 3 Data : The friction coefficient for the material under test varies continually throughout the duration of the test.

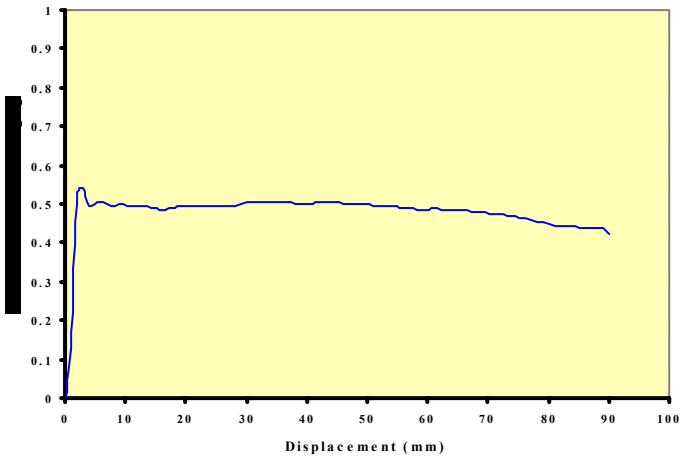
a) Generic Examples of Big Friction Rig Class 1 Data.

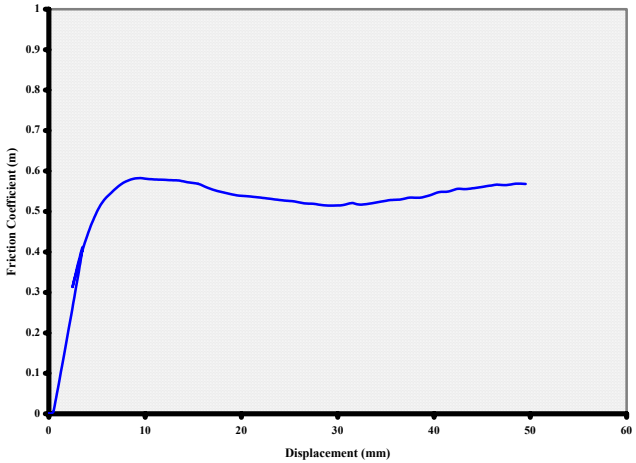


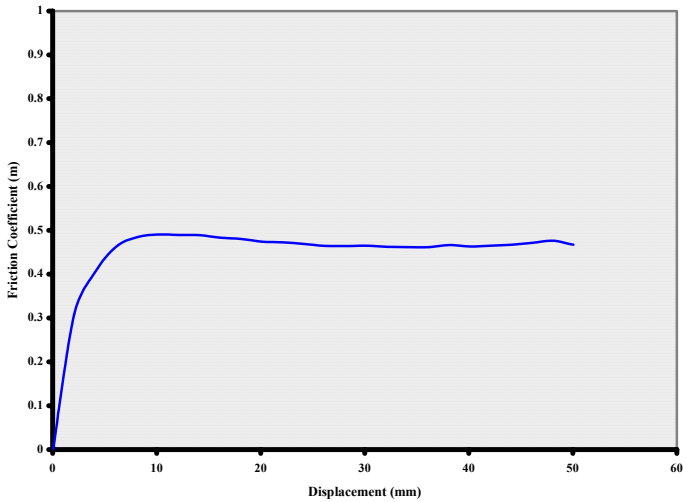




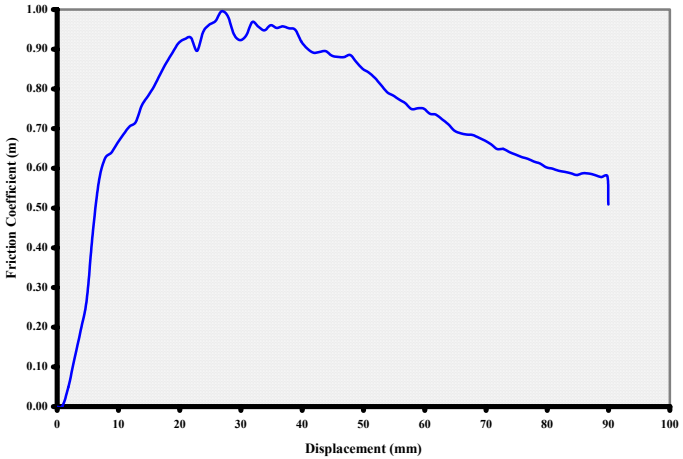
b) Generic Examples of Big Friction Rig Class 2 Data

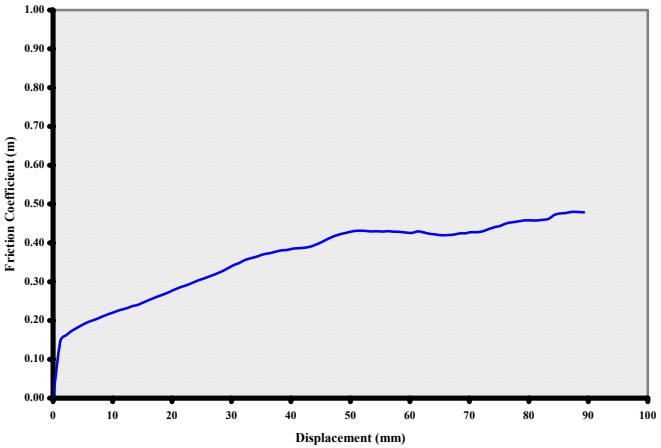


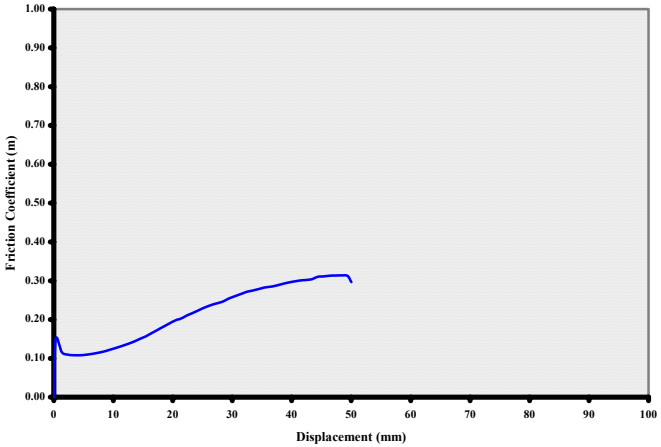


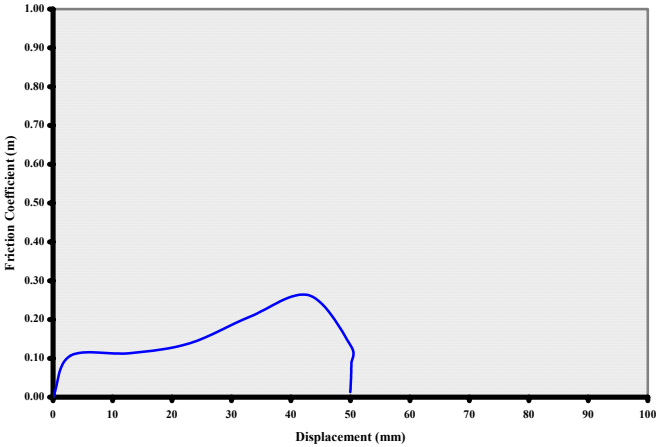


C) Generic Examples of Big Friction Rig Class 3 Data

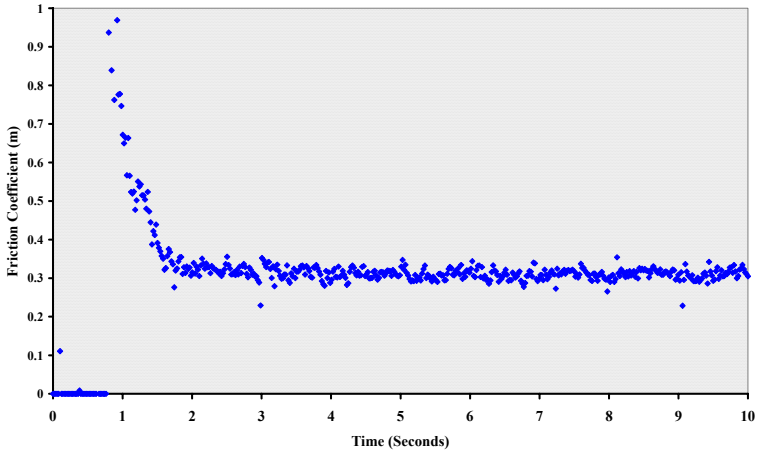


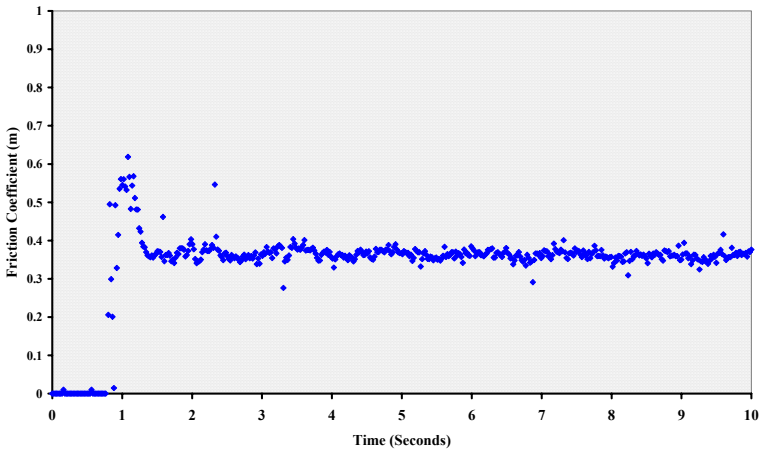


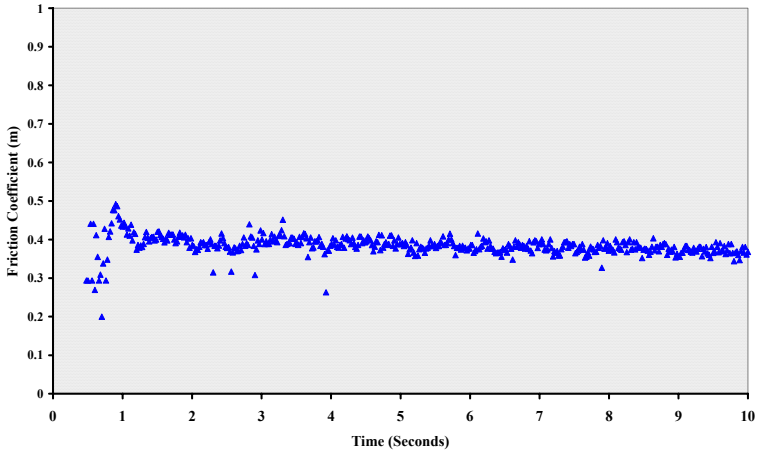




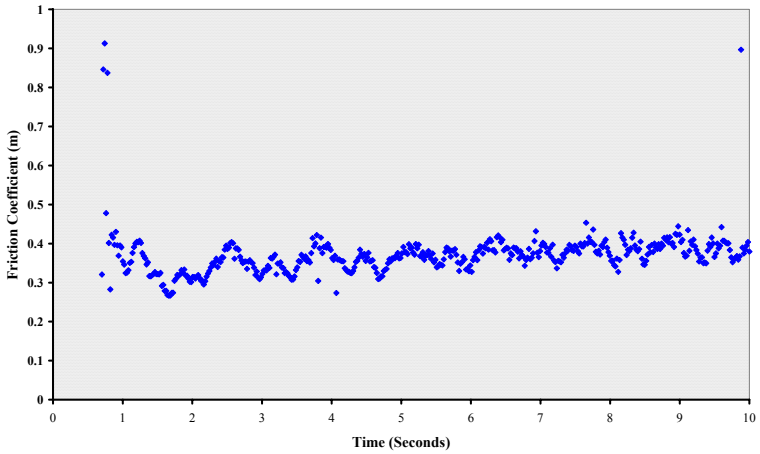
c) Generic Examples of Pin on Disc Class 1 Friction Data

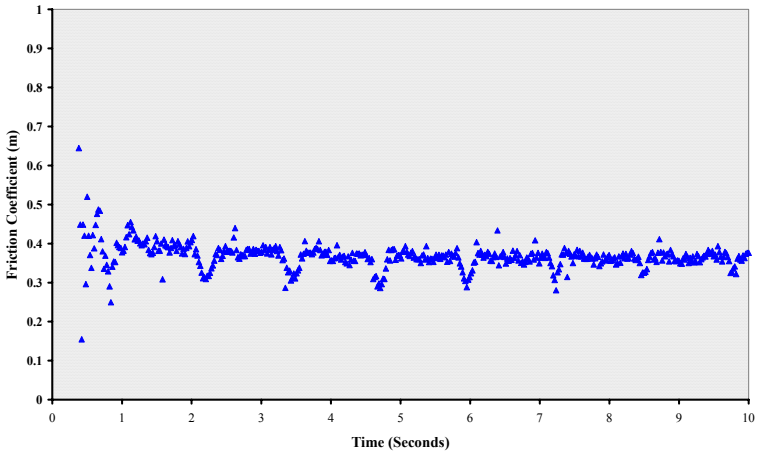


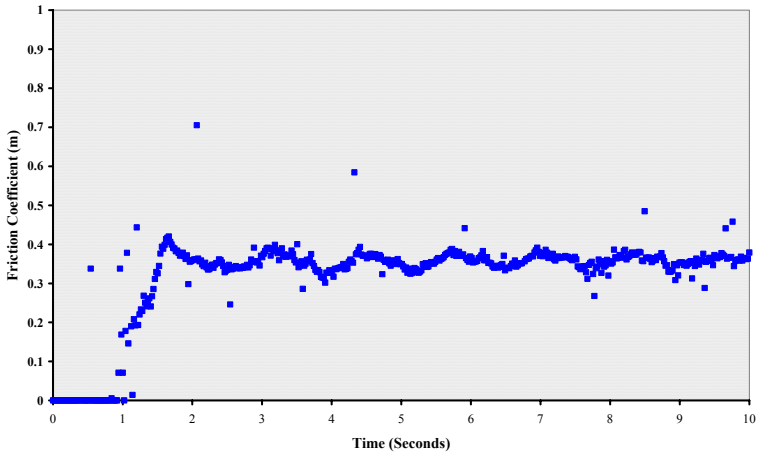




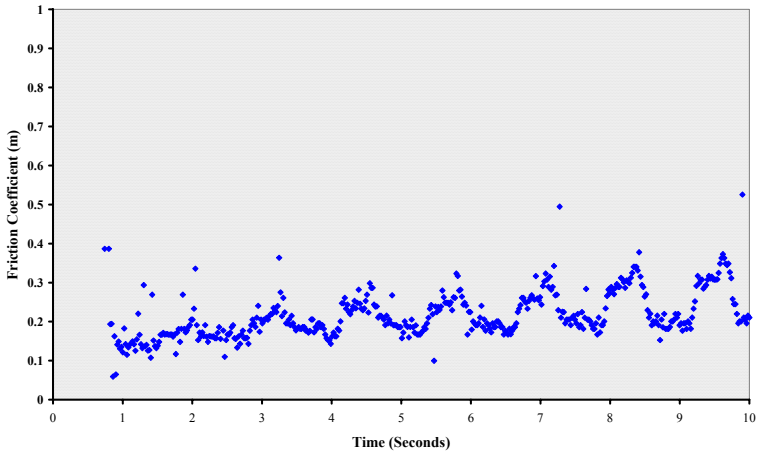
d) Generic Examples of Class 2 Pin on Disc Friction Data

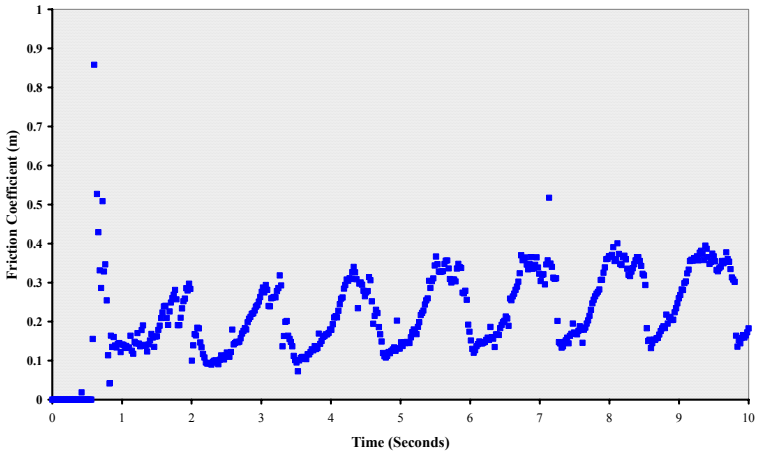


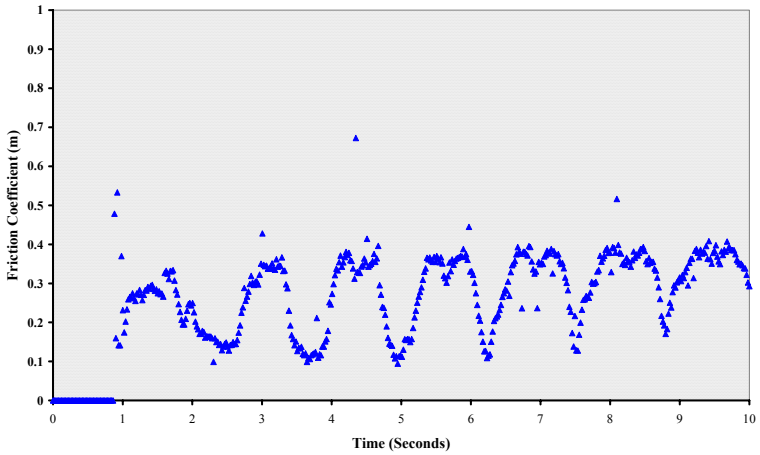




e) Generic Examples of Class 3 Pin on Disc Friction Data







Appendix 2 : Friction Database (Hard Copy).

Summary of Results in Database

Big Friction Rig

Material	No of Results
Mild Steel	93
Aluminium	106
IN718	44
Copper	48
Total	***291***

Pin on Disc Friction Rig

Material	No of Results
Mild Steel	119
Aluminium	36
IN718	78
Total	***233***

Friction Test Results for Mild Steel, Big Friction Rig.

Test No	Filename	Test Piece	Oxide	Test Temp C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ Peak	Friction Coeff, μ Average	Standard Deviation	Data Class
5	frict 5	GCM 30	Thin	22	10.0	None	5.09	****	0.19	****	3
6	frict 6	GCM 30	Thin	22	10.0	None	12.48	****	0.19	****	3
7	frict 7	GCM 30	Thin	22	10.0	None	7.13	****	0.20	****	3
8	frict 8	GCM 30	Thin	22	1.0	None	7.41	****	0.21	****	3
11	frict 11	GCM 30	Thin	22	100.0	None	38.53	****	0.15	****	3
12	frict 12	GCM 30	Thin	22	100.0	None	38.55	****	0.15	****	3
13	frict 13	GCM 30	Thin	22	100.0	None	38.66	****	0.15	****	3
14	frict 14	GCM 30	Thin	22	100.0	None	38.60	****	0.15	****	3
15	frict 15	GCM 30	Thin	22	100.0	None	38.60	****	0.15	****	3
16	frict 16	GCM 30	Thin	22	100.0	None	38.48	****	0.15	****	3
17	frict 17	GCM 30	Thin	22	100.0	None	38.45	****	0.15	****	3
23	frict 23	GCM 30	Thin	22	10.0	None	39.47	****	0.15	****	3
24	frict 24	GCM 30	Thin	22	10.0	None	40.59	****	0.15	****	3
27	frict 27	GCM 30	Thin	22	10.0	None	39.73	****	0.16	****	3
28	frict 28	GCM 30	Thin	22	10.0	None	39.73	****	0.15	****	3
29	frict 29	GCM 20	Thin	22	10.0	None	39.73	****	0.17	****	3
30	frict 30	GCM 20	Thin	22	10.0	**Oil**	40.23	****	0.16	****	3
31	frict 31	GCM 20	Thin	22	10.0	None	40.23	****	0.15	****	3
32	frict 32	GCM 20	Thin	22	100.0	**Oil**	40.23	****	0.20	****	3
36	Frict 36	GCM 20	Thin	22	10.0	**Oil**	40.74	****	0.14	****	3
37	Frict 37	GCM 20	Thin	22	10.0	**Oil**	40.74	****	0.13	****	3
38	Frict 38	GCM 20	Thin	22	100.0	**Oil**	41.25	****	0.23	****	3
39	Frict 39	GCM 20	Thin	22	10.0	**Oil**	21.00	0.13	0.13	0.00	1
40	Frict 40	GCM 20	Thin	22	10.0	None	42.10	0.13	0.13	0.00	1
41	Frict 41	GCM 20	**Thick**	560	10.0	None	42.20	0.42	0.34	0.03	3
43	Frict 43	GCM 22	**Thick**	****	10.0	None	38.90	0.32	0.35	0.02	2
44	Frict 44	GCM 22	Thin	22	10.0	None	38.60	0.20	0.20	0.00	2
50	Frict 50	GCM 13	**Thick**	****	10.0	None	74.80	0.54	0.45	0.02	3
51	Frict 51	GCM 12	Thin	22	10.0	None	112.60	0.19	0.20	0.01	2
151	Frict 141	GCM 16	Thin	22	0.2	None	46.30	0.15	0.13	0.01	1
152	Frict 142	GCM 16	**Thick**	****	0.2	None	80.10	0.16	0.13	0.01	2
155	Frict 143	GCM 16	**Thick**	****	0.2	None	103.60	0.18	0.17	0.01	2

Friction Test Results for Mild Steel, Big Friction Rig.

