

Consideration of High Temperature Friction Measurement Uncertainty

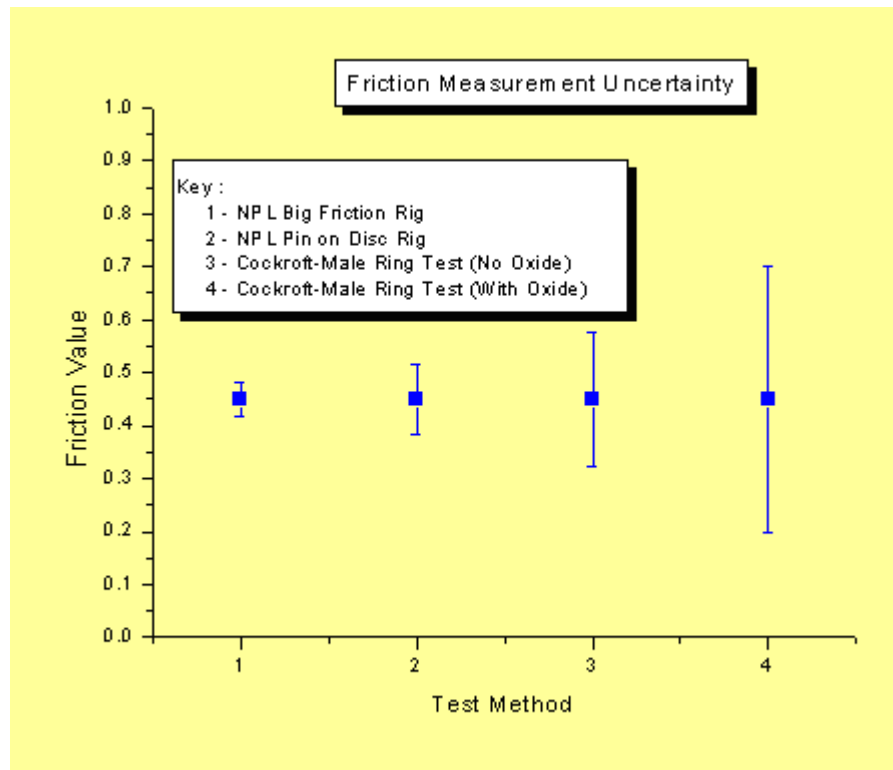


Figure 1. Schematic representation of Friction Measurement Uncertainty for various methods. Error bars represent the 95% confidence level.

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1 Introduction

As part of a DTI Funded Project concerned with the determination of Friction Coefficients for use as input data for process control models, the issues concerning the estimation of uncertainty of measurement have been addressed. A summary is presented here of the measurement uncertainty for three methods used for the determination of interfacial friction namely a) the Cockroft - Male Ring Test , b) the NPL Big Friction Rig and c) the NPL Pin on Disc Rig. Full details of the method used to estimate the measurement uncertainty is given elsewhere (Loveday & Brooks, 2000)

It is now widely recognised that all experimental measurements should be accompanied by an estimate of the Uncertainty of Measurement as outlined in the ISO TAG4 '*Guide to the expression of uncertainty in measurement*,' (1994), colloquially know as the 'GUM'.

Further information and guidance on estimating measurement uncertainties are available elsewhere including a '*Beginners Guide*' (Bell, 1999) as well as more comprehensive documents (UKAS, M3003, 1997 and Kandil *et al*, 2000)

The friction measurement methods considered here have been developed or evaluated in two DTI funded project concerning measurement of friction and heat transfer for process modelling and control; further details are given elsewhere (Loveday, Gee & Brooks, 2000). In addition information concerning the development of measurement methods for procuring reliable data for process modelling can be found on the following web site: www.npl.co.uk/npl/cmmt/procmetal/rpfp.html

2 Three Friction Measurement Methods

2.1 The Cockcroft -Male Ring Test

One of the most important pieces of data for modelling forging and forming processes is the friction coefficient, which describes the amount of friction between the deforming metal work-piece and the tool. These coefficients can be estimated using the simple ring up-setting test, generally known as the Cockcroft and Male Ring Test (Male & Cockcroft, 1964). However a number of simplifying assumptions have to be made which can lead to large errors and uncertainties, (Fletcher *et al*, 1998). Moreover, since the values vary with other parameters such as relative velocity and contact pressure, any estimate of friction can only be an average. In the ring test an annular sample of specified dimensions is deformed between platens. From a measurement of the changes of the internal diameter of the testpiece it is possible to deduce a 'friction factor', m , by interpolation of theoretically calculated calibration curves. If the friction is high the central hole is reduced in diameter when the ring is subjected to compression, and increases in diameter when the friction is low. Friction coefficients, μ , may then be derived from the empirical relationship