Test No	Filename	Test Piece	Oxide	Test Temp C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
157	Frict 147	GCM 16	**Thick**	****	0.2	None	73.60	0.25	0.22	0.01	3
158	Frict 148	GCM 16	**Thick**	****	0.2	None	96.04	0.40	0.33	0.03	3
161	Frict 151	GCM 16	**Thick**	****	0.2	None	91.11	0.39	0.41	0.01	1
175	Frict 165	GCM 5	Thin	22	0.2	None	18.56	0.16	0.18	0.01	2
176	Frict 166	GCM 14	**Thick**	190	0.2	None	88.60	0.25	0.23	0.02	3
177	Frict 167	GCM 14	**Thick**	140	0.2	None	54.14	0.30	0.26	0.02	2
178	Frict 168	GCM 14	**Thick**	240	0.2	None	34.25	0.36	0.31	0.02	2
179	Frict 169	GCM 15	**Thick**	300	0.2	None	56.19	0.41	0.36	0.01	2
180	Frict 170	GCM 14	**Thick**	410	0.2	None	21.46	0.34	0.28		2
238	Repeatability 22	GCM 70	**Thick**	575	10.0	None	100.61	0.76	0.42	0.01	2
241	Repeatability 25	GCM 74	**Thick**	587	10.0	None	95.73	0.45	0.42	0.02	2
242	Repeatability 26	GCM 75	**Thick**	575	10.0	None	100.49	0.44	0.43	0.01	1
243	Repeatability 27	GCM 76	**Thick**	670	50.0	None	97.81	0.57	0.44	0.03	3
245	Repeatability 29	GCM 78	**Thick**	****	10.0	None	99.02	0.54	0.49	0.02	2
246	Repeatability 30	GCM 79	**Thick**	500	10.0	None	97.76	0.42	0.42	0.02	2
341	Taguchi 45	GBZ 107	**Thick**	****	50.0	None		0.55			
342	Taguchi 46	GBZ 103	**Thick**	747	50.0	None	112.55	0.42	0.42	0.01	1
343	Taguchi 47	GBZ 100	**Thick**	743	90.0	None	106.96	0.46	0.37	0.03	2
344	Taguchi 48	GBZ 104	**Thick**	402	90.0	None	108.39	0.40	0.44	0.06	3
345	Taguchi 49	GBZ 105	**Thick**	406	10.0	None	115.39	0.40	0.50	0.03	2
346	Taguchi 50	GBZ 105	**Thick**	458	50.0	None	114.92	0.38	0.42	0.05	3
347	Taguchi 51	GBZ 108	**Thick**	364	50.0	None	103.88	0.45	0.45	0.03	2
348	Taguchi 52	GBZ 109	Thin	687	10.0	None	98.77	0.47	0.41	0.01	2
349	Taguchi 53	GBZ 110	Thin	RT	10.0	None	113.62	0.18	0.20	0.03	2
350	Taguchi 54	GBZ 111	Thin	RT	10.0	None	112.57	0.40	0.22	0.06	3
351	Taguchi 55	GBZ 112	Thin	664	10.0	None	96.75	0.40	0.44	0.01	2
355	Taguchi 59	GBZ 114	Thin	334	10.0	None	108.69	0.43	0.48	0.03	3
356	Taguchi 60	GBZ 115	**Thick**	340	50.0	None	105.77	0.46	0.48	0.03	2
357	Taguchi 61	GBZ 117	**Thick**	664	50.0	None	100.37	0.45	0.44	0.01	1
359	Taguchi 63	GBZ 116	Thin	RT	10.0	None	111.24	0.40	0.40	0.00	1
360	Taguchi 64	GBZ 118	Thin	656	10.0	**DAG 2543**	98.96	0.23	0.16	0.01	2
361	Taguchi 65	GBZ 119	Thin	****	90.0	**DAG 2543**	107.23	0.18	0.18	0.01	2

Friction Test Results for Mild Steel, Big Friction Rig.

Test No	Filename	Test Piece	Oxide	Test Temp C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ Peak	Friction Coeff, μ Average	Standard Deviation	Data Class
362	System Test 01	GCM 078	Thin	RT	10.0	**Graphite**	113.15	0.09	0.11	0.00	1
363	System Test 02	GCM 078	Thin	RT	10.0	**Graphite**	112.79	0.09	0.11	0.00	1
364	System Test 03	GCM 078	Thin	RT	50.0	**Graphite**	111.73	0.10	0.12	0.00	1
365	System Test 04	GCM 078	Thin	RT	90.0	**Graphite**	111.14	0.10	0.12	0.00	1
366	System Test 05	GCM 071	**Thick**	940	90.0	**Graphite**	111.19	0.14	0.19	0.02	2
367	System Test 06	GCM 078	**Thick**	977	90.0	**Graphite**	111.19	0.20	0.27	0.02	3
368	System Test 07	GCM 080	**Thick**	800	90.0	**Graphite**	80.81	0.26	0.26	0.01	1
369	System Test 08	GCM 081	**Thick**	800	90.0	**Graphite**	90.78	0.25	0.28	0.01	1
416	BFR Interim 09	GDQ 19	Thin	RT	50.0	None	114.9	0.44	0.48	0.03	2
417	BFR Interim 10	GDQ 01	Thin	RT	50.0	None	115.5	0.50	0.48	0.03	2
426	BFR Interim 19	GDQ 24	**Thick**	195	60.0	None	111.7	0.55	0.49	0.04	3
427	BFR Interim 20	GDQ 31	**Thick**	155	10.0	None	113.1	0.52	0.51	0.02	2
428	BFR Interim 21	GDQ 27	**Thick**	75	50.0	None	111.6	0.47	0.45	0.02	2
429	BFR Interim 22	GDQ 32	**Thick**	190	90.0	None	112.3	0.20	0.38	0.13	3
430	BFR Interim 23	GDQ 23	**Thick**	205	50.0	None	115.2	0.49	0.48	0.01	2
431	BFR Interim 24	GDQ 22	**Thick**	160	50.0	None	115.8	0.50	0.46	0.03	3
442	BFR Interim 35	GDQ 30	**Thick**	280	10.0	None	113.1	0.45	0.45	0.01	1
443	BFR Interim 36	GDQ 21	**Thick**	290	50.0	None	116.1	0.53	0.45	0.04	3
444	BFR Interim 37	GDQ 26	**Thick**	310	90.0	None	115.3	0.68	0.49	0.15	3
446	BFR Interim 39	GDQ 28	**Thick**	320	50.0	None	115.0	0.63	0.49	0.03	3
447	BFR Interim 40	GDQ 29	**Thick**	320	50.0	None	114.0	0.62	0.49	0.02	2
466	BFR Interim 59	GDQ 20	**Thick**	405	50.0	None	115.9	0.40	0.36	0.01	1
468	BFR Interim 61	GDQ 14	**Thick**	440	50.0	None	114.5	0.58	0.46	0.02	2
469	BFR Interim 62	GDQ 17	**Thick**	525	10.0	None	103.1	0.60	0.39	0.02	3
470	BFR Interim 63	GDQ 16	**Thick**	515	10.0	None	106.6	0.45	0.31	0.03	2
471	BFR Interim 64	GDQ 15	**Thick**	610	50.0	None	105.1	0.48	0.37	0.02	3
473	BFR Interim 66	GDQ 18	**Thick**	645	90.0	None	105.9	0.56	0.42	0.02	2
474	BFR Interim 67	GDQ 25	**Thick**	570	50.0	None	105.8	0.43	0.38	0.01	2
475	BFR Interim 68	GDQ 12	**Thick**	600	50.0	None	102.4	0.50	0.45	0.01	2

Friction Test Results for Aluminium, Big Friction Rig

Test No	Filename	Testpiece	Oxide	Avg Test Temp °C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
52	Frict 52	GAZ-1- 5	****	22	10.0	None	110.4	0.52	0.5	0.02	2
53	Frict 53	GAZ-1- 5	****	22	10.0	None	108.8	0.49	0.47	0.01	2
54	Frict 54	GAZ-1- 5	****	22	10.0	**Oil**	105.0	0.13	0.13	0.01	2
55	Frict 55	GAZ-1- 5	****	22	10.0	None	31.3	0.18	0.14	0.01	2
56	Frict 56	GAZ-1- 6	****	22	10.0	**Oil**	40.1	0.13	0.14	0.01	3
57	Frict 57	GAZ-1- 7	****	22	10.0	**Oil**	35.0	0.11	0.14	0.01	3
58	Frict 58	GAZ-1- 7	****	22	10.0	None	32.8	0.18	0.16	0.01	2
59	Frict 59	GAZ-1- 7	****	22	50.0	None	62.3	0.16	0.19	0.00	3
60	Frict 60	GAZ-1- 7	****	22	100.0	None	61.4	0.19	0.18	0.01	3
61	Frict 61	GAZ-1- 7	****	22	100.0	**Oil**	60.0	0.06	0.06	0.01	2
62	Frict 62	GAZ-1- 7	****	22	50.0	**Oil**	46.1	0.06	0.06	0.01	2
63	Frict 63	GAZ-1- 7	****	22	100.0	**Oil**	113.6	0.16	0.15	0.01	1
64	Frict 64	GAZ-1- 7	****	22	50.0	**Oil**	113.8	0.14	0.12	0.01	2
65	Frict 65	GAZ-1- 7	****	22	50.0	**Oil**	114.2	0.15	0.16	0.01	2
66	Frict 66	GAZ-1- 1	**Thick**	****	10.0	**Oil**	33.0	0.2	0.18	0.01	2
67	Frict 67	GAZ-1- 7	****	22	20.0	None	109.3		0.19	0.00	3
68	Frict 68	GAZ-1- 7	****	22	10.0	None	115.5	0.15	0.2	0.04	3
69	Frict 69	GAZ-1- 1	****	****	10.0	None	109.6	0.16	0.26	0.08	3
70	frict 70	GAZ-1- 2	**Thick**	22	10.0	None	77.2	0.13	0.55	0.22	2
71	Frict 71	GAZ-1-1	****	22	2.0	None	112.9	0.47	0.47	0.01	2
72	Frict 72	GAZ-1-1	****	22	2.0	**Oil**	111.9	0.13	0.14	0.00	1
73	Frict 73	GAZ-1-1	****		10.0	None	111.7	0.14	0.22	0.04	3
149	Frict 138	GAZ-1-19	****	22	0.2	None	96.9	0.14	0.14	0.01	1
150	Frict 139	GAZ-1-19	****	22	0.2	None	96.8	0.14	0.13	0.01	1
162	Frict 152	GAZ-1-19	****	22	0.2	None	80.3	0.15	0.16	0.01	2
163	Frict 153	GAZ-1-19	**Thick**	125	0.2	None	31.3	0.38	0.25	0.02	2
165	Frict 155	GAZ-1-2	**Thick**	100	0.2	None	33.1	0.21	0.21	0.02	2
166	Frict 156	GAZ-1-2	**Thick**	150	0.2	None	83.6	0.2	0.2	0.01	2
167	Frict 157	GAZ-1-2	**Thick**	150	0.2	None	39.2	0.26	0.24	0.01	2
168	Frict 158	GAZ-1-2	**Thick**	80	0.2	None	45.7	0.21	0.21	0.01	2
169	Frict 159	GAZ-1-2	**Thick**	95	0.2	None	26.7	0.23	0.21	0.01	2
170	Frict 160	GAZ-1-2	**Thick**	125	0.2	None	27.2	****	0.42	0.02	3

Friction Test Results for Aluminium, Big Friction Rig

Test No	Filename	Testpiece	Oxide	Avg Test Temp °C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
173	Frict 163	GAZ -1-2	**Thick**	150	0.2	None	28.7	0.27	0.23	0.01	3
202	Repeatability 1	GAZ-1-15	****	22	10.0	None	106.1		0.16	0.04	3
203	Repeatability 2	GAZ-1-23	****	22	10.0	None	105.6		0.22	0.07	3
204	Repeatability retest 1	GAZ-1-13	****	22	10.0	None	105.5		0.21	0.02	2
205	Repeatability retest 2	GAZ-1-17	****	22	10.0	None	105.6		0.29	0.10	3
207	Repeatability 3	GAZ-1-25	****	22	10.0	**Oil**	105.7		0.09	0.02	3
211	Repeatability 7	GAZ-1-12	****	22	10.0	None	109.99	0.31	0.33	0.01	1
212	Repeatability 8	GAZ-1-12	****	22	10.0	None	109.57	0.29	0.34	0.05	3
213	Repeatability 9	GAZ-1-12	****	22	10.0	None	109.51	0.29	0.32	0.05	3
214	Repeatability 10	GAZ-1-12	****	22	10.0	None	109.82	0.30	0.30	0.02	2
215	Repeatability 11	GAZ-1-12	****	22	10.0	None	109.68	0.28	0.31	0.03	3
221	Displacement 6	GAZ-1-8	****	22	5.0	None	107.2	0.15	0.51	0.01	2
222	Displacement 7	GAZ-1-8	****	22	10.0	None	108.8	****	0.51	0.01	1
223	Displacement 8	GAZ-1-8	****	22	20.0	None	109.2	0.6	0.52	0.03	2
224	Displacement 9	GAZ-1-8	****	22	50.0	None	108.7	0.58	0.5	0.01	2
225	Displacement 10	GAZ-1-8	****	22	100.0	None	108.8	0.58	0.51	0.01	2
227	Displacement 12	GAZ-1-9	****	22	5.0	None	107.7	0.58	0.46	0.01	3
228	Repeatability 13	GAZ-1-11	****	22	10.0	None	110.38	0.16	0.41	0.10	3
232	Repeatability 16	GAZ-1-16	****	22	10.0	None	110.19	0.50	0.49	0.06	2
235	Repeatability 19	GAZ-1-14	****	22	10.0	None	107.29	0.44	0.41	0.02	2
236	Repeatability 20	GAZ-1-18	****	22	10.0	None	109.17	0.18	0.27	0.04	3
237	Repeatability 21	GAZ-1-4	****	22	10.0	None	107.05	0.50	0.48	0.01	2
247	Whard 1	GAZ-1-9	****	22	100.0	None	108.4	0.20	0.17	0.05	3
248	Whard 2	GAZ-1-9	****	22	50.0	None	108.6	0.12	0.35	0.04	3
249	Whard 3	GAZ-1-9	****	22	25.0	None	108.2	0.15	0.39	0.02	2
250	Whard 4	GAZ-1-9	****	22	10.0	None	106.7	0.36	0.37	0.03	2
252	Whard 6	GAZ-1-9	****	22	100.0	None	108.2		0.24	0.06	3
253	Whard 7	GAZ-1-10	****	22	100.0	None	110.1	0.18	0.51	0.10	3
279	Whard 15	GAZ-2-126	****	22	100.0	None	107.5	0.33	0.83	0.01	2
280	Whard 16	GAZ-2-126	****	22	50.0	None	106.4	0.34	0.72	0.11	2
281	Whard 17	GAZ-2-126	****	22	20.0	None	105.2	0.60	0.74	0.04	3
282	Whard 18	GAZ-2-126	****	22	10.0	None	104.9	0.75	0.75	0.03	2
283	Whard 19	GAZ-2-126	****	22	5.0	None	104.8	0.7	0.76	0.02	2

Friction Test Results for Aluminium, Big Friction Rig

Test No	Filename	Testpiece	Oxide	Avg Test Temp °C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
284	Taguchi 1	GAZ-2-100	**Thick**	173	10.0	None	105.4	0.51	0.31	0.09	3
285	Frict check 1	GAZ-2-125	****	22	5.0	None	94.7	0.14	0.16	0.03	3
286	Frict check 2	GAZ-2-125	****	22	5.0	None	96.6	0.10	0.17	0.04	3
287	Frict check 3	GAZ-2-125	****	22	50.0	None	96.9	0.10	0.13	0.01	3
288	Frict check 4	GAZ-2-125	****	22	100.0	None	95.5	0.14	0.3	0.01	3
289	Taguchi 2	GAZ-2-127	**Thick**	188	10.0	None	97.2	1.00	0.76	0.15	3
291	Taguchi 4	GAZ-2-101	**Thick**	218	50.0	None	95.3	0.76	0.56	0.15	3
293	Taguchi 6	GAZ-2-102	**Thick**	173	10.0	None	80.1	0.63	0.30	0.01	3
295	Taguchi 8	GAZ-2-103	**Thick**	161	90.0	None	93.2	0.84	0.73	0.02	3
296	Taguchi 9	GAZ-2-104	****	22	90.0	None	105.5	0.49	0.47	0.03	2
297	Taguchi 10	GAZ-2-105	**Thick**	227	50.0	None	99.2	0.87	0.76	0.16	3
299	Taguchi 12	GAZ-2-106	**Thick**	194	10.0	None	93.7	0.90	0.84	0.04	3
302	Taguchi 15	GAZ-2-111	**Thick**	208	10.0	None	97.1	1.03	0.97	0.03	3
303	Taguchi 16	GAZ-2-108	**Thick**	222	10.0	None	78.7	1.00	0.67	0.17	3
304	Taguchi 17	GAZ-2-107	**Thick**	****	50.0	None	76.3	0.84	0.77	0.03	3
305	Taguchi 18	GAZ-2-110	****	22	10.0	**DAG 2543**	110.3	0.04	0.03	0.00	3
317	Taguchi 30	GAZ-2-116	**Thick**	172	10.0	None	107.9	0.10	0.26	0.01	2
319	Taguchi 32	GAZ-2-115	**Thick**	205	10.0	None	104.8	0.01	0.29	0.04	3
320	Taguchi 33	GAZ-2-110	**Thick**	****	90.0	**DAG 2543**	94.5	0.06	0.10	0.03	2
324	Taguchi 37	GAZ-2-118	**Thick**	****	90.0	None	93.4	0.04	0.21	0.14	3
325	Taguchi 38	GAZ-2-109	**Thick**	245	90.0	**DAG 2543**	95.0	0.08	0.10	0.04	3
326	Taguchi 39	GAZ-2-113	**Thick**	****	90.0	**DAG 2543**	41.6	0.09	0.09	0.02	2
327	Taguchi 40	GAZ-2-120	**Thick**	260	90.0	**DAG 2543**	94.8	0.05	0.08	0.03	3
328	Taguchi 41	GAZ-2-121	**Thick**	275	90.0	None	77.1	0.70	0.57	0.05	3
329	Taguchi 42	GAZ-2-122	****	22	10.0	None	103.8	0.50	0.47	0.02	2
330	Taguchi 43	GAZ-2-123	****	22	10.0	None	98.2	0.48	0.45	0.02	2
333	Taguchi 43A	GAZ-2-124	**Thick**	193	50.0	None	86.9	0.76	0.53	0.13	3
418	BFR Interim 11	GDK 24	****	RT	10.0	None	115.1	0.51	0.44	0.03	3
419	BFR Interim 12	GDK 25	****	RT	30.0	None	117.3	0.56	0.46	0.03	3
420	BFR Interim 13	GDK 23	****	RT	50.0	None	117.2	0.57	0.49	0.02	2
421	BFR Interim 14	GDK 22	****	RT	80.0	None	114.6	0.51	0.51	0.01	1
422	BFR Interim 15	GDK 21	****	RT	100.0	None	114.1	0.60	0.61	0.09	2
423	BFR Interim 16	GDK 11	**Thick**	100	50.0	None	113.7	0.46	0.42	0.01	2

Friction Test Results for Aluminium, Big Friction Rig

Test No	Filename	Testpiece	Oxide	Avg Test Temp °C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
424	BFR Interim 17	GDK 10	**Thick**	115	90.0	None	114.3	0.49	0.59	0.04	3
433	BFR Interim 26	GDK 13	**Thick**	235	90.0	None	103.5	0.67	0.55	0.05	3
434	BFR Interim 27	GDK 08	**Thick**	245	50.0	None	95.4	0.80	0.79	0.02	2
435	BFR Interim 28	GDK 12	**Thick**	200	90.0	None	94.7	0.81	0.81	0.02	2
481	BFR Interim 74	GDK 07	**Thick**	215	50.0	None	98.7	0.51	0.51	0.01	2
482	BFR Interim 75	GDK 09	**Thick**	240	50.0	None	103.3	0.54	0.51	0.02	3
483	BFR Interim 76	GDK 06	**Thick**	****	90.0	None	102.8	0.62	0.51	0.01	2
484	BFR Interim 77	GDK 01	**Thick**	****	10.0	None	81.2	0.67	0.54	0.09	3

Friction Test Results for IN718, Big Friction Rig

Test No	Filename	Test Piece	Oxide	Test Temp °C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
49	Frict 49	GCN 1	****	22	10.0	**Oil**	107.5	0.15	0.15	0.01	1
74	Frict 74	GCN 7	****	22	10.0	None	110.9	0.16	0.21	0.03	3
75	Frict 75	GCN 8	****	22	10.0	None	115.6	0.15	0.26	0.08	3
76	Frict 76	GCN 7	****	22	10.0	**Oil**	109.4	0.11	0.18	0.06	3
77	Frict 77	GCN 7	****	22	50.0	**Oil**	107.9	0.11	0.17	0.63	3
78	Frict 78	GCN 8	****	22	10.0	**Dag 580**	110.0	0.09	0.11	0.03	3
79	Frict 79	GCN 8	****	22	50.0	**Dag 580**	111.0	0.40	0.1	0.02	3
80	Frict 80	GCN 8	****	22	100.0	**Dag 580**	107.8	0.15	0.16	0.03	3
81	Frict 81	GCN 7	****	22	10.0	None	24.7	0.03	0.03	0.00	1
82	Frict 82	GCN 10	****	22	10.0	None	30.1	0.14	0.14	0.31	3
83	Frict 83	GCN 8	**Thick**	350	10.0	None	105.8	0.15	0.46	0.01	2
84	Frict 84	GCN 3	**Thick**	310	10.0	**Dag 580**	109.7	0.05	0.06	0.03	3
85	Frict 85	GCN 3	**Thick**	450	10.0	**Dag 580**	109.3	0.05	0.06	0.01	3
86	Frict 86	GCN 3	**Thick**	450	10.0	**Dag 580**	1213.4	0.06	0.03	0.01	2
87	Frict 87	GCN 3	**Thick**	350	10.0	**Dag 580**	113.5	0.06	0.04	0.00	2
88	Frict 88	GCN 3	**Thick**	580	50.0	**Dag 580**	114.6	0.03	0.04	0.01	3
89	Frict 89	GCN 4	**Thick**	550	100.0	None	119.2	0.03	0.03	0.01	3
90	Frict 90	GCN 4	**Thick**	560	50.0	None	113.0	0.04	0.04	0.01	2
181	Frict 171	GCN 6	**Thick**	22	0.2	None	114.0	0.18	0.18	0.00	3
182	Frict 172	GCN 6	****	22	0.2	None	117.9	0.18	0.18	0.00	3
208	Repeatability 4	GCN 6	****	22	10.0	None	117.85	0.12	0.18	0.03	3
209	Repeatability 5	GCN 6	****	22	10.0	None	114.01	0.39	0.36	0.02	2
210	Repeatability 6	GCN 6	****	22	10.0	None	173.70	0.42	0.41	0.01	2
234	Repeatability 18	GCNxx	****	22	10.0	None	64.79	0.15	0.37	0.09	3
408	BFR Interim 01	GDT 01	****	22	0.2	None	108.0	0.74	0.49	0.01	2
409	BFR Interim 02	GDT 02	****	22	10.0	None	119.1	0.66	0.53	0.06	3
410	BFR Interim 03	GDT 03	****	22	30.0	None	116.1	0.78	0.59	0.04	2
411	BFR Interim 04	GDT 04	****	22	80.0	None	117.2	0.79	0.46	0.04	2
415	BFR Interim 08	GDT 18	****	22	60.0	None	115.9	0.52	0.54	0.03	2
425	BFR Interim 18	GDT 23	**Thick**	85	60.0	None	116.7	0.52	0.45	0.03	3

Friction Test Results for IN718, Big Friction Rig

Test No	Filename	Test Piece	Oxide	Test Temp °C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
432	BFR Interim 25	GDT 26	**Thick**	150	60.0	None	113.9	0.43	0.44	0.01	2
445	BFR Interim 38	GDT 29	**Thick**	320	60.0	None	115.3	0.60	0.52	0.04	3
448	BFR Interim 41	GDT 21	**Thick**	70	0.2	None	115.4	0.59	0.52	0.03	2
449	BFR Interim 42	GDT 24	**Thick**	315	30.0	None	113.6	0.69	0.55	0.04	3
450	BFR Interim 43	GDT 25	**Thick**	355	50.0	None	113.9	0.60	0.55	0.03	2
451	BFR Interim 44	GDT 27	**Thick**	330	80.0	None	115.0	0.71	0.48	0.03	2
452	BFR Interim 45	GDT 22	**Thick**	330	100.0	None	114.3	0.64	0.48	0.06	3
467	BFR Interim 60	GDT 30	**Thick**	390	60.0	None	113.8	0.70	0.51	0.03	2
472	BFR Interim 65	GDT 28	**Thick**	565	60.0	None	113.8	0.46	0.40	0.01	2
476	BFR Interim 69	GDT 20	**Thick**	560	10.0	None	110.6	0.70	0.61	0.01	2
477	BFR Interim 70	GDT 17	**Thick**	640	30.0	None	114.9	0.72	0.51	0.02	2
478	BFR Interim 71	GDT 16	**Thick**	660	50.0	None	115.0	0.80	0.49	0.02	2
479	BFR Interim 72	GDT 19	**Thick**	655	80.0	None	114.5	0.72	0.45	0.04	2
480	BFR Interim 73	GDT 15	**Thick**	604	100.0	None	112.9	0.89	0.44	0.05	2

Friction Test Results For Copper, Big Friction Rig

Test No	Filename	Testpiece	Oxide	Test Temp °C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
42	Frict 42	GCE 001	Thin	22	10.0	None	112.0	0.18	0.23	0.04	2
206	Repeatability retest 3	GCE 020	Thin	22	10.0	None	105.0	0.13	0.25	0.07	3
216	Displacement 1	GCE 025	Thin	22	5.0	None	105.4	0.15	0.21	0.02	1
217	Displacement 2	GCE 025	Thin	22	10.0	None	109.5	0.20	0.24	0.01	1
218	Displacement 3	GCE 025	Thin	22	20.0	None	109.9	0.24	0.26	0.01	1
219	Displacement 4	GCE 025	Thin	22	50.0	None	108.8	0.27	0.27	0.01	1
220	Displacement 5	GCE 025	Thin	22	100.0	None	110.1	0.29	0.29	0.01	2
273	Whard 9	GCE 016	Thin	22	100.0	None	107.5	0.22	0.34	0.08	3
274	Whard 10	GCE 016	Thin	22	50.0	None	107.3	0.26	0.34	0.08	3
275	Whard 11	GCE 016	Thin	22	20.0	None	106.3	0.28	0.29	0.00	3
276	Whard 12	GCE 016	Thin	22	10.0	None	104.5	0.34	0.38	0.03	2
277	Whard 13	GCE 016	Thin	22	5.0	None	104.8	0.31	0.38	0.03	2
278	Whard 14	GCE 016	Thin	22	100.0	None	107.6	0.32	0.41	0.06	3
290	Taguchi 3	GCE 100	**Thick**	267	90.0	None	68.3	0.38	0.36	0.01	2
292	Taguchi 5	GCE 101	**Thick**	335	90.0	None	99.8	0.60	0.49	0.02	2
294	Taguchi 7	GCE 102	**Thick**	228	90.0	None	102.4	0.55	0.40	0.03	2
298	Taguchi 11	GCE 106	**Thick**	347	90.0	None	101.3	0.53	0.49	0.07	2
301	Taguchi 14	GCE 113	**Thick**	256	90.0	None	103.7	0.52	0.45	0.01	1
306	Taguchi 19	GCE 115	Thin	22	50.0	**DAG 2543**	109.4	0.04	0.09	0.00	3
310	Taguchi 23	GCE 104	Thin	292	10.0	**DAG 2543**		0.04	0.07	0.01	3
314	Taguchi 27	GCE 103	Thin	22	10.0	**DAG 2543**	103.6	0.10	0.05	0.01	3
315	Taguchi 28	GCE 105	Thin	22	10.0	**DAG 2543**	109.5	0.00	0.02	0.01	3
316	Taguchi 29	GCE 111	Thin	22	50.0	**DAG 2543**	109.1	0.01	0.01	0.00	3
318	Taguchi 31	GCE 109	Thin	22	50.0	None	107.5	0.02	0.06	0.00	3
322	Taguchi 35	GCE 116	Thin	359	50.0	**DAG 2543**	101.2	0.03	0.05	0.00	3
323	Taguchi 36	GCE 117	**Thick**	438	50.0	None	68.5	0.24	0.09	0.01	3
412	BFR Interim 05	GDS 19	Thin	22	30.0	None	115.7	0.46	0.42	0.01	2
413	BFR Interim 06	GDS 20	Thin	22	65.0	None	115.6	0.46	0.44	0.06	1
414	BFR Interim 07	GDS 18	Thin	22	85.0	None	114.5	0.45	0.44	0.01	2
436	BFR Interim 29	GDS 27	**Thick**	190	5.0	None	111.6	0.40	0.36	0.03	2

Friction Test Results For Copper, Big Friction Rig

Test No	Filename	Testpiece	Oxide	Test Temp °C	Ram Speed mm/s	Lubrication	Axial Stress Mpa	Friction Coeff, μ		Standard Deviation	Data Class
								Peak	Average		
437	BFR Interim 30	GDS 32	**Thick**	215	10.0	None	111.2	0.38	0.29	0.01	2
438	BFR Interim 31	GDS 31	**Thick**	235	20.0	None	112.4	0.39	0.28	0.02	2
439	BFR Interim 32	GDS 27	**Thick**	280	50.0	None	113.5	0.32	0.27	0.04	3
440	BFR Interim 33	GDS 28	**Thick**	270	65.0	None	112.5	0.30	0.26	0.02	2
441	BFR Interim 34	GDS 30	**Thick**	280	85.0	None	113.9	0.37	0.26	0.02	2
453	BFR Interim 46	GDS 16	**Thick**	245	5.0	None	103.5	0.56	0.37	0.03	2
454	BFR Interim 47	GDS 15	**Thick**	280	10.0	None	100.0	0.49	0.37	0.01	2
455	BFR Interim 48	GDS 26	**Thick**	300	20.0	None	99.7	0.47	0.37	0.01	2
456	BFR Interim 49	GDS 13	**Thick**	375	50.0	None	105.6	0.45	0.30	0.02	3
457	BFR Interim 50	GDS 12	**Thick**	340	65.0	None	106.0	0.34	0.23	0.02	2
458	BFR Interim 51	GDS 25	**Thick**	365	85.0	None	104.3	0.47	0.33	0.02	2
459	BFR Interim 52	GDS 11	**Thick**	295	5.0	None	100.2	0.47	0.44	0.02	2
460	BFR Interim 53	GDS 14	**Thick**	270	5.0	None	96.0	0.56	0.43	0.01	2
461	BFR Interim 54	GDS 29	**Thick**	305	10.0	None	98.8	0.55	0.48	0.01	2
462	BFR Interim 55	GDS 24	**Thick**	320	20.0	None	100.3	0.50	0.37	0.01	2
463	BFR Interim 56	GDS 21	**Thick**	355	50.0	None	98.8	0.51	0.39	0.01	2
464	BFR Interim 57	GDS 22	**Thick**	420	65.0	None	103.3	0.39	0.29	0.01	1
465	BFR Interim 58	GDS 23	**Thick**	390	85.0	None	101.4	0.41	0.30	0.01	1

Friction Test Results for Mild Steel, Pin on Disc Rig

Test No	Filename	Test piece	Tool Disc	Lubricant	Temperature		Oxide Thickness	Linear Speed	Axial Stres (MPa)		Avg Friction	Standard Deviation	Data Class
					Initital	Steady State	µm	mm/s	Nominal	Actual	µ	σ	
1	MS 900 No Dwell	MS 01	GCJ14 A	None	900	350	Thin	50	76.4		0.30	0.04	1
3	MS3 900 No Dwell	MS 03	GCJ14 A	None	900	600	Thin	50	76.4		0.40	0.09	1
6	MS4 700 No Dwell	MS 04	GCJ14 A	None	700		Thin	50	74.7		0.38	0.07	1
7	MS5 500 No Dwell	MS 05	GCJ14 A	None	500		Thin	50	76.7		0.32	0.02	1
8	MS6 RT No Dwell	MS 06	GCJ14 A	None	RT	RT	Thin	50	77.9		0.32	0.02	1
9	MS6 RT No Dwell B	MS 07	GCJ14 A	None	RT	RT	Thin	50	75.9		0.40	0.02	1
10	MS8 500 No Dwell	MS 08	GCJ14 A	None	500	370	Thin	50	76.9		0.39	0.05	1
11	MS9 700 No Dwell	MS 09	GCJ14 A	None	700	220	Thin	50	80.9	134.8	0.39	0.07	2
12	MS10 900 No Dwell	MS 10	GCJ14 A	None	900	325	Thin	50	78.6		0.31	0.05	2
13	MS11 900 No Dwell Fast	MS 11	GCJ14 A	None	900	490	Thin	200	76.1		0.28	0.15	2
15	MS13 700 No Dwell Fast	MS 13	GCJ14 A	None	700	480	Thin	200	74.3		0.23	0.05	2
16	MS14 700 No Dwell Fast	MS 14	GCJ14 A	None	700	282	Thin	200	0.0 - 80.0		0.28	0.09	3
17	MS15 500 No Dwell Fast	MS 15	GCJ14 B	None	500	310	Thin	200	67.9		0.39	0.1	3
18	MS16 RT No Dwell Fast	MS 16	GCJ14 B	None	RT	RT	Thin	200	76.0		0.33	0.08	3
35	MS17 RT 20 Dwell 900C	MS 17	GCJ7 A	None	RT	RT	Thin	50	76.8		0.36	0.08	3
36	MS18 900C 20 Dwell 900	MS 18	GCJ7 A	None	900	300	Thin	50	76.3		0.43	0.04	1
37	MS19 900C No Dwell Graphite Lub	MS 19	GCJ7 A	**Graphite**	900	266	Thin	50	77.3	306.7	0.26	0.09	3
38	MS20 RT 500N	MS 20	GCJ4 A	None	RT	RT	Thin	50	19.5		0.17	0.06	3
39	MS21 RT 1000N	MS 21	GCJ4 A	None	RT	RT	Thin	50	38.9		0.16	0.06	3
40	MS22 RT 2000N	MS 22	GCJ4 A	None	RT	RT	Thin	50	79.3		0.29	0.08	2
41	MS23 RT 3000N	MS 23	GCJ4 A	None	RT	RT	Thin	50	118.8		0.27	0.03	1
42	MS24 RT 4000N	MS 24	GCJ4 A	None	RT	RT	Thin	50	159.0		0.32	0.05	3
43	MS25 RT 5000N	MS 25	GCJ4 A	None	RT	RT	Thin	50	198.6		0.23	0.05	2
44	MS26 RT 6000N	MS 26	GCJ4 A	None	RT	RT	Thin	50	200.0		0.23	0.04	2
45	MS27 500C 2kN	MS 27	GCJ4 B	**1 layer Graphite**	500	140	Thin	50	199.4	249.3	0.16	0.05	3
46	MS28 500C 5kN 2 Layer Graphite	MS 28	GCJ4 B	**2 layer Graphite**	500	135	Thin	50	201.4	201.4	0.08	0.06	3
47	MS29 500C 5kN 3 Layer Graphite	MS 29	GCJ4 B	**3 layer Graphite**	500	****	Thin	50	199.2	332.0	0.11	0.05	3
56	General Test 1	MS 37	GCJ 3A	None	350	65	Thin	62	18.9	94.5	0.20	0.08	2
57	General Test 2	MS 32	GCJ 3A	None	350	110	Thin	62	38.4	76.8	0.34	0.11	3
58	General Test 3	MS 31	GCJ 3A	None	350	155	Thin	62	79.0	87.8	0.41	0.07	2
59	General Test 4	MS 34	GCJ 3A	None	350	220	Thin	62	197.8	303.4	0.29	0.01	1
60	General Test 5	MS 39	GCJ 3A	None	350	160	Thin	124	18.8	20.9	0.59	0.12	3
61	General Test 6	MS 33	GCJ 3A	None	350	170	Thin	124	38.3	69.4	0.47	0.05	2
62	General Test 7	MS 44	GCJ 3A	None	350	180	Thin	124	79.2	99.0	0.42	0.03	2
63	General Test 8	MS 45	GCJ 3A	None	350	235	Thin	124	198.4	198.4	0.26	0.01	1
84	Oxide Test 1	MS 47	GCJ 8A	None	700	230	**100**	59	38.5		0.60	0.06	2
85	Oxide Test 2	MS 43	GCJ 8A	None	700	100	**100**	59	79.1		0.46	0.04	2
86	Oxide Test 3	MS 48	GCJ 8A	None	700	280	**100**	59	198.3	220.3	0.30	0.03	2
87	Oxide Test 4	MS 46	GCJ 8A	None	1050	330	**100**	59	38.5	38.5	0.57	0.06	2
88	Oxide Test 5	MS 49	GCJ 8A	None	1050	250	**100**	59	79.3	198.4	0.43	0.04	2
89	Oxide Test 6	MS 40	GCJ 8A	None	1050	460	**100**	59	198.2	263.6	0.26	0.01	2
90	General Test 29	MS 35	GCJ 8B	None	700	180	Thin	59	18.9	94.5	0.34	0.15	3
91	General Test 30	MS 36	GCJ 8B	None	700	155	Thin	59	38.9	77.8	0.52	0.06	1
92	General Test 31	MS 38	GCJ 8B	None	700	210	Thin	59	79.0	79.0	0.45	0.03	2
93	General Test 32	MS 42	GCJ 8B	None	700	300	Thin	59	197.4	329.0	0.28	0.01	1
94	Oxide Test 7	MS 73	GCJ 12A	None	700	320	**200**	66	78.8	223.9	0.43	0.05	2
95	Oxide Test 8	MS 60	GCJ 12A	None	700	390	**300**	66	79.0	263.2	0.44	0.03	2
96	Oxide Test 9	MS 75	GCJ 12A	None	700	300	**400**	66	79.2		0.47	0.02	2
97	Oxide Test 10	MS 70	GCJ 12A	None	1050	510	**200**	66	78.8		0.49	0.03	1
98	Oxide Test 11	MS 54	GCJ 12A	None	1050	90	**300**	66	79.2	99.0	0.48	0.03	2
100	Oxide Test 13	MS 67	GCJ 12A	None	1100	420	**400**	66	79.2	79.2	0.39	0.05	3
112	P_Repeatability 12	MS 79	GCJ 10B	None	400	180	Thin	62	78.5	157.0	0.20	0.1	3

Friction Test Results for Mild Steel, Pin on Disc Rig

Test No	Filename	Test piece	Tool Disc	Lubricant	Temperature		Oxide Thickness	Linear Speed	Axial Stres (MPa)		Avg Friction	Standard Deviation	Data Class
					Initital	Steady State	µm	mm/s	Nominal	Actual	µ	σ	
113	P_Repeatability 13	MS 80	GCJ 10B	None	400	210	Thin	62	78.4	104.3	0.42	0.06	2
114	P_Repeatability 14	MS 69	GCJ 10B	None	400	235	Thin	62	78.8		0.43	0.04	2
115	P_Repeatability 15	MS 64	GCJ 10B	None	400	235	Thin	62	78.8	262.7	0.43	0.02	2
116	P_Repeatability 16	MS 68	GCJ 10B	None	400	245	Thin	62	79.2	158.4	0.47	0.02	2
117	General Test 33	MS 77	GCJ 9A	None	700	232	Thin	62	137.6	211.0	0.33	0.05	3
118	General Test 34	MS 78	GCJ 9A	None	1050	338	Thin	62	139.1	173.9	0.31	0.02	2
134	Lub Test 10	MS 71	GCJ 19B	**1 Layer DAG 2543**	800	162	Thin	62	78.9	78.9	0.02	0.03	3
135	Lub Test 11	MS 59	GCJ 11A	**2 Layer DAG 2543**	800	144	Thin	62	78.9	78.9	0.02	0.03	3
136	Lub Test 12	MS 41	GCJ 16B	**3 Layer DAG 2543**	800	153	Thin	62	78.9	78.9	0.01	0.04	3
140	Lub Test 16	MS 63	GCJ 11A	**1 Layer DAG 2543**	1000	219	Thin	62	78.7	78.7	0.01	0.04	3
141	Lub Test 17	MS 76	GCJ 16B	**2 Layer DAG 2543**	1000	184	Thin	62	79.0	98.8	0.01	0.07	3
142	Lub Test 18	MS 65	GCJ 18B	**1 Layer DAG 2543**	800	163	Thin	57	18.7	7.8	0.02	0.06	3
143	Lub Test 19	MS 55	GCJ 17A	**2 Layer DAG 2543**	800	176	Thin	59	18.8	18.8	-0.01	0.11	3
144	Lub Test 20	MS 53	GCJ 11A	**3 Layer DAG 2543**	800	191	Thin	62	18.5	30.8	-0.03	0.09	3
145	Lub Test 21	MS 62	GCJ 19B	**1 Layer DAG 2543**	800	185	Thin	62	38.1	58.4	0.02	0.09	3
146	Lub Test 22	MS 58	GCJ 16A	**2 Layer DAG 2543**	800	192	Thin	64	37.9	189.4	-0.02	0.05	3
147	Lub Test 23	MS 57	GCJ 18B	**3 Layer DAG 2543**	800	160	Thin	59	38.0	84.1	0.00	0.06	3
148	Lub Test 24		GCJ 17A	**1 Layer DAG 2543**	800	174	Thin	62	139.1		0.02	0.03	3
149	Lub Test 25	MS 74	GCJ 11A	**2 Layer DAG 2543**	800	167	Thin	59	139.2	146.2	0.02	0.03	3
150	Lub Test 26	MS 61	GCJ 19B	**3 Layer DAG 2543**	800	151	Thin	59	139.0	146.0	0.05	0.06	3
188	System test 07	MS 101	GDR 11B	None	22	22	Thin	50	21.2	212.0	0.15	0.05	2
189	System test 08	MS 102	GDR 11B	None	22	22	Thin	50	20.5	205.0	0.18	0.09	3
190	System test 09	MS 103	GDR 11B	None	22	22	Thin	57	81.1	108.2	0.35	0.08	3
191	System test 10	MS 104	GDR 11B	None	22	22	Thin	57	119.9	119.9	0.31	0.04	2
192	System test 11	MS 100	GDR 11B	None	22	22	Thin	57	160.6	160.6	0.29	0.02	2
197	PoD Interim 01	GDO 02	GDR 12B	None	350	130	Thin	61	59.5	108.2	0.27	0.13	3
198	PoD Interim 02	GDO 10	GDR 12B	None	350	****	Thin	59	112.9	112.9	0.35	0.06	3
199	PoD Interim 03	GDO 09	GDR 12B	None	350	****	Thin	59	170.4	179.4	0.30	0.01	2
200	PoD Interim 04	GDO 08	GDR 12B	None	700	370	Thin	59	59.6	79.5	0.47	0.04	3
201	PoD Interim 05	GDO 07	GDR 12B	None	700	235	Thin	59	109.8	146.4	0.37	0.04	2
202	PoD Interim 06	GDO 06	GDR 06A	None	700	170	Thin	64	170.3	340.6	0.33	0.02	2
203	PoD Interim 07	GDO 04	GDR 06A	None	1050	440	Thin	64	20.7	46.0	0.62	0.11	3
204	PoD Interim 08	GDO 14	GDR 06A	None	1050	305	Thin	64	40.3	57.6	0.85	0.08	3
205	PoD Interim 09	GDO 18	GDR 06A	None	1050	****	Thin	64	59.2	59.2	0.52	0.06	3
206	PoD Interim 10	GDO 17	GDR 06A	None	1050	300	Thin	64	81.0	81.0	0.46	0.03	2
207	PoD Interim 11	GDO 16	GDR 06B	None	1050	360	Thin	57	142.8	155.2	0.33	0.02	2
208	PoD Interim 12	GDO 13	GDR 06B	None	1050	365	Thin	52	141.8	149.3	0.34	0.02	2
209	PoD Interim 13	GDO 26	GDR 06B	None	1050	330	Thin	54	170.4	170.4	0.31	0.02	1
210	PoD Interim 14	GDO 20	GDR 06B	None	1050	335	Thin	57	201.4	201.4	0.27	0.01	1
211	PoD Interim 15	GDO 23	GDR 07A	None	350	160	**100**	44	40.2	402.0	0.22	0.06	3
212	PoD Interim 16	GDO 24	GDR 07A	None	350	95	**100**	59	59.5	119.0	0.22	0.06	3
213	PoD Interim 17	GDO 22	GDR 07A	None	350	155	Thin	54	80.8	161.6	0.29	0.09	3
214	PoD Interim 18	GDO 21	GDR 07A	None	650	185	Thin	54	111.8	223.6	0.32	0.05	3
215	PoD Interim 19	GDO 33	GDR 07A	None	350	190	Thin	54	140.6	175.8	0.30	0.03	2
216	PoD Interim 20	GDO 37	GDR 07B	None	350	170	Thin	49	176.5	196.1	0.23	0.05	3
217	PoD Interim 21	GDO 25	GDR 07B	None	350	205	Thin	59	200.9	236.4	0.24	0.01	2
228	PoD Interim 22	GDO 38	GDR 07B	None	700	260	**100**	57	59.4	79.2	0.46	0.14	3
229	PoD Interim 23	GDO 40	GDR 07B	None	700	225	**100**	57	110.2	110.2	0.35	0.02	2
230	PoD Interim 24	GDO 34	GDR 07B	None	700	280	**100**	57	140.8	140.8	0.31	0.06	3
231	PoD Interim 25	GDO 36	GDR 08A	None	700	290	**100**	52	176.5	196.1	0.19	0.08	3