$$\mu = m / (2\sqrt{3}) \text{ (Male \& Depierre, 1970)} \quad (\text{Eqn 1})$$

Although this test is widely used as a simple ranking test for assessing lubricants or surface finishes of tools, it is not ideal for generating reliable quantitative data for modelling purposes. Values obtained are highly dependent on the assumptions made for calculating the calibration curves, and the shape of the curves dictate that at low values of deformation, say less than $\sim 20\%$, the method is not sufficiently sensitive, and is highly dependent upon the accuracy of the thermo-mechanical material description, (Fletcher *et al*, 1998).

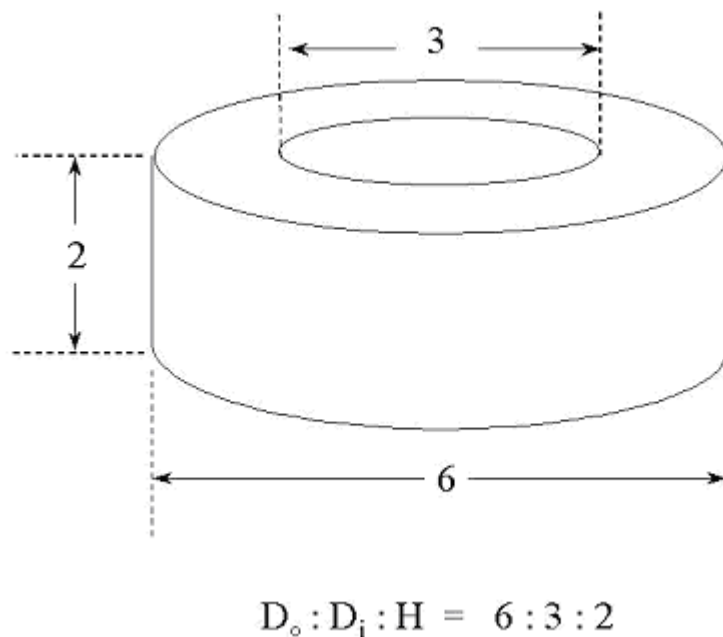


Figure 2. Schematic Diagram of Cockcroft - Male Ring

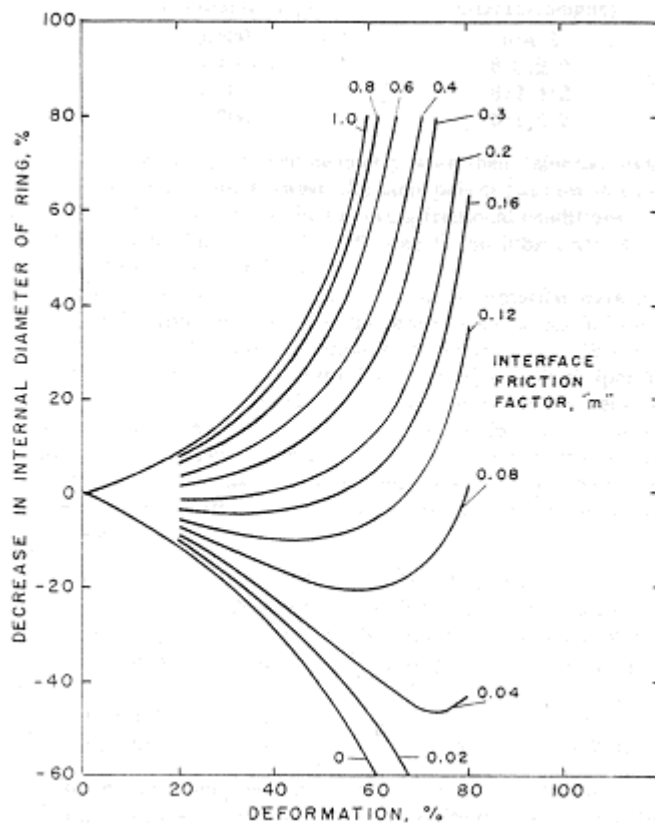


Figure 3 Calibration curves for ring test. (Male, A.T. and Depierre, V. (1970))

Typically the preferred ring geometry is shown in [Figure 2](#), and an example of the theoretical calibration are curves shown in [Figure 3](#). It should be noted that if different theoretical assumptions are made concerning the generation of such curves then there can be significant differences in the shape of the curves and hence the magnitude of the value of the friction factor subsequently determined (Fletcher *et al*, 1998).