Friction Test Results for Mild Steel, Pin on Disc Rig

Test No	Filename	Test piece	Tool Disc	Lubricant	Temperature		Oxide Thickness	Linear Speed	Axial Stres (MPa)		Avg Friction	Standard Deviation	Data Class
					Initital	Steady State	µm	mm/s	Nominal	Actual	µ	σ	
232	PoD Interim 26	GDO 35	GDR 08A	None	1050	285	**100**	54	59.6	66.2	0.36	0.08	3
233	PoD Interim 27	GDO 32	GDR 08A	None	1050	300	**100**	54	110.4	110.4	0.33	0.02	2
234	PoD Interim 28	GDO 31	GDR 08A	None	1050	320	**100**	57	140.9	140.9	0.31	0.01	1
235	PoD Interim 29	GDO 29	GDR 08A	None	1050	335	**100**	59	169.8	178.7	0.28	0.01	1
251	PoD Interim 35	GDO 03	GDR 02A	None	350	145	Thin	59	58.9	196.3	0.15	0.06	3
252	PoD Interim 36	GDO 28	GDR 02A	None	350	140	Thin	54	108.3	154.7	0.23	0.07	3
253	PoD Interim 37	GDO 39	GDR 02A	None	350	200	Thin	54	140.6	175.8	0.28	0.04	3
254	PoD Interim 38	GDO 38	GDR 02A	None	350	200	Thin	54	166.9	208.6	0.26	0.02	2
255	PoD Interim 40	GDO 48	GDR 02B	None	350	170	Thin	104	59.3	593.0	0.14	0.03	2
256	PoD Interim 41	GDO 46	GDR 02B	None	350	200	Thin	119	109.3	136.6	0.24	0.07	3
257	PoD Interim 42	GDO 50	GDR 02B	None	350	290	Thin	119	137.1	137.1	0.28	0.04	2
258	PoD Interim 43	GDO 49	GDR 03A	None	350	305	Thin	119	165.0	165.0	0.23	0.03	2
273	PoD Interim 58	GDO 12	GDR 04B	None	22	22	Thin	59	109.7	365.7	0.16	0.07	2
274	PoD Interim 59	GDO 11	GDR 04B	None	100	80	Thin	59	110.1	367.0	0.17	0.08	3
275	PoD Interim 60	GDO 45	GDR 04B	None	200	125	Thin	59	110.6	245.8	0.19	0.05	3
276	PoD Interim 61	GDO 44	GDR 04B	None	400	190	Thin	59	110.7	246.0	0.26	0.06	3
277	PoD Interim 62	GDO 41	GDR 04B	None	600	230	Thin	59	109.6	146.1	0.30	0.04	3
278	PoD Interim 63	GDO 19	GDR 04B	None	800	275	Thin	59	110.5	122.8	0.30	0.04	2

Friction Test Results for Alumimium, Pin on Disc Rig

Test No	Filename	Test piece	Tool Disc	Lubricant	Temperature		Oxide Thickness	Linear Speed	Axial Stres (MPa)		Avg Friction	Standard Deviation	Data Class
					Initial	Steady State	µm	mm/s	Nominal	Actual	µ	σ	
28	GAY34 RT No Dwell	GAY 34	GCJ5 A	None	RT	RT	Thin	50	71.6	143.2	0.31	0.10	2
29	GAY31 RT No Dwell	GAY 31	GCJ5 A	None	RT	RT	Thin	50	59.6		0.45	0.10	3
30	GAY21 RT No Dwell 0.25kN	GAY 21	GCJ5 B	None	RT	RT	Thin	50	8.8	147.0	0.36	0.17	3
31	GAY9 RT No Dwell 0.5kN	GAY 09	GCJ5 B	None	RT	RT	Thin	50	18.4		0.50	0.30	3
32	GAY7 RT No Dwell 0.75kN	GAY 07	GCJ5 B	None	RT	RT	Thin	50	28.6	30.0	0.51	0.08	3
33	GAY24 RT No Dwell 1kN	GAY 24	GCJ5 B	None	RT	RT	Thin	50	28.6	30.0	0.51	0.07	3
34	GAY26 100C No Dwell 250N	GAY 26	GCJ5 B	None	100	62	Thin	50	9.0	35.8	0.57	0.13	3
101	P_Repeatability 1	GAY 35	GCJ 12B	None	RT	RT	Thin	59	78.8	98.5	0.45	0.03	1
102	P_Repeatability 2	GAY 5	GCJ 12B	None	RT	RT	Thin	59	78.9	82.9	0.46	0.02	1
103	P_Repeatability 3	GAY 68	GCJ 12B	None	RT	RT	Thin	59	78.3	78.3	0.38	0.04	2
104	P_Repeatability 4	GAY 61	GCJ 12B	None	RT	RT	Thin	59	78.6	78.6	0.31	0.03	2
105	P_Repeatability 5	GAY 13	GCJ 12B	None	RT	RT	Thin	59	78.2	78.2	0.40	0.06	3
106	P_Repeatability 6	GAY 67	GCJ 12B	None	RT	RT	Thin	59	78.6		0.30	0.05	3
125	Lub Test 01	GAY 43	GCJ 16A	None	RT	RT	Thin	59	78.9	82.9	0.42	0.03	2
126	Lub Test 02	GAY 41	GCJ 16A	**1 Layer DAG 2543**	RT	RT	Thin	59	78.9	78.9	0.12	0.07	3
127	Lub Test 03	GAY 22	GCJ 16A	**2 Layer DAG 2543**	RT	RT	Thin	59	78.6	87.3	0.09	0.06	3
128	Lub Test 04	GAY 49	GCJ 16A	**3 Layer DAG 2543**	RT	RT	Thin	59	78.8	82.8	0.07	0.06	3
129	Lub Test 05	GAY 69	GCJ 16A	**4 Layer DAG 2543**	RT	RT	Thin	59	78.8	82.8	0.07	0.06	3
130	Lub Test 06	GAY 42	GCJ 16A	**5 Layer DAG 2543**	RT	RT	Thin	59	79.2	83.2	0.09	0.06	3
193	System test 12	GAY 40	GDR 12A	None	22	22	Thin	57	21.1	52.6	0.30	0.12	3
194	System test 13	GAY 46	GDR 12A	None	22	22	Thin	59	40.1	40.1	0.46	0.05	3
195	System test 14	GAY 45	GDR 12A	None	22	22	Thin	59	80.9	80.9	0.42	0.03	2
218	PoD Interim Al Repeat 01	GAY 03	GDR 10A	None	22	22	Thin	54	80.6	94.8	0.37	0.04	3
219	PoD Interim Al Repeat 02	GAY 02	GDR 10A	None	22	22	Thin	57	80.8	85.1	0.39	0.02	1
220	PoD Interim Al Repeat 03	GAY 12	GDR 10A	None	22	22	Thin	57	80.5	80.5	0.36	0.02	2
221	PoD Interim Al Repeat 04	GAY 11	GDR 10A	None	22	22	Thin	57	80.5	80.5	0.38	0.02	2
222	PoD Interim Al Repeat 05	GAY 06	GDR 10A	None	22	22	Thin	57	80.4	80.4	0.38	0.02	2
223	PoD Interim Al Repeat 06	GAY 17	GDR 10B	None	22	22	Thin	57	80.8	89.8	0.34	0.05	3
224	PoD Interim Al Repeat 07	GAY 15	GDR 10B	None	22	22	Thin	57	80.6	80.6	0.36	0.02	2
225	PoD Interim Al Repeat 08	GAY 14	GDR 10B	None	22	22	Thin	57	80.6	80.6	0.37	0.02	1
226	PoD Interim Al Repeat 09	GAY 04	GDR 10B	None	22	22	Thin	57	80.3	80.3	0.37	0.02	2
279	PoD Interim Al Repeat 11	GAY 48	GDR 11A	None	22	22	Thin	59	80.7	134.5	0.35	0.03	3
280	PoD Interim Al Repeat 12	GAY 60	GDR 11B	None	22	22	Thin	57	80.5	84.7	0.38	0.03	2
281	PoD Interim Al Repeat 13	GAY 63	GDR 12A	None	22	22	Thin	62	80.2	100.3	0.33	0.3	3
282	PoD Interim Al Repeat 14	GAY 59	GDR 12B	None	22	22	Thin	62	79.1	105.5	0.29	0.09	3
283	PoD Interim Al Repeat 15	GAY 57	GDR 13A	None	22	22	Thin	59	78.9	105.2	0.23	0.09	3

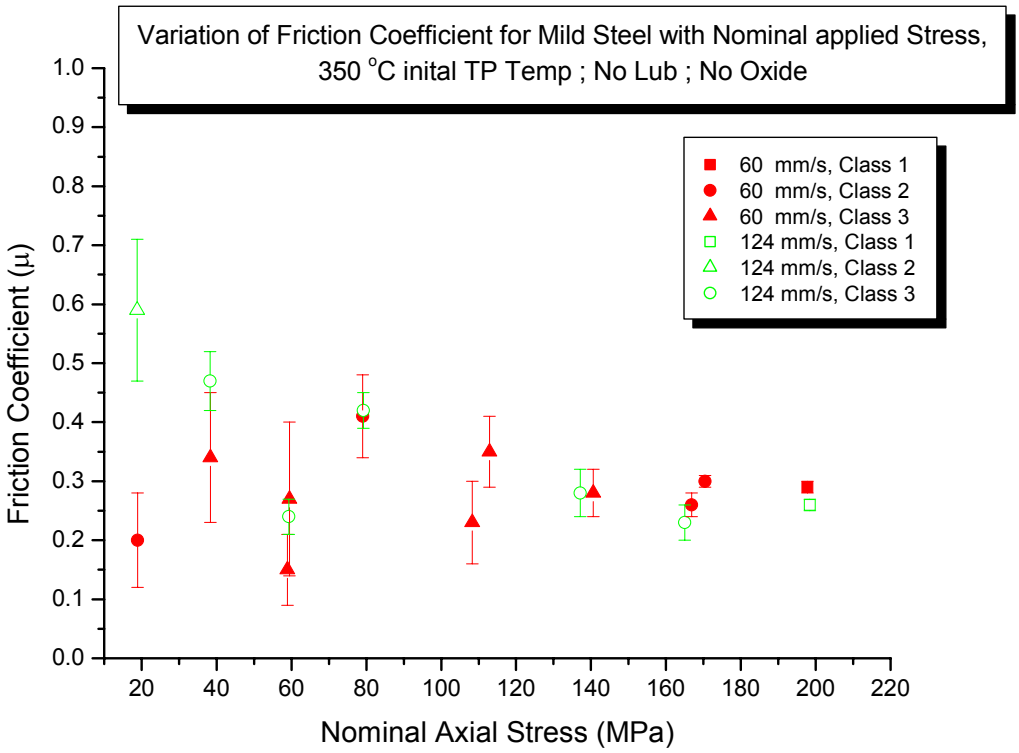
Friction Test Results for IN718, Pin on Disc Rig

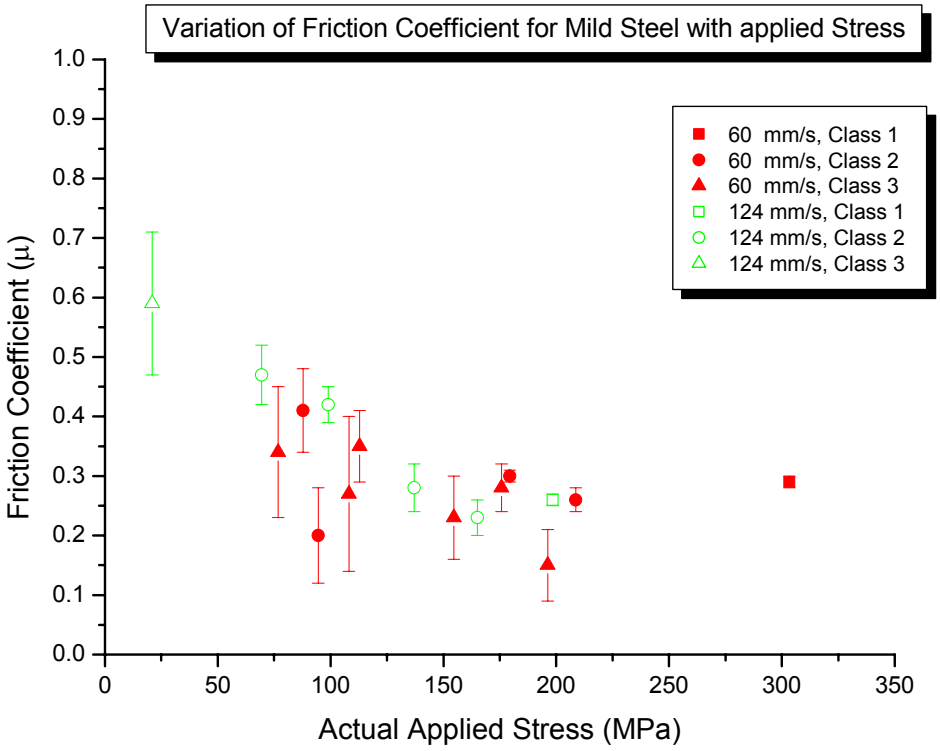
Test No	Filename	Test piece	Tool Disc	Lubricant	Temperature		Oxide Thickness	Linear Speed	Axial Stres (MPa)		Avg Friction	Standard Deviation	Data Class
					Initial	Steady State	µm	mm/s	Nominal	Actual	µ	σ	
19	GCO13 1000 No Dwell Slow	GCO 13	GCJ14 B	None	1000	368	Thin	50	77.4		0.33	0.08	3
20	GCO12 700C No Dwell	GCO 12	GCJ6 A	None	700	429	Thin	50	78.4	222.7	0.37	0.07	3
21	GCO32 350C No Dwell	GCO 32	GCJ6 A	None	350	244	Thin	50	76.8	192.0	0.36	0.07	3
22	GCO16 RT No Dwell	GCO 16	GCJ6A	None	RT	RT	Thin	50	76.6	169.5	0.34	0.08	3
23	GCO31 1000C No Dwell Fast	GCO 31	GCJ6 A	None	1000	450	Thin	200	74.3	78.0	0.32	0.08	3
24	GCO27 700C No Dwell Fast	GCO 27	GCJ6 A	None	700	480	Thin	200	75.3	115.5	0.34	0.08	3
25	GCO11 350C No Dwell Fast	GCO 11	GCJ6 B	None	350	260	Thin	200	74.9	135.7	0.37	0.13	3
26	GCO17 RT No Dwell	GCO 17	GCJ 6B	None	RT	RT	Thin	200	76.0	126.7	0.40	0.2	3
27	GCO30 900C 20 Dwell Fast	GCO 30	GCJ6 B	None	900	430	Thin	200	61.6	102.7	0.41	0.2	3
48	GCO5 GCJ15A 800C No Dwell 2000 N	GCO 5	GCJ15 A	None	800	****	Thin	?	78.2	97.8	0.34	0.07	2
50	GCO28 GCJ15A RT No Dwell 2	GCO 28	GCJ15A	None	RT	RT	Thin	30	79.7		0.07	0.01	3
51	GCO28 GCJ15A RT No Dwell 3	GCO 28	GCJ15A	None	RT	RT	Thin	124	79.7		0.02	0.01	3
52	GCO28 GCJ15A RT 2kN No Dwell 4	GCO 28	GCJ15A	None	RT	RT	Thin	30	79.6		0.07	0.01	3
54	GCO24 GCJ15A RT No Dwell	GCO 24	GCJ15A	None	RT		Thin	62	80.2		0.44	0.02	2
64	General Test 9	GCO 23	GCL 3B	None	400	150	Thin	62	18.9	47.3	0.28	0.07	3
65	General Test 10	GCO 25	GCL 3B	None	400	200	Thin	62	38.8	59.5	0.35	0.08	3
66	General Test 11	GCO 20	GCL 3B	None	400	157	Thin	62	78.8	78.8	0.41	0.04	3
67	General Test 12	GCO 21	GCL 3B	None	400	230	Thin	62	199.9	204.0	0.27	0.02	2
68	General Test 13	GCO 07	GCL 3B	None	800	400	Thin	62	18.8	22.1	0.62	0.07	3
69	General Test 14	GCO 10	GCL 3B	None	800	330	Thin	62	38.9	40.9	0.38	0.06	3
70	General Test 15	GCO 04	GCL 3B	None	800	330	Thin	62	79.3		0.43	0.02	2
71	General Test 16	GCO 06	GCL 3B	None	800	335	Thin	62	196.6		0.29	0.02	3
72	General Test 17	GCO 60	GCJ 2A	None	400	170	Thin	124	18.5		0.09	0.01	1
73	General Test 18	GCO 53	GCJ 2A	None	400	170	Thin	124	38.0	38.0	0.03	0	1
74	General Test 19	GCO 56	GCJ 13A	None	400	190	Thin	114	19.0	19.0	0.30	0.14	3
75	General Test 20	GCO 51	GCJ 13A	None	400	220	Thin	114	19.2	20.2	0.51	0.09	3
76	General Test 21	GCO 66	GCJ 13A	None	400	220	Thin	114	38.6	40.5	0.48	0.05	3
77	General Test 22	GCO 61	GCJ 13A	None	400	250	Thin	114	78.9	78.9	0.40	0.03	2
78	General Test 23	GCO 38	GCJ 13A	None	400	285	Thin	114	198.4	198.4	0.27	0.02	2
79	General Test 24	GCO 08	GCJ 13B	None	1200	480	Thin	57	18.6	20.7	0.44	0.12	3
80	General Test 25	GCO 03	GCJ 13B	None	1000	360	Thin	57	18.8	20.9	0.51	0.07	3
81	General Test 26	GCO 01	GCJ 13B	None	1000	350	Thin	57	38.4	38.4	0.50	0.04	2
82	General Test 27	GCO 58	GCJ 13B	None	1000	360	Thin	57	79.1	79.1	0.45	0.02	1
83	General Test 28	GCO 19	GCJ 13B	None	1000	330	Thin	57	198.0	198.0	0.29	0.02	1
107	P_Repeatability 7	GCO 70	GCJ 10A	None	400	205	Thin	62	78.7	39.4	0.39	0.1	3
108	P_Repeatability 8	GCO 37	GCJ 10A	None	400	220	Thin	62	79.1	80.7	0.45	0.04	2
109	P_Repeatability 9	GCO 52	GCJ 10A	None	400	230	Thin	62	78.7	92.4	0.47	0.03	2
110	P_Repeatability 10	GCO 36	GCJ 10A	None	400	215	Thin	62	79.5	79.5	0.48	0.03	2
111	P_Repeatability 11	GCO 39	GCJ 10A	None	400	220	Thin	62	79.0	79.0	0.48	0.04	2
119	General Test 35	GCO 47	GCJ 9A	None	400	209	Thin	62	139.4	163.6	0.36	0.02	2
120	General Test 36	GCO 50	GCJ 9A	None	800	288	Thin	62	138.7	162.8	0.37	0.02	2
122	General Test 38	GCO 55	GCJ 9A	None	1000	354	Thin	62	139.2	163.4	0.36	0.02	2
131	Lub Test 07	GCO 18	GCJ 16 B	**1 Layer DAG 2543**	800	195	Thin	62	79.0	197.5	0.01	0.02	3
132	Lub Test 08	GCO 41	GCJ 18B	**2 Layer DAG 2543**	800	169	Thin	62	79.0	131.7	0.07	0.06	3
133	Lub Test 09	GCO 09	GCJ 17A	**3 Layer DAG 2543**	800	166	Thin	62	79.0	79.0	0.03	0.03	3
137	Lub Test 13	GCO 24	GCJ 18B	**1 Layer DAG 2543**	1000	168	Thin	62	79.0	98.8	0.02	0.02	3
138	Lub Test 14	GCO 43	GCJ 17A	**2 Layer DAG 2543**	1000	239	Thin	62	79.0	313.5	0.05	0.02	2
139	Lub Test 15	GCO 34	GCJ 19B	**3 Layer DAG 2543**	1000	216	Thin	62	79.0	197.5	0.05	0.03	2
151	Lub Test 27	GCO 65	GCJ 16A	**1 Layer DAG 2543**	800	203	Thin	59	18.5		0.08	0.04	2
152	Lub Test 28	GCO 57	GCJ 18B	**2 Layer DAG 2543**	800	247	Thin	64	18.7	23.4	0.00	0.07	3
153	Lub Test 29	GCO 44	GCJ 17A	**3 Layer DAG 2543**	800	230	Thin	66	18.5	40.9	0.01	0.04	3
154	Lub Test 30	GCO 63	GCJ 11A	**1 Layer DAG 2543**	800	143	Thin	66	38.0	50.5	-0.01	0.05	3

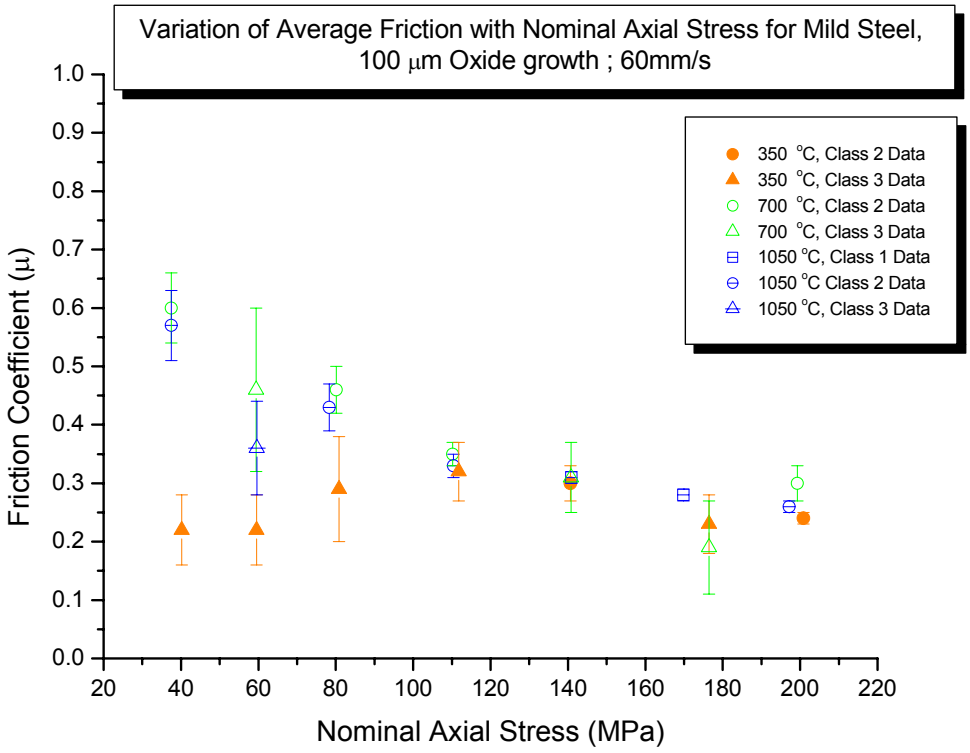
Friction Test Results for IN718, Pin on Disc Rig

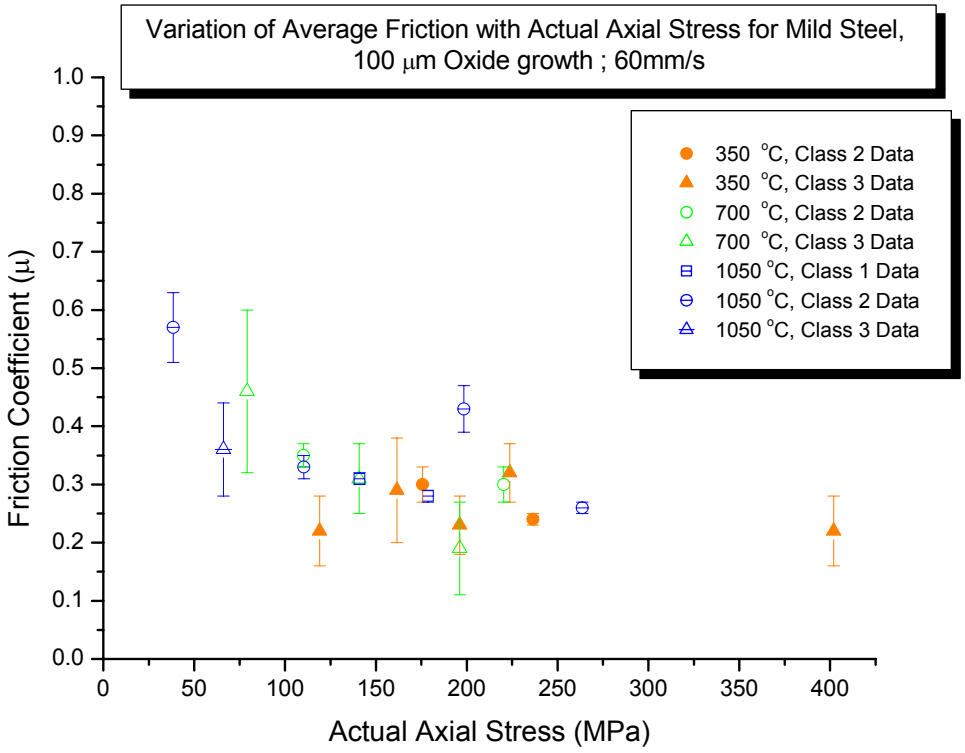
Test No	Filename	Test piece	Tool Disc	Lubricant	Temperature		Oxide Thickness	Linear Speed	Axial Stres (MPa)		Avg Friction	Standard Deviation	Data Class
					Initial	Steady State	µm	mm/s	Nominal	Actual	µ	σ	
155	Lub Test 31	GCO 40	GCJ 19B	**2 Layer DAG 2543**	800	178	Thin	62	38.0	76.0	-0.01	0.03	3
156	Lub Test 32	GCO 71	GCJ 16A	**3 Layer DAG 2543**	800	179	Thin	64	38.1	50.7	0.02	0.04	3
157	Lub Test 33	GCO 48	GCJ 18B	**1 Layer DAG 2543**	800	179	Thin	59	138.8	307.1	0.04	0.03	3
158	Lub Test 34	GCO 59	GCJ 17A	**2 Layer DAG 2543**	800	124	Thin	62	139.0	231.7	0.00	0.03	3
159	Lub Test 35	GCO 42	GCJ 11A	**3 Layer DAG 2543**	800	203	Thin	59	138.8		0.03	0.06	3
183	System test 02	GCO 62	GDR 11A	None	22	22	Thin	62	80.6	1611.2	0.10	0.02	2
184	System test 03	GCO 64	GDR 11A	None	22	22	Thin	62	80.6	1611.2	0.08	0.01	1
186	System test 05	GCO 45	GDR 11A	None	22	22	Thin	62	159.9	177.7	0.22	0.05	3
187	System test 06	GCO 49	GDR 11A	None	22	22	Thin	62	159.9	266.5	0.26	0.04	3
236	PoD Interim 30	GDN 13	GDR 01A	None	400	140	Thin	54	61.2	174.9	0.40	0.14	3
237	PoD Interim 31	GDN 10	GDR 01A	None	400	190	Thin	54	110.2	367.3	0.36	0.02	1
238	PoD Interim 32	GDN 06	GDR 01A	None	400	195	Thin	54	170.4	486.9	0.29	0.01	1
239	PoD Interim 33	GDN 09	GDR 01A	None	800	220	Thin	57	59.6	198.7	0.47	0.03	2
240	PoD Interim 34	GDN 07	GDR 01A	None	800	265	Thin	59	109.9	549.5	0.35	0.02	1
241	PoD Interim IN718 Repeat 01	GDN 25	GDR 01B	None	22	22	Thin	59	79.7	159.4	0.15	0.03	2
242	PoD Interim IN718 Repeat 02	GDN 21	GDR 01B	None	22	22	Thin	57	79.9	199.8	0.14	0.03	3
243	PoD Interim IN718 Repeat 03	GDN 22	GDR 01B	None	22	22	Thin	57	79.9	133.2	0.22	0.1	3
244	PoD Interim IN718 Repeat 04	GDN 23	GDR 01B	None	22	22	Thin	54	78.4	98.0	0.35	0.07	3
245	PoD Interim IN718 Repeat 05	GDN 24	GDR 01B	None	22	22	Thin	54	82.2	205.5	0.42	0.05	2
246	PoD Interim IN718 Repeat 06	GDN 26	GDR 08B	None	22	22	Thin	57	79.9	159.8	0.14	0.04	3
247	PoD Interim IN718 Repeat 07	GDN 27	GDR 08B	None	22	22	Thin	57	78.9	157.8	0.22	0.11	3
248	PoD Interim IN718 Repeat 08	GDN 28	GDR 08B	None	22	22	Thin	57	80.7	161.4	0.25	0.1	3
249	PoD Interim IN718 Repeat 09	GDN 29	GDR 08B	None	22	22	Thin	57	80.8	80.8	0.42	0.03	2
250	PoD Interim IN718 Repeat 10	GDN 30	GDR 08B	None	22	22	Thin	57	78.2	111.7	0.39	0.04	3
259	PoD Interim 44	GDN 04	GDR 03A	None	400	125	Thin	57	58.1	193.7	0.18	0.08	3
260	PoD Interim 45	GDN 08	GDR 03A	None	400	80	Thin	52	107.8	239.6	0.23	0.09	3
262	PoD Interim 47	GDN 32	GDR 03B	None	400	130	Thin	114	58.9	196.3	0.21	0.1	3
263	PoD Interim 48	GDN 05	GDR 03B	None	400	210	Thin	114	110.3	367.7	0.34	0.03	3
264	PoD Interim 49	GDN 34	GDR 05A	None	800	240	Thin	57	110.2	367.3	0.25	0.1	2
265	PoD Interim 50	GDN 35	GDR 05A	None	1000	300	Thin	54	59.9	99.9	0.46	0.03	3
266	PoD Interim 51	GDN 33	GDR 05A	None	1000	300	Thin	57	109.8	183.0	0.34	0.02	2
267	PoD Interim 52	GDN 36	GDR 05B	None	22	22	Thin	54	109.4	218.8	0.16	0.06	2
268	PoD Interim 53	GDN 37	GDR 05B	None	100	90	Thin	57	109.8	219.6	0.23	0.07	3
269	PoD Interim 54	GDN 01	GDR 05B	None	200	130	Thin	57	110.0	220.0	0.27	0.04	3
270	PoD Interim 55	GDN 12	GDR 04A	None	400	170	Thin	52	110.0	220.0	0.18	0.07	3
271	PoD Interim 56	GDN 15	GDR 04A	None	600	180	Thin	52	110.2	220.4	0.35	0.06	3
272	PoD Interim 57	GDN 02	GDR 04A	None	800	230	Thin	52	109.7	219.4	0.36	0.05	3
284	PoD Interim IN718 Repeat 11	GDN 38	GDR 13B	None	22	22	Thin	57	80.4	160.8	0.12	0.01	1
285	PoD Interim IN718 Repeat 12	GDN 11	GDR 14A	None	22	22	Thin	57	79.9	266.3	0.15	0.05	3
286	PoD Interim IN718 Repeat 13	GDN 03	GDR 14B	None	22	22	Thin	57	79.4	264.7	0.11	0.01	1
287	PoD Interim IN718 Repeat 14	GDN 51	GDR 15A	None	22	22	Thin	57	80.6	201.5	0.17	0.07	3
288	PoD Interim IN718 Repeat 15	GDN 52	GDR 15B	None	22	22	Thin	59	79.9	145.3	0.14	0.02	2

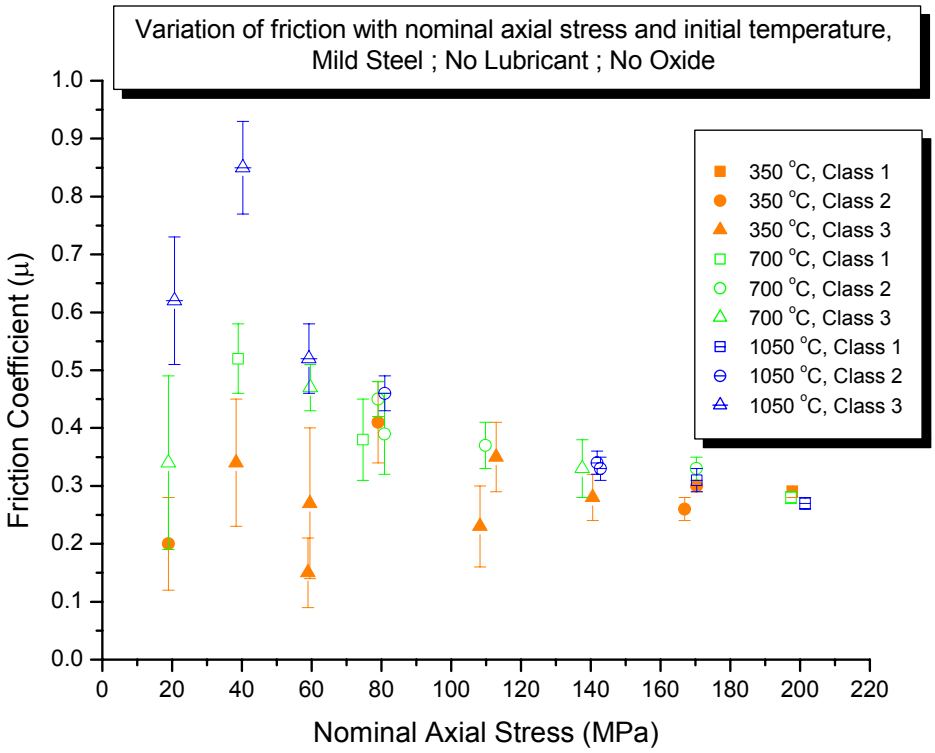
Appendix 3 : Friction Summary Plots for Pin on Disc Rig.

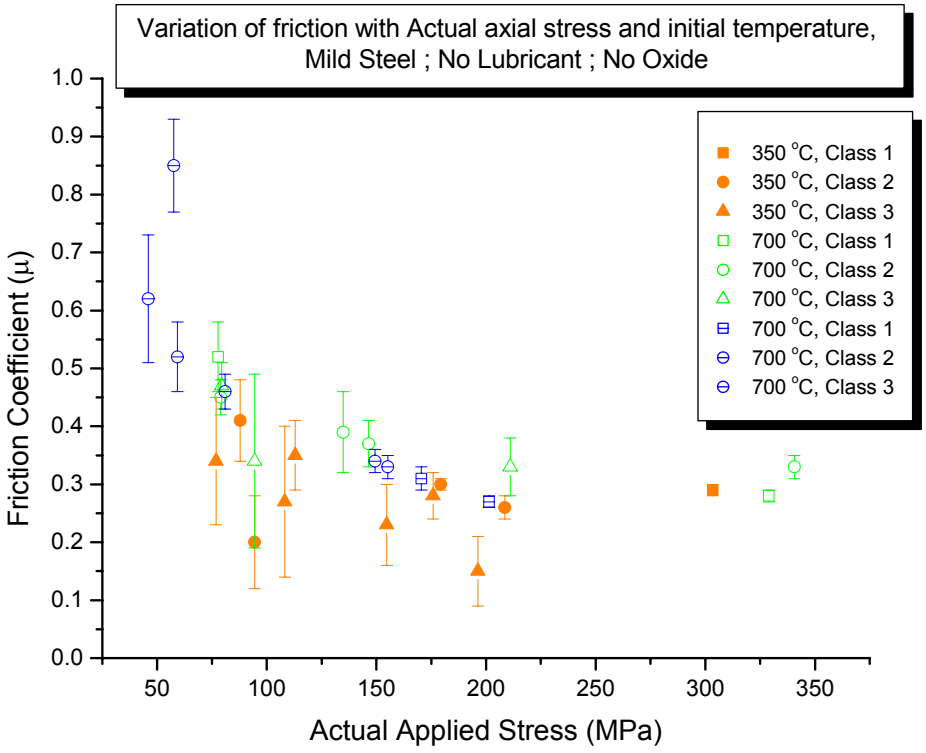


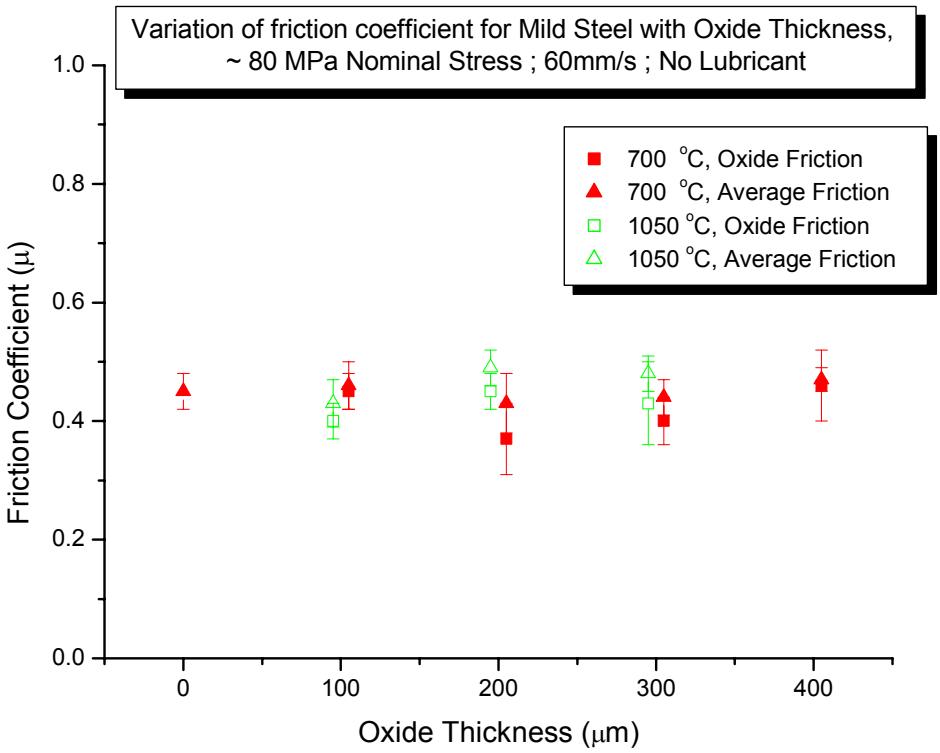


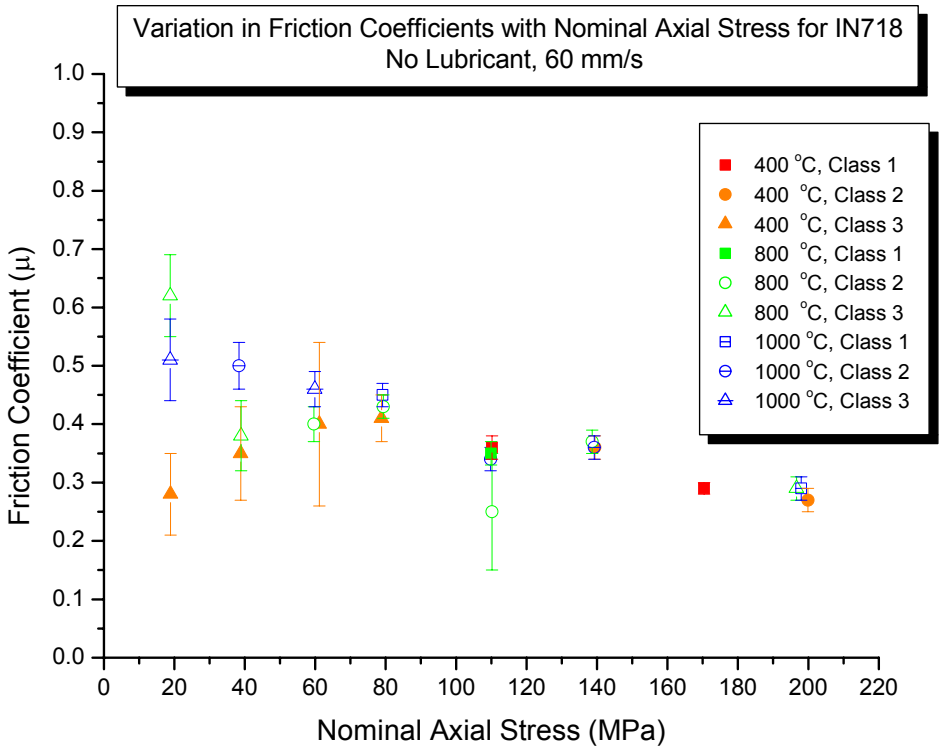

Variation of Average Friction with Nominal Axial Stress for Mild Steel,
100 μm Oxide growth ; 60mm/s
350 °C, Class 2 Data
350 °C, Class 3 Data
700 °C, Class 2 Data
700 °C, Class 3 Data
1050 °C, Class 1 Data
1050 °C Class 2 Data
1050 °C, Class 3 Data
Friction Coefficient (μ)
Nominal Axial Stress (MPa)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
20
40
60
80
100
120
140
160
180
200
220