2.2 The NPL 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 (~700 ton) press, [Figure 4](#). The rig can be used with two sizes of cylindrical billets, of 30 and 50 mm in diameter, which are pre-heated in a furnace up to 1000°C and then transferred manually into the "grabber arm" on the friction rig, [Figure 5](#). An axial load is applied using the press, and the load is monitored using a three column load cell designed by NPL. As the billets are compressed between platens they can be dragged horizontally up to 100 mm between the platens, at rates up to 100 mm/s, using a 250kN actuator controlled by an Instron 8500 Series controller. By recording the vertical and horizontal loads, the coefficient of friction can then be determined, an allowance being made for the fact that both the upper and lower surfaces of the billet are in contact with tool steel platens. The loads, displacement and temperature of the billet are recorded using a PC based data logger, operating with customised Labview software. Further details of the design and calibration of the Big Friction Rig are given elsewhere (Loveday *et al*, 2000).



Figure 4. The NPL Big Friction Rig



Figure 5. Hot billet being transferred from a furnace to the grabber arm on the Big Friction Rig.

2.3 The NPL Pin-on-Disc Friction Rig

This apparatus heats strip samples up to 1000°C in a few seconds using a DC electrical current of up to 200 A, [Gee et al 1997]. The sample may then be rapidly brought into contact with a rotating disc of tool steel using a motorised drive mechanism, with transducers measuring the resultant vertical and horizontal forces. A schematic diagram of the apparatus is shown in [Figure 6](#) and a photograph in [Figure 7](#). To prevent the thin strip sample collapsing it is supported on a zirconia thermal insulator and its temperature monitored using a thermo-couple. In principle this rig could be fully encased so that measurements may be carried out in an inert atmosphere. The sample size in contact with the disc is typically 5 mm x 5 mm x 2 mm, while the disc is 100 mm in diameter. Contact speeds of up to 2 m/s can be obtained.

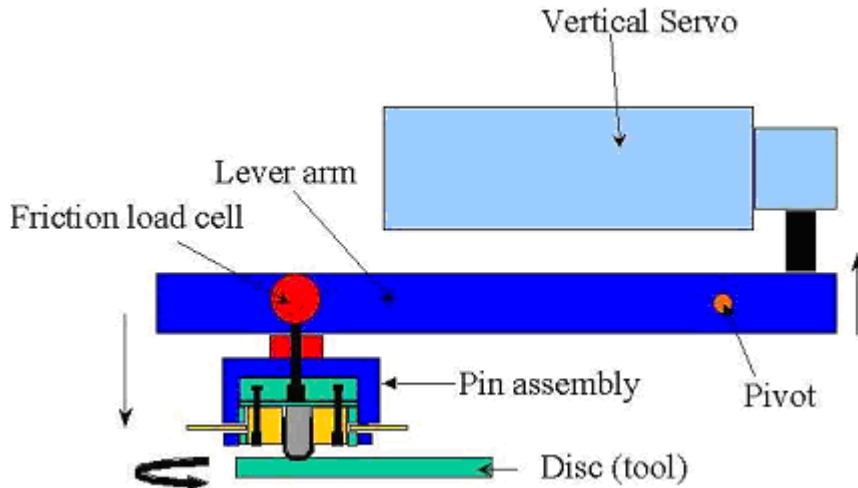


Figure 6 Schematic layout of Pin-on-Disc Rig.



Figure 7. Pin-on-Disc Rig

3 Measurement Uncertainties

3.1 Uncertainty Estimates for Cockcroft -Male ring test

In general, the measurements of the internal diameter of the hole are made at a number of positions and the average value calculated. Measurements may be undertaken using a vernier calliper or a shadowgraph projector. However, it should be recognised that reproducible measurements involve operator skill which can lead to a

systematic error between one laboratory and another. Thus, although the technique is suitable for evaluating the relative performance of different lubricants or surface finish of dies within a single laboratory, it will be shown that the quantitative assessment of friction factors is prone to a large measurement uncertainty.

Full details of the approach adopted to estimate the uncertainty in the friction factor, m , based on the measurement uncertainties associated with the diameter and height measurements used in conjunction with the calibration curves are given elsewhere (Loveday & Brooks, 2000) however a summary of the findings is given in [Table 1](#).