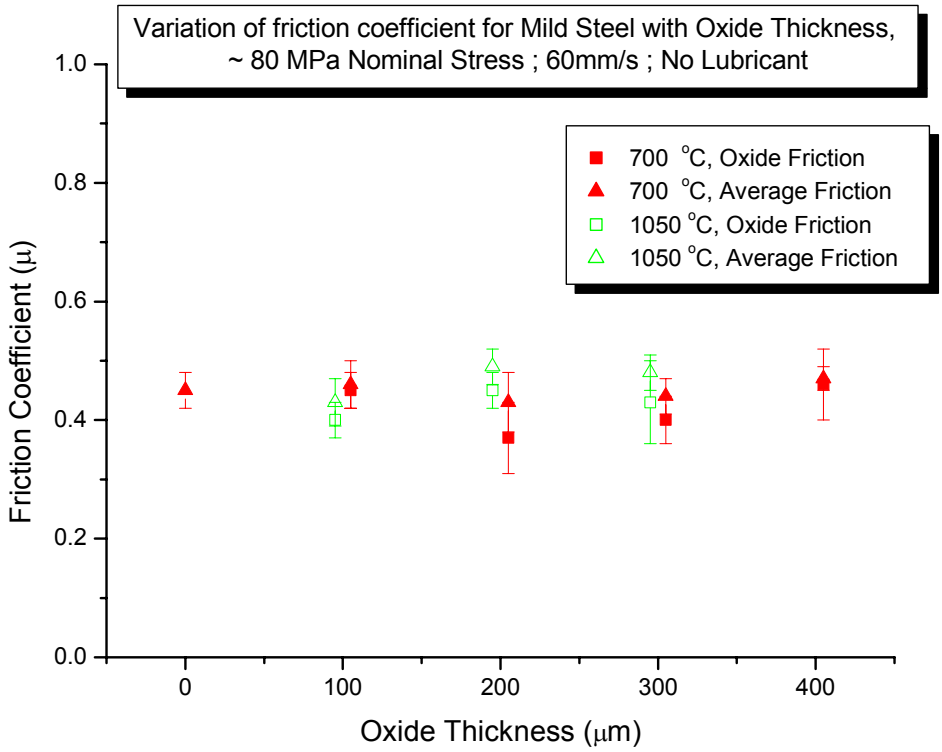

Variation of Average Friction with Actual Axial Stress for Mild Steel,
100 μm Oxide growth ; 60mm/s
350 °C, Class 2 Data
350 °C, Class 3 Data
700 °C, Class 2 Data
700 °C, Class 3 Data
1050 °C, Class 1 Data
1050 °C, Class 2 Data
1050 °C, Class 3 Data
Friction Coefficient (μ)
Actual Axial Stress (MPa)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200
250
300
350
400

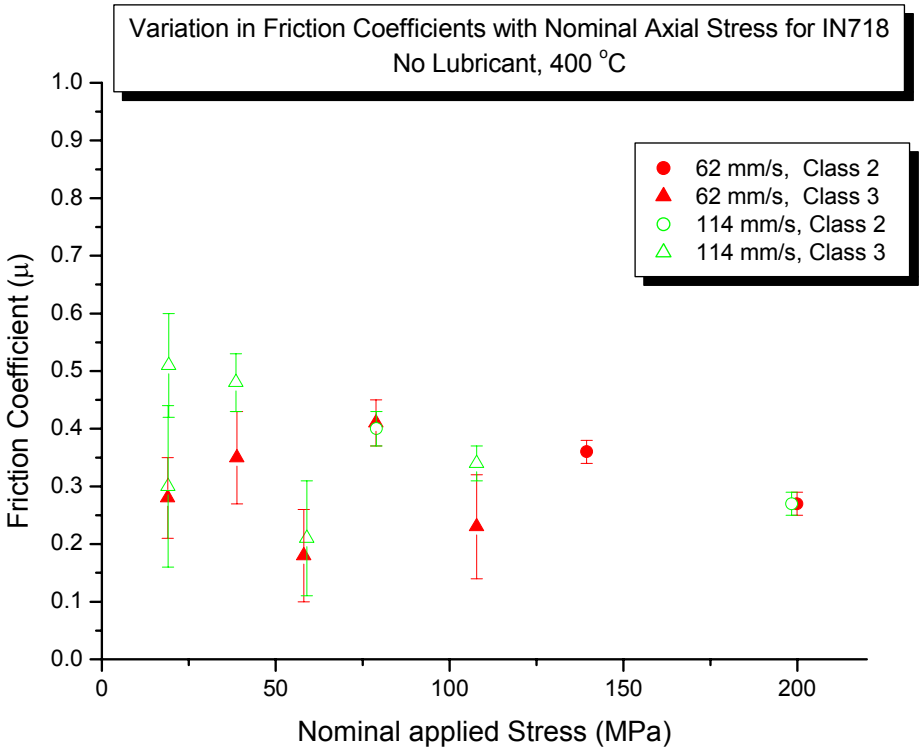

Variation of friction with nominal axial stress and initial temperature,
Mild Steel ; No Lubricant ; No Oxide
Friction Coefficient (μ)
Nominal Axial Stress (MPa)
350 °C, Class 1
350 °C, Class 2
350 °C, Class 3
700 °C, Class 1
700 °C, Class 2
700 °C, Class 3
1050 °C, Class 1
1050 °C, Class 2
1050 °C, Class 3

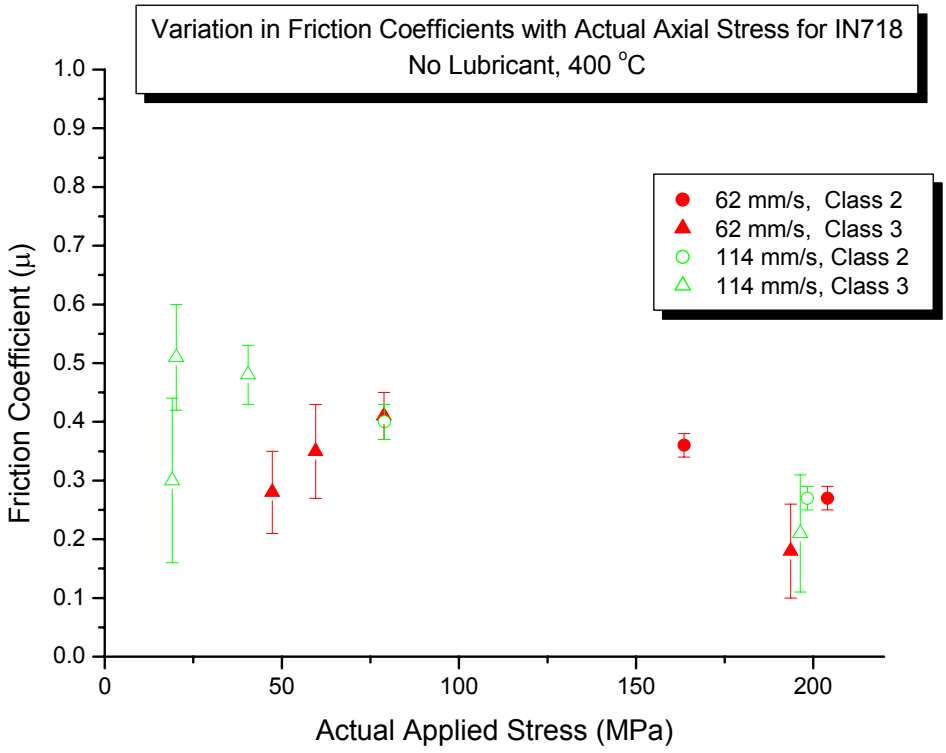

Variation of friction with Actual axial stress and initial temperature,
Mild Steel ; No Lubricant ; No Oxide
Friction Coefficient (μ)
Actual Applied Stress (MPa)
350 °C, Class 1
350 °C, Class 2
350 °C, Class 3
700 °C, Class 1
700 °C, Class 2
700 °C, Class 3
700 °C, Class 1
700 °C, Class 2
700 °C, Class 3

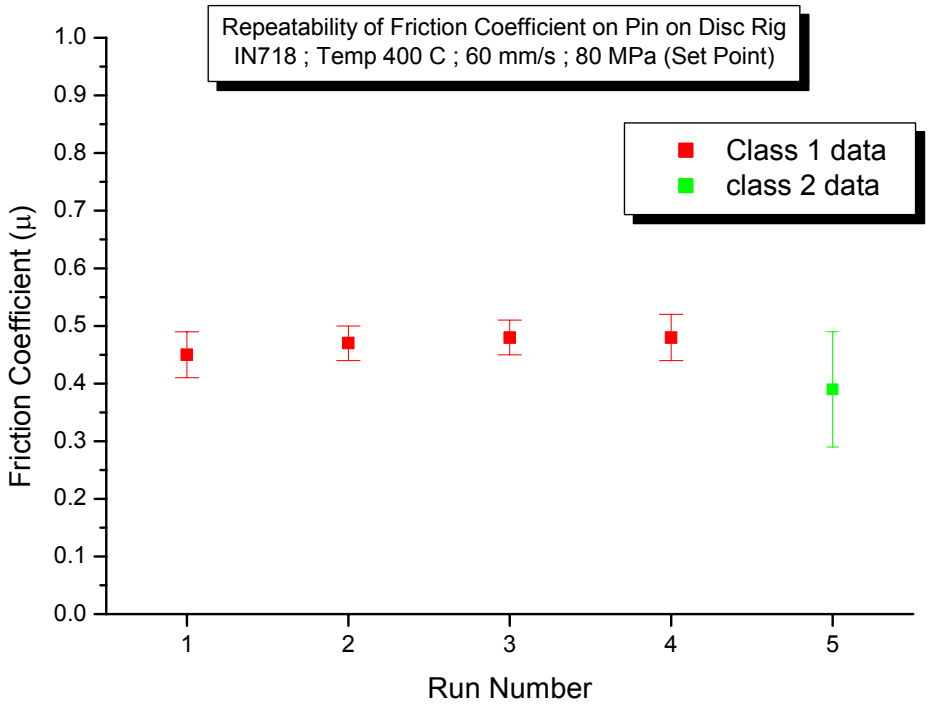

Variation of friction coefficient for Mild Steel with Oxide Thickness,
~ 80 MPa Nominal Stress ; 60mm/s ; No Lubricant
700 °C, Oxide Friction
700 °C, Average Friction
1050 °C, Oxide Friction
1050 °C, Average Friction
Friction Coefficient (μ)
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
Oxide Thickness (μm)

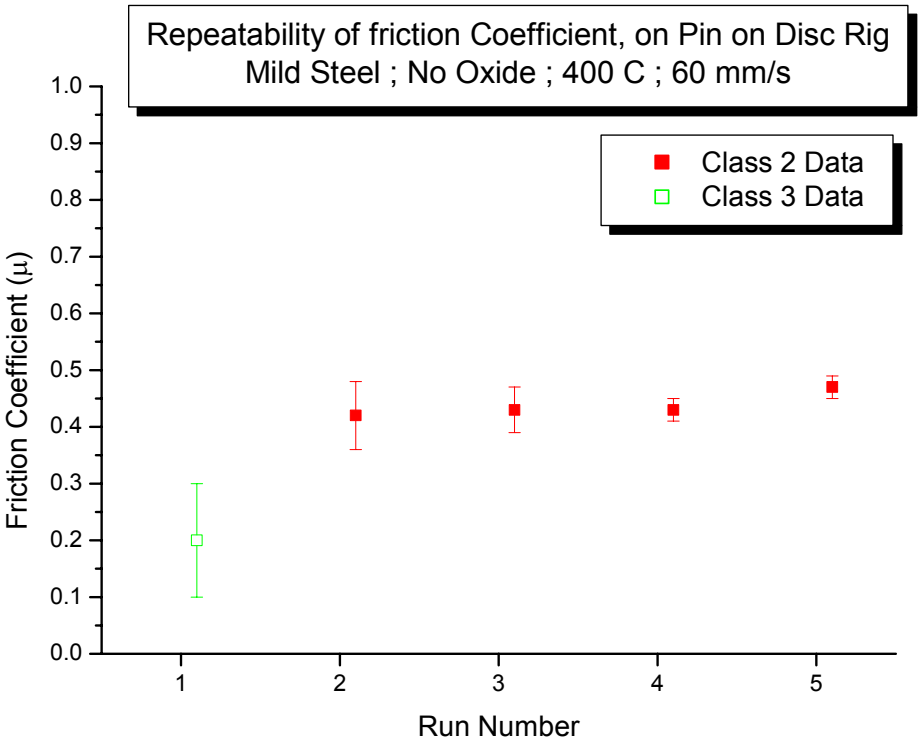

Variation in Friction Coefficients with Nominal Axial Stress for IN718
No Lubricant, 60 mm/s
Friction Coefficient (μ)
Nominal Axial Stress (MPa)
400 °C, Class 1
400 °C, Class 2
400 °C, Class 3
800 °C, Class 1
800 °C, Class 2
800 °C, Class 3
1000 °C, Class 1
1000 °C, Class 2
1000 °C, Class 3

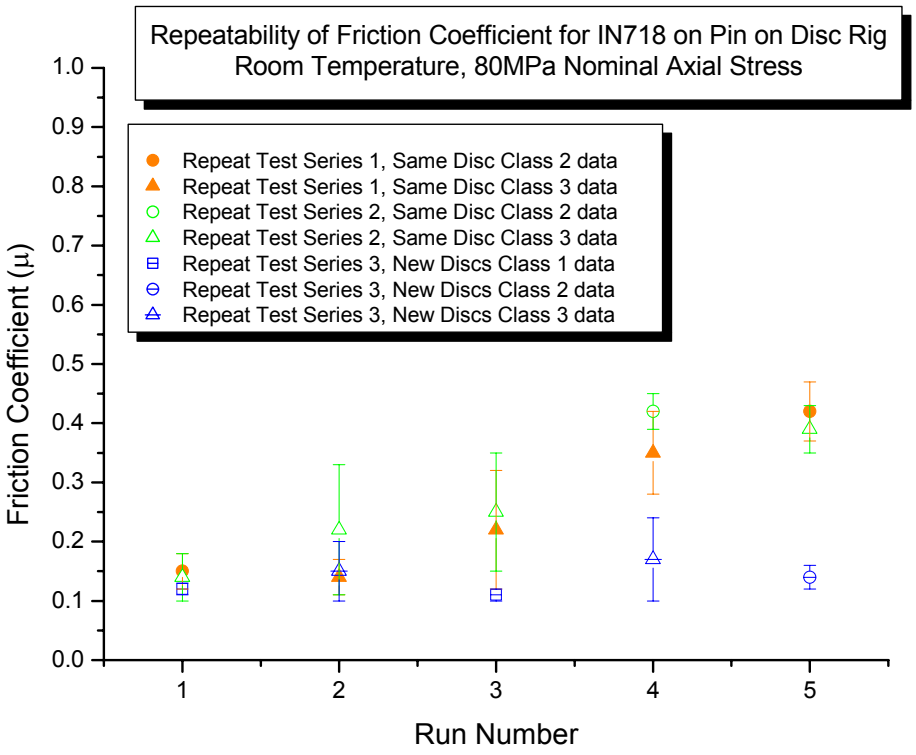

Variation of friction coefficient for Mild Steel with Oxide Thickness,
~ 80 MPa Nominal Stress ; 60mm/s ; No Lubricant
Friction Coefficient (μ)
Oxide Thickness (μm)
700 °C, Oxide Friction
700 °C, Average Friction
1050 °C, Oxide Friction
1050 °C, Average Friction

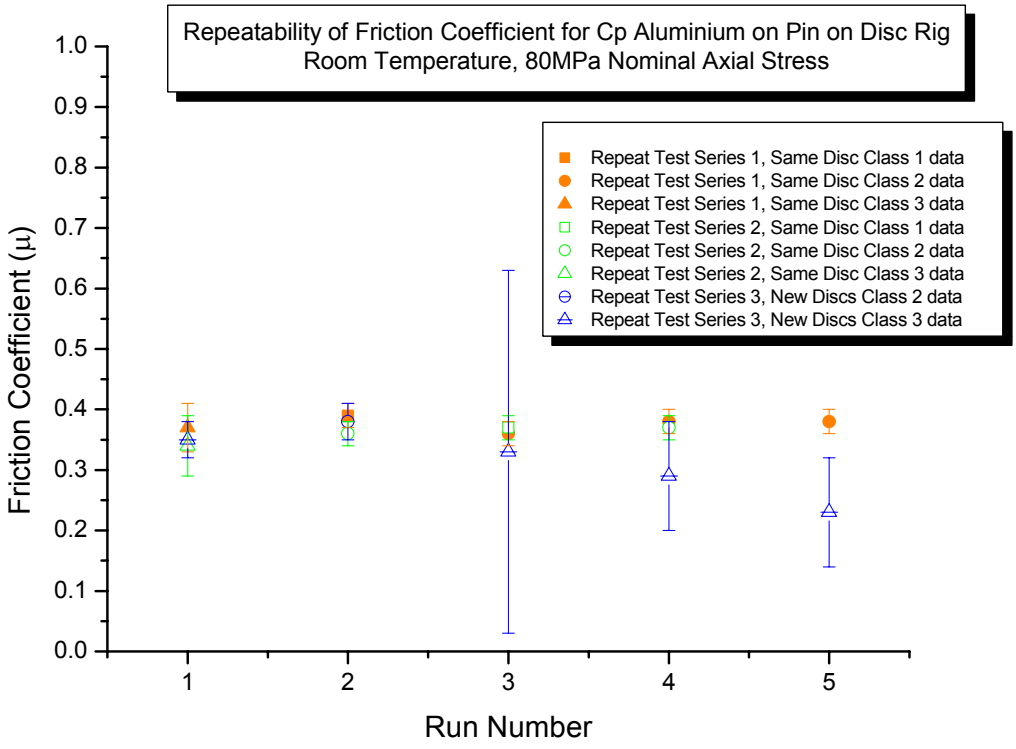

Variation in Friction Coefficients with Nominal Axial Stress for IN718
No Lubricant, 400 °C
62 mm/s, Class 2
62 mm/s, Class 3
114 mm/s, Class 2
114 mm/s, Class 3
Friction Coefficient (μ)
Nominal applied Stress (MPa)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200


Variation in Friction Coefficients with Actual Axial Stress for IN718
No Lubricant, 400 °C
62 mm/s, Class 2
62 mm/s, Class 3
114 mm/s, Class 2
114 mm/s, Class 3
Friction Coefficient (μ)
Actual Applied Stress (MPa)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200

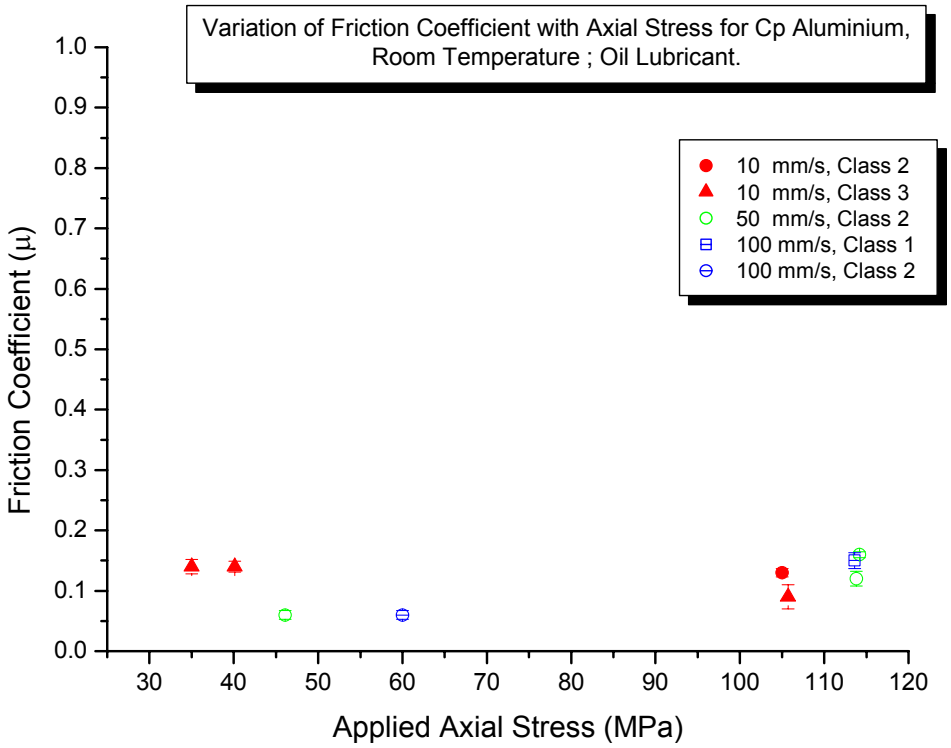

Repeatability of Friction Coefficient on Pin on Disc Rig
IN718 ; Temp 400 C ; 60 mm/s ; 80 MPa (Set Point)
Class 1 data
class 2 data
Friction Coefficient (μ)
Run Number
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1
2
3
4
5

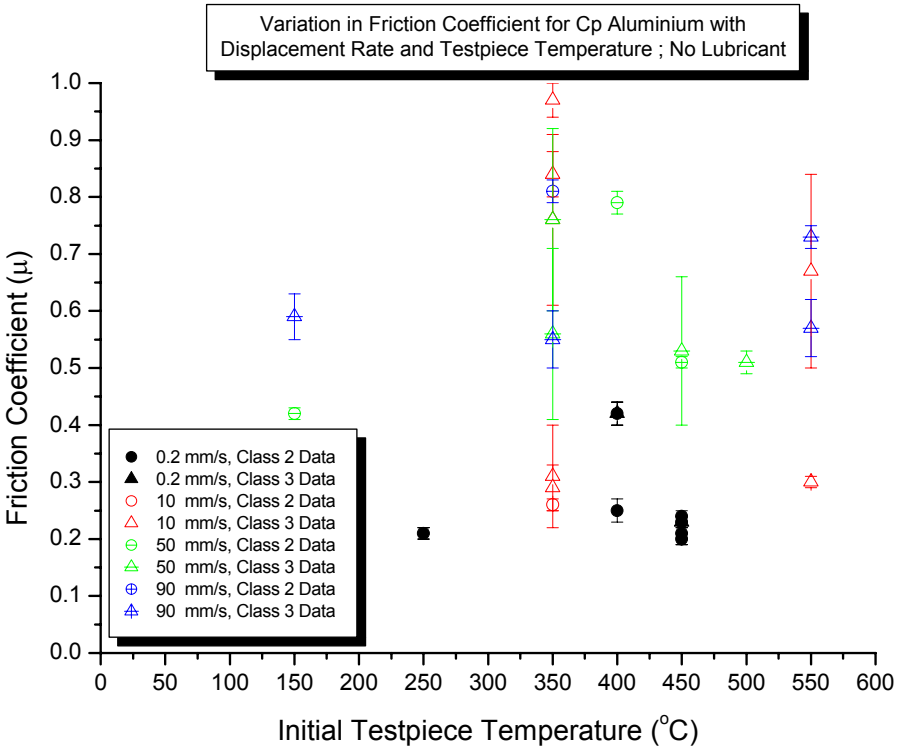

Repeatability of friction Coefficient, on Pin on Disc Rig
Mild Steel ; No Oxide ; 400 C ; 60 mm/s
Class 2 Data
Class 3 Data
Friction Coefficient (μ)
Run Number
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1
2
3
4
5

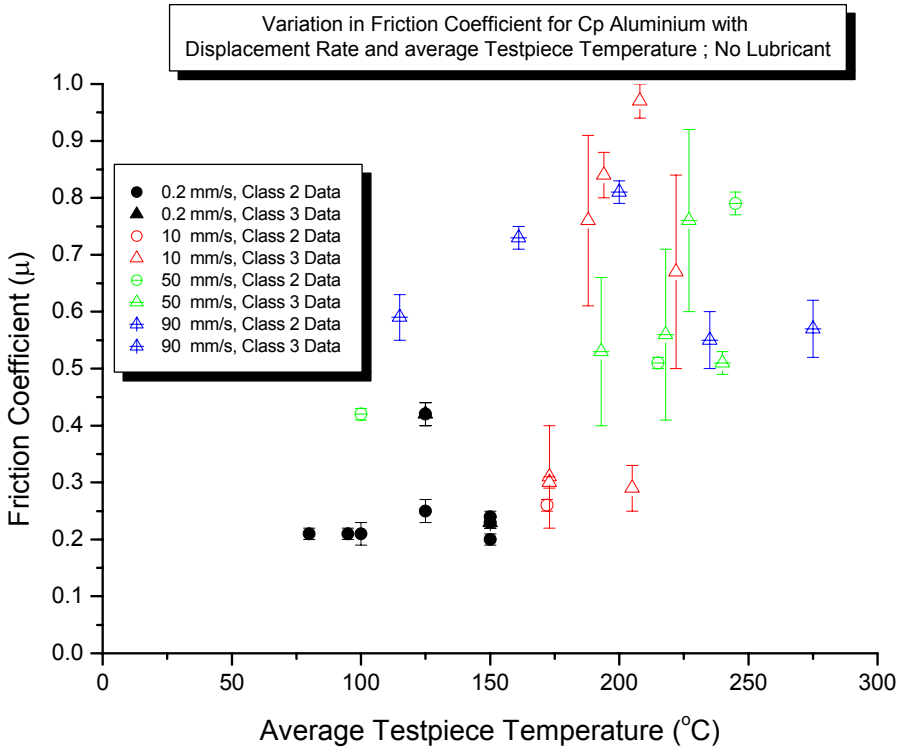

Repeatability of Friction Coefficient for IN718 on Pin on Disc Rig
Room Temperature, 80MPa Nominal Axial Stress
Repeat Test Series 1, Same Disc Class 2 data
Repeat Test Series 1, Same Disc Class 3 data
Repeat Test Series 2, Same Disc Class 2 data
Repeat Test Series 2, Same Disc Class 3 data
Repeat Test Series 3, New Discs Class 1 data
Repeat Test Series 3, New Discs Class 2 data
Repeat Test Series 3, New Discs Class 3 data
Friction Coefficient (μ)
Run Number
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1
2
3
4
5

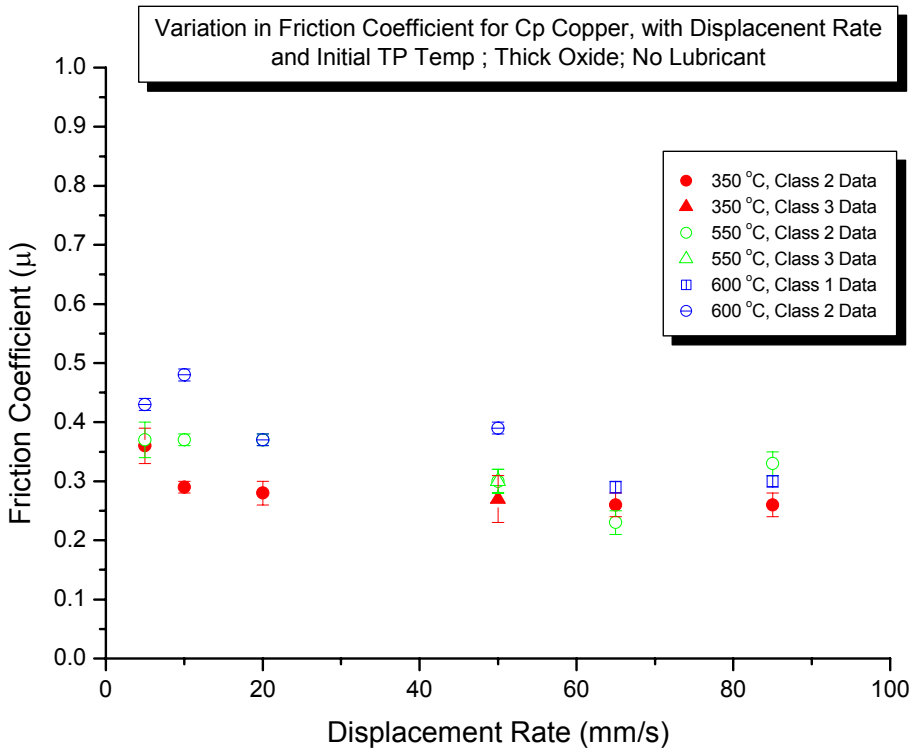

Repeatability of Friction Coefficient for Cp Aluminium on Pin on Disc Rig
Room Temperature, 80MPa Nominal Axial Stress
Repeat Test Series 1, Same Disc Class 1 data
Repeat Test Series 1, Same Disc Class 2 data
Repeat Test Series 1, Same Disc Class 3 data
Repeat Test Series 2, Same Disc Class 1 data
Repeat Test Series 2, Same Disc Class 2 data
Repeat Test Series 2, Same Disc Class 3 data
Repeat Test Series 3, New Discs Class 2 data
Repeat Test Series 3, New Discs Class 3 data
Friction Coefficient (μ)
Run Number
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1
2
3
4
5

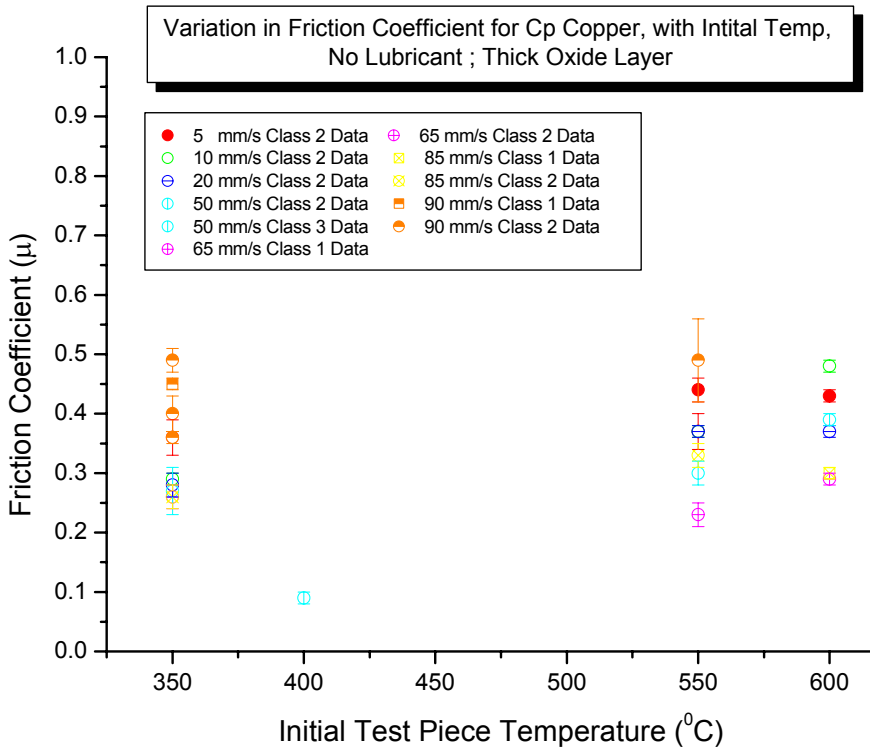
Appendix 4 : Friction Summary Plots for Big Friction Rig.

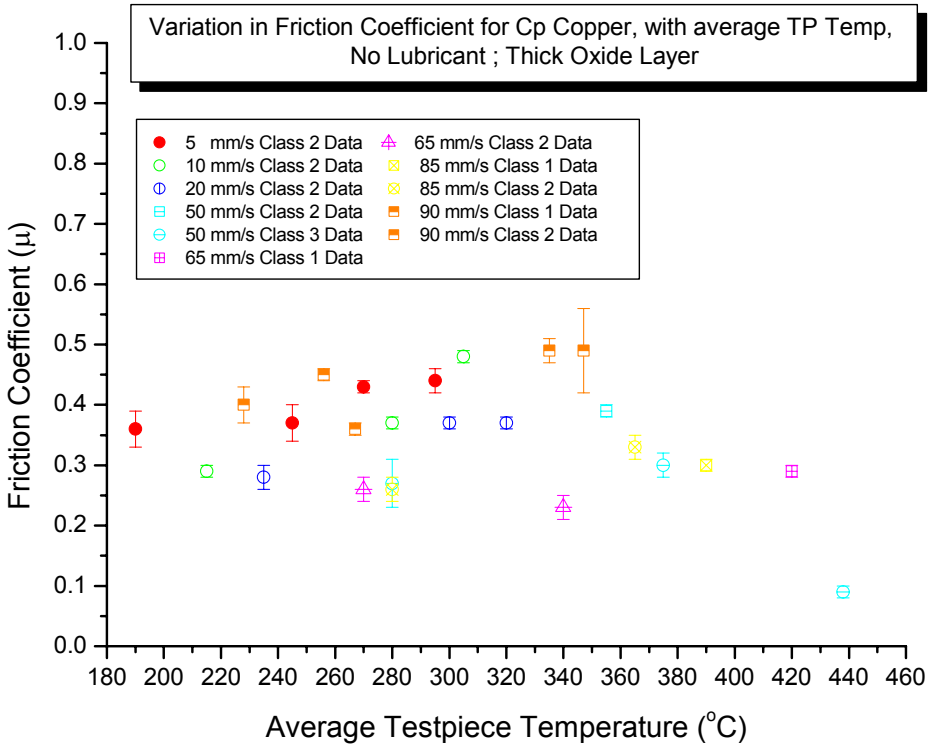


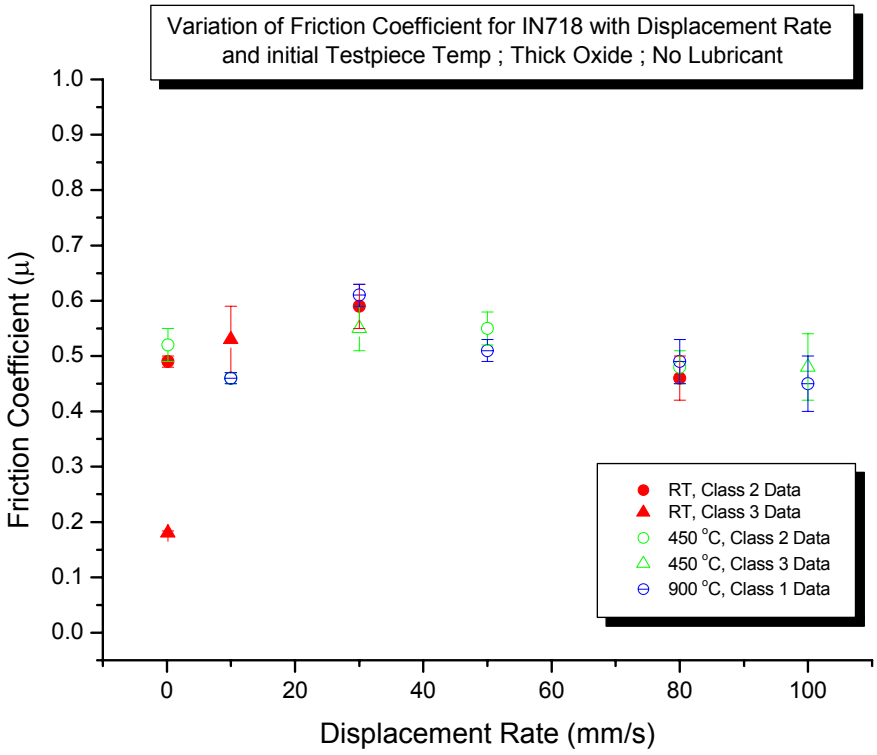


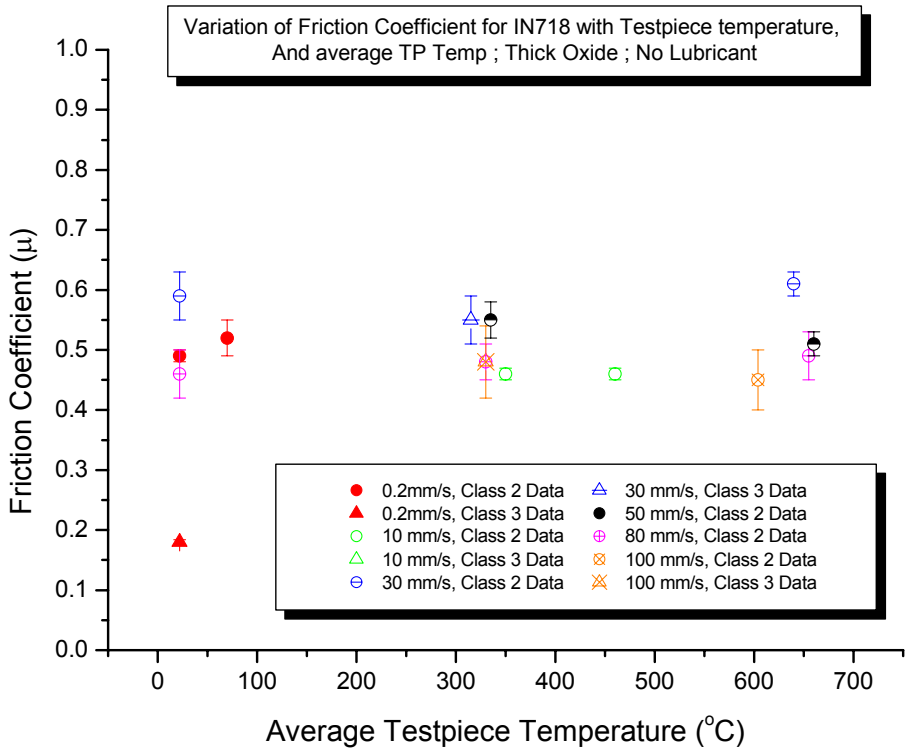

Variation in Friction Coefficient for Cp Aluminium with
Displacement Rate and average Testpiece Temperature ; No Lubricant
0.2 mm/s, Class 2 Data
0.2 mm/s, Class 3 Data
10 mm/s, Class 2 Data
10 mm/s, Class 3 Data
50 mm/s, Class 2 Data
50 mm/s, Class 3 Data
90 mm/s, Class 2 Data
90 mm/s, Class 3 Data
Friction Coefficient (μ)
Average Testpiece Temperature (°C)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200
250
300

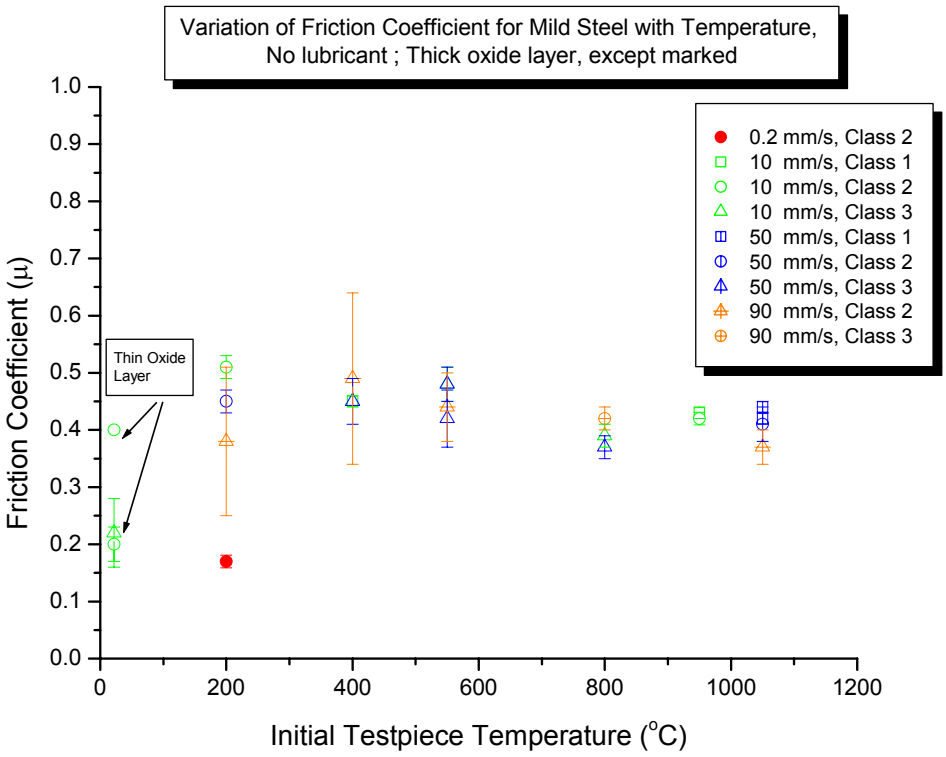

Variation in Friction Coefficient for Cp Copper, with Displacenent Rate and Initial TP Temp ; Thick Oxide; No Lubricant
350 °C, Class 2 Data
350 °C, Class 3 Data
550 °C, Class 2 Data
550 °C, Class 3 Data
600 °C, Class 1 Data
600 °C, Class 2 Data
Friction Coefficient (μ)
Displacement Rate (mm/s)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
20
40
60
80
100

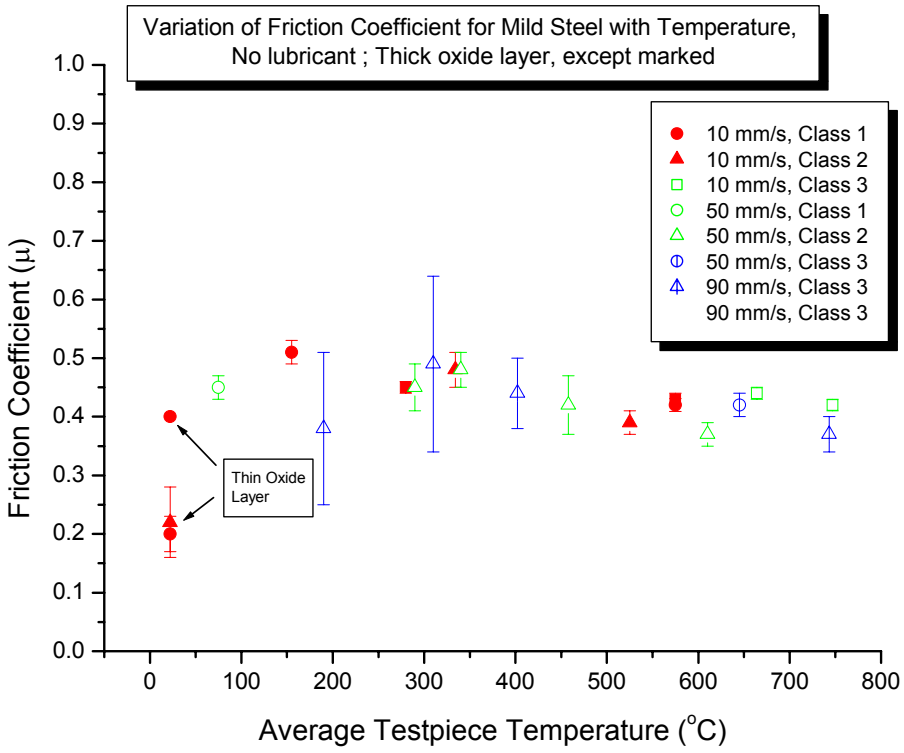

Variation in Friction Coefficient for Cp Copper, with Intital Temp, No Lubricant ; Thick Oxide Layer
5 mm/s Class 2 Data
10 mm/s Class 2 Data
20 mm/s Class 2 Data
50 mm/s Class 2 Data
50 mm/s Class 3 Data
65 mm/s Class 1 Data
65 mm/s Class 2 Data
85 mm/s Class 1 Data
85 mm/s Class 2 Data
90 mm/s Class 1 Data
90 mm/s Class 2 Data
Friction Coefficient (μ)
Initial Test Piece Temperature (0C)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
350
400
450
500
550
600

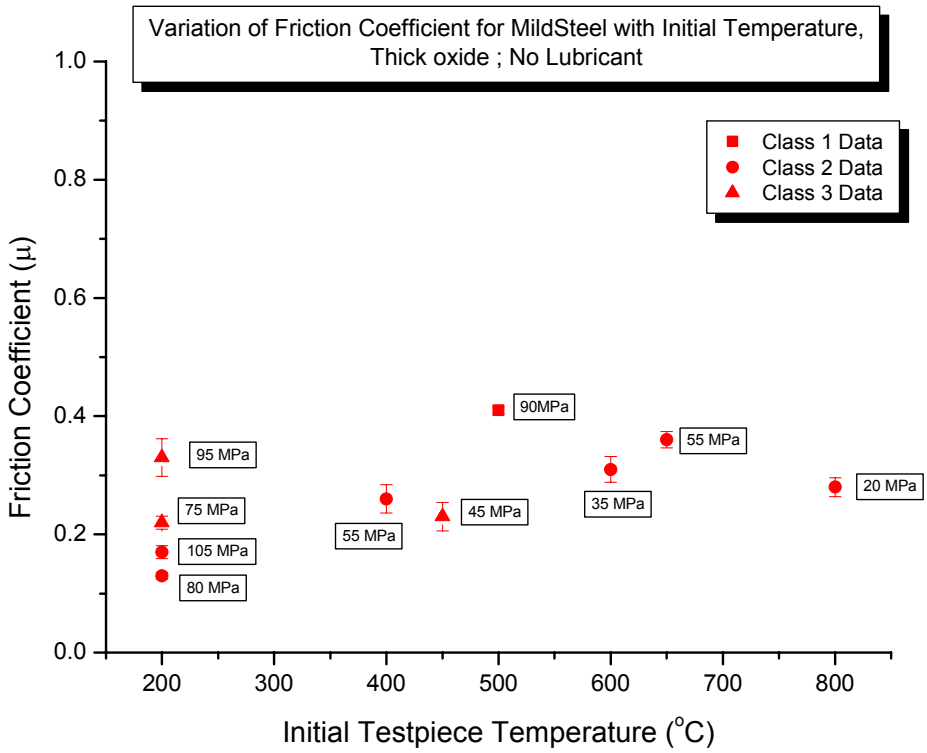

Variation in Friction Coefficient for Cp Copper, with average TP Temp,
No Lubricant ; Thick Oxide Layer
5 mm/s Class 2 Data
10 mm/s Class 2 Data
20 mm/s Class 2 Data
50 mm/s Class 2 Data
50 mm/s Class 3 Data
65 mm/s Class 1 Data
65 mm/s Class 2 Data
85 mm/s Class 1 Data
85 mm/s Class 2 Data
90 mm/s Class 1 Data
90 mm/s Class 2 Data
Friction Coefficient (μ)
Average Testpiece Temperature (°C)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
180 200 220 240 260 280 300 320 340 360 380 400 420 440 460

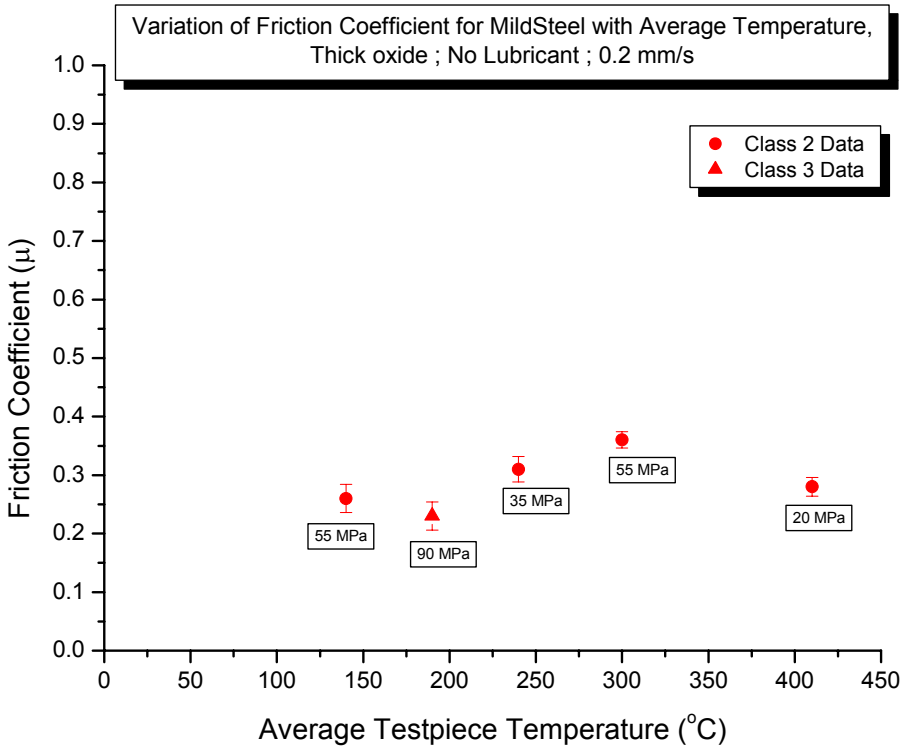

Variation of Friction Coefficient for IN718 with Displacement Rate and initial Testpiece Temp ; Thick Oxide ; No Lubricant
Friction Coefficient (μ)
Displacement Rate (mm/s)
RT, Class 2 Data
RT, Class 3 Data
450 °C, Class 2 Data
450 °C, Class 3 Data
900 °C, Class 1 Data

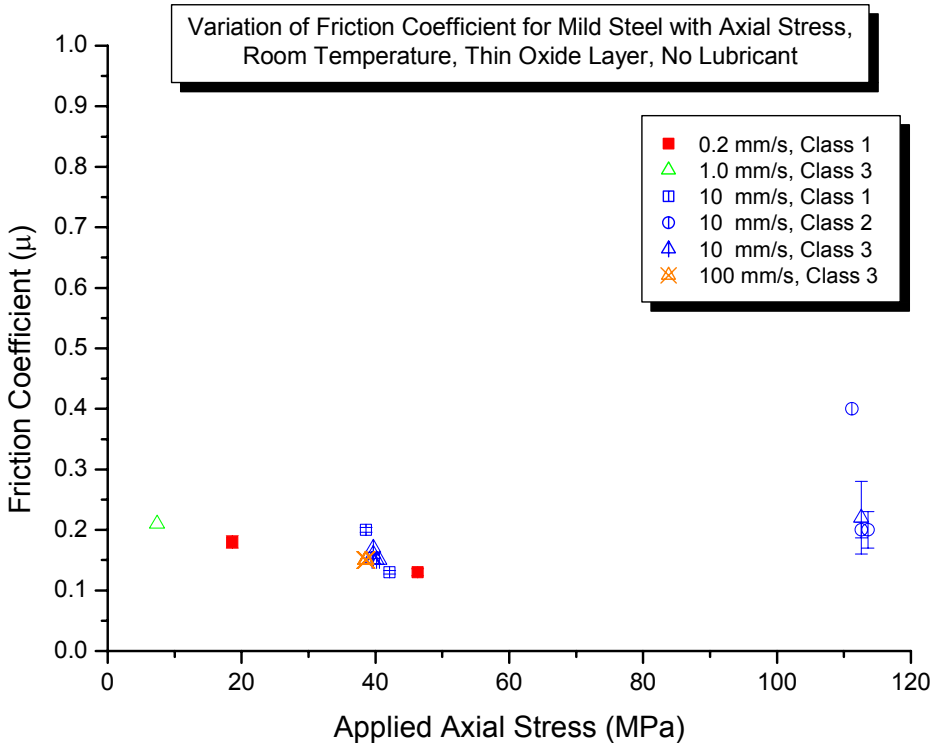

Variation of Friction Coefficient for IN718 with Testpiece temperature, And average TP Temp ; Thick Oxide ; No Lubricant
Friction Coefficient (μ)
Average Testpiece Temperature (°C)
0.2mm/s, Class 2 Data
0.2mm/s, Class 3 Data
10 mm/s, Class 2 Data
10 mm/s, Class 3 Data
30 mm/s, Class 2 Data
30 mm/s, Class 3 Data
50 mm/s, Class 2 Data
80 mm/s, Class 2 Data
100 mm/s, Class 2 Data
100 mm/s, Class 3 Data


Variation of Friction Coefficient for Mild Steel with Temperature,
No lubricant ; Thick oxide layer, except marked
0.2 mm/s, Class 2
10 mm/s, Class 1
10 mm/s, Class 2
10 mm/s, Class 3
50 mm/s, Class 1
50 mm/s, Class 2
50 mm/s, Class 3
90 mm/s, Class 2
90 mm/s, Class 3
Thin Oxide Layer
Friction Coefficient (μ)
Initial Testpiece Temperature (°C)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
200
400
600
800
1000
1200

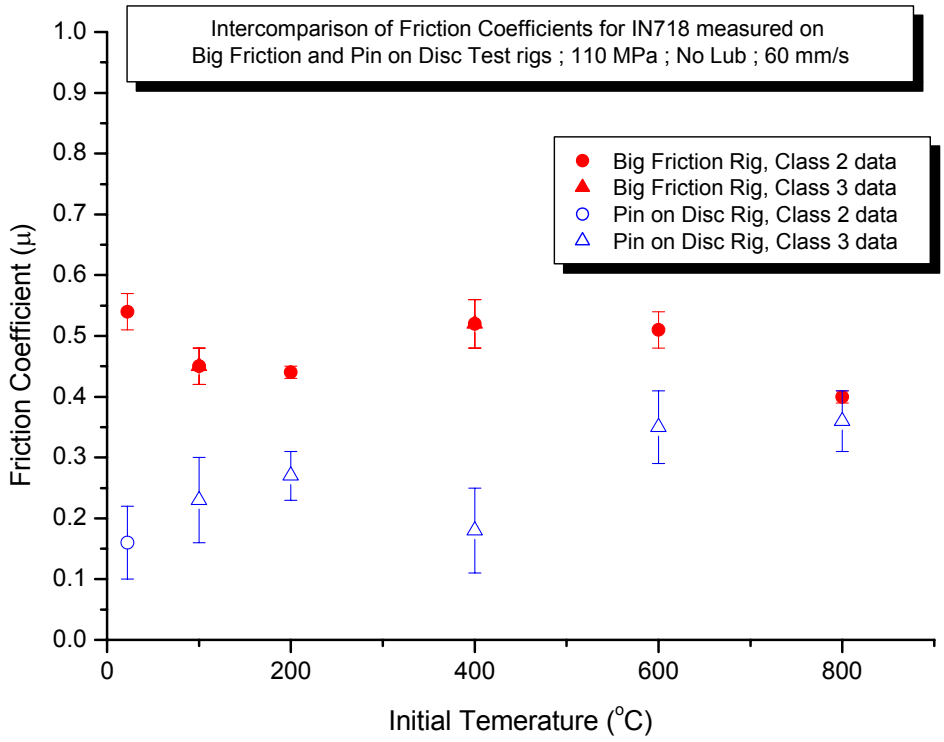

Variation of Friction Coefficient for Mild Steel with Temperature,
No lubricant ; Thick oxide layer, except marked
10 mm/s, Class 1
10 mm/s, Class 2
10 mm/s, Class 3
50 mm/s, Class 1
50 mm/s, Class 2
50 mm/s, Class 3
90 mm/s, Class 3
90 mm/s, Class 3
Thin Oxide Layer
Friction Coefficient (μ)
Average Testpiece Temperature (°C)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
100
200
300
400
500
600
700
800

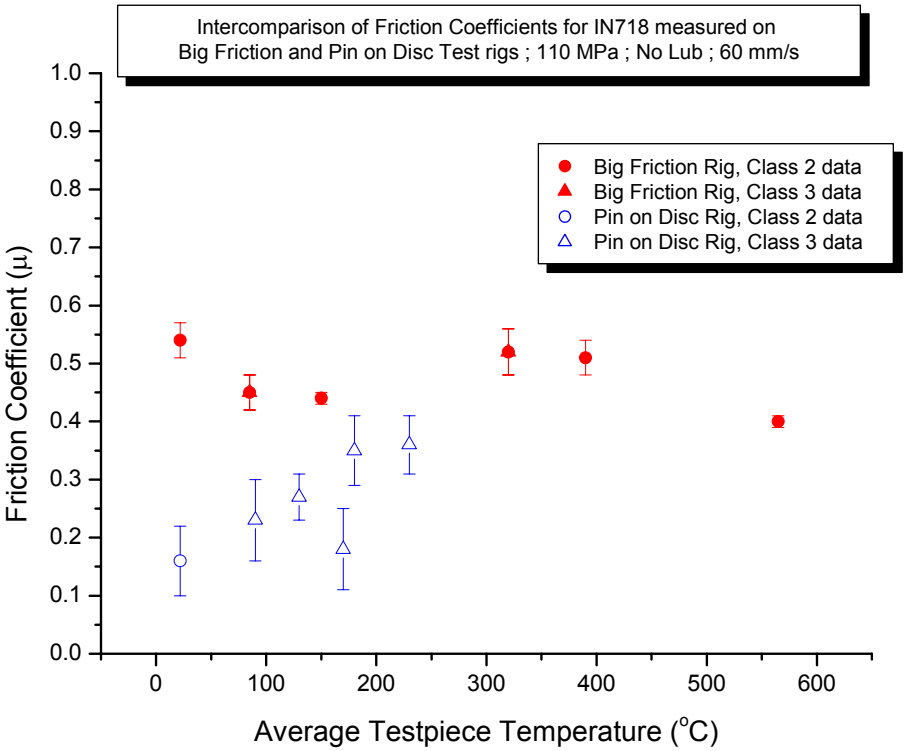

Variation of Friction Coefficient for MildSteel with Initial Temperature,
Thick oxide ; No Lubricant
Class 1 Data
Class 2 Data
Class 3 Data
Friction Coefficient (μ)
Initial Testpiece Temperature (°C)
95 MPa
75 MPa
105 MPa
80 MPa
55 MPa
45 MPa
90MPa
35 MPa
55 MPa
20 MPa

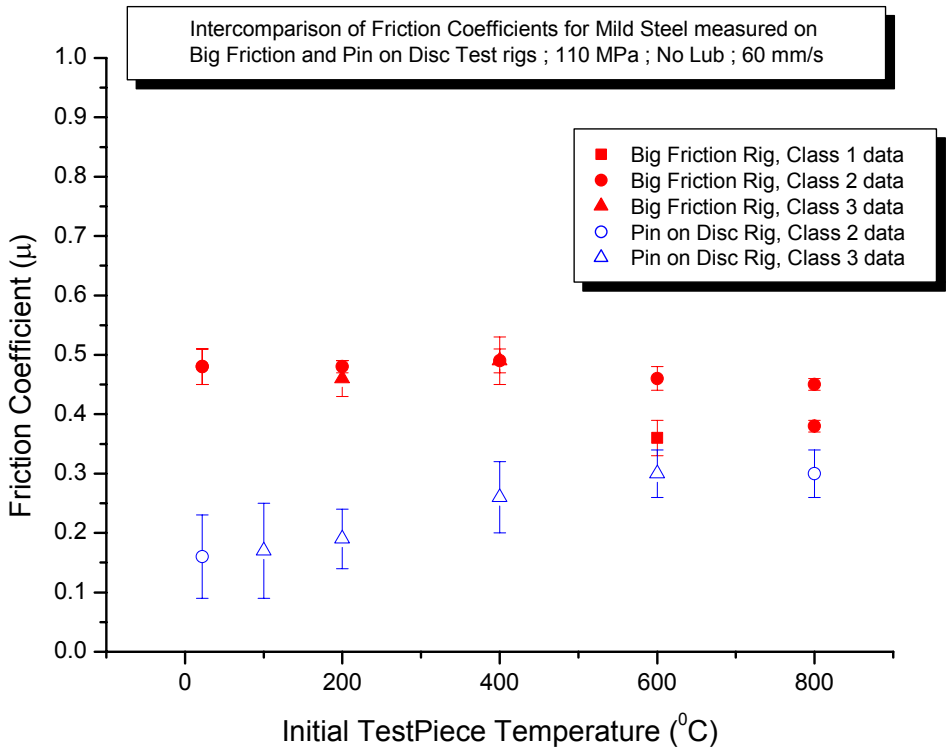

Variation of Friction Coefficient for MildSteel with Average Temperature,
Thick oxide ; No Lubricant ; 0.2 mm/s
Class 2 Data
Class 3 Data
Friction Coefficient (μ)
Average Testpiece Temperature (°C)
55 MPa
90 MPa
35 MPa
55 MPa
20 MPa

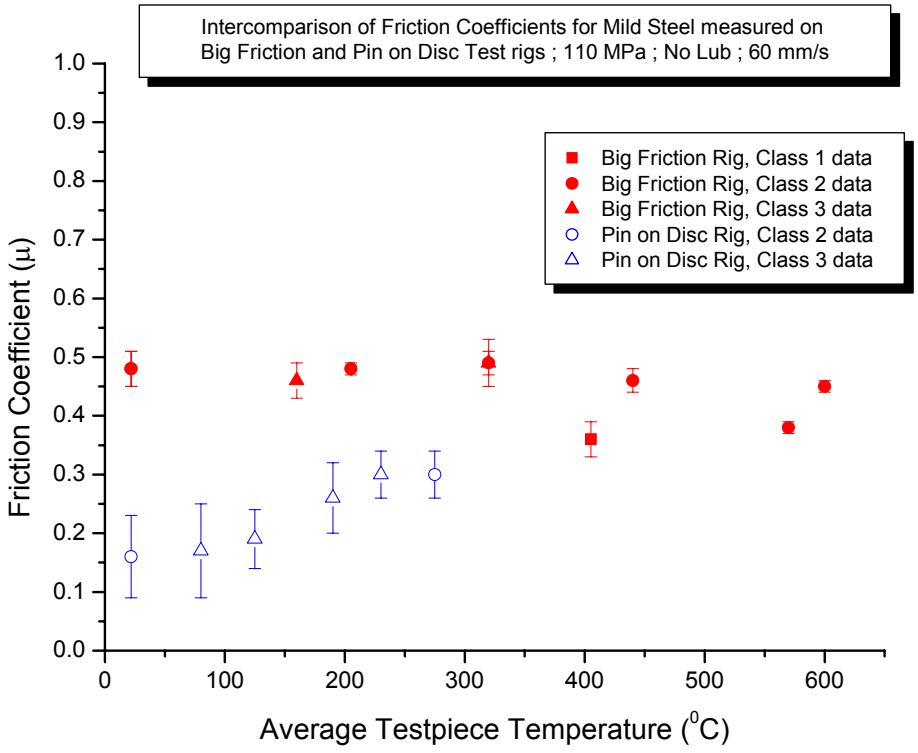

Variation of Friction Coefficient for Mild Steel with Axial Stress,
Room Temperature, Thin Oxide Layer, No Lubricant
0.2 mm/s, Class 1
1.0 mm/s, Class 3
10 mm/s, Class 1
10 mm/s, Class 2
10 mm/s, Class 3
100 mm/s, Class 3
Friction Coefficient (μ)
Applied Axial Stress (MPa)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
20
40
60
80
100
120

Appendix 5 : Intercomparison of Friction Results






Intercomparison of Friction Coefficients for Mild Steel measured on
Big Friction and Pin on Disc Test rigs ; 110 MPa ; No Lub ; 60 mm/s
Big Friction Rig, Class 1 data
Big Friction Rig, Class 2 data
Big Friction Rig, Class 3 data
Pin on Disc Rig, Class 2 data
Pin on Disc Rig, Class 3 data
Friction Coefficient (μ)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
200
400
600
800
Initial TestPiece Temperature (0C)


Intercomparison of Friction Coefficients for Mild Steel measured on
Big Friction and Pin on Disc Test rigs ; 110 MPa ; No Lub ; 60 mm/s
Big Friction Rig, Class 1 data
Big Friction Rig, Class 2 data
Big Friction Rig, Class 3 data
Pin on Disc Rig, Class 2 data
Pin on Disc Rig, Class 3 data
Friction Coefficient (μ)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
500
600
Average Testpiece Temperature (0C)