Table 1 Final Uncertainty Budget for variation of Friction Factor, m , attributable to the measured uncertainties in height and diameter measurements

a) Without Oxide

Symbol	Source of Uncertainty	Value +/- %	Probability Distribution	Divisor	$U_i(y)$ +/- %
δm_h	Uncertainty in m due to height measurements	25	Normal	2	12.5
δm_d	Uncertainty in m due to diameter measurements	10	Normal	2	5
u_c	Combined Uncertainty	-	-	-	13.5
u_e	Expanded Uncertainty ($k=2$, 95% confidence)	-	-	-	27

b) With Oxide

Symbol	Source of Uncertainty	Value +/- %	Probability Distribution	Divisor	$U_i(y)$ +/- %
δm_h	Uncertainty in m due to height measurements	25	Normal	2	12.5
δm_d	Uncertainty in m due to diameter measurements	50	Normal	2	25
u_c	Combined Uncertainty	-	-	-	28
u_e	Expanded Uncertainty ($k=2$, 95% confidence)	-	-	-	56

3.2 Uncertainty Estimates for Big Friction Rig

As explained in [Section 2.2](#), friction coefficients are determined using the Big Friction Rig from the ratio of the horizontal and axial loads, measured using load cells whilst the hot billet is dragged horizontally between compression platens and the billet is being deformed. The approach adopted here for estimating the uncertainty of measurement is to utilise the uncertainty values for the two load cells determined during calibration to provide traceability to the National Measurement System (NMS), and to include the uncertainty attributable to repeatability determined from the type of curves shown in [Figure 8](#).

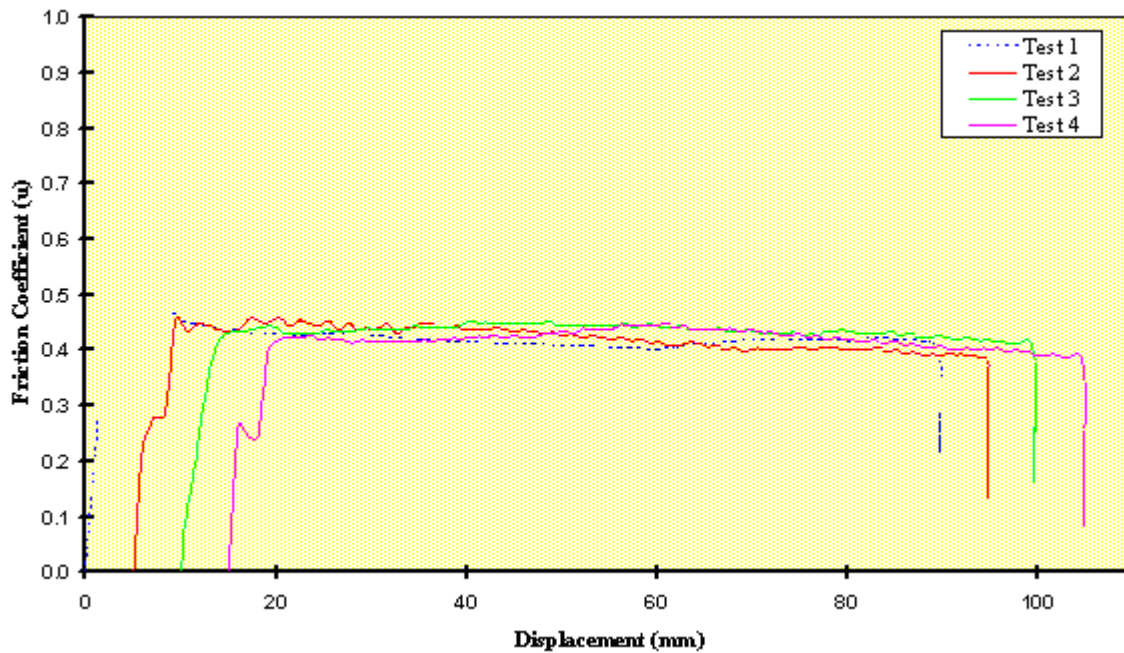


Figure 8 Repeat test measurements Big Friction Rig

The various sources of uncertainty are listed in [Table 2](#) and the Combined and Expanded Uncertainties are calculated using the conventional root mean square technique.

Table 2. Uncertainty Budget for Large Friction Rig (BFR).

Symbol	Source of Uncertainty	Value +/- %	Probability Distribution	Divisor	U _i (y) +/- %
U _{e cal}	Calibration of 250 kN INSTRON Load cell in BFR	0.62	Normal	2	0.31
U _{std}	Verification of 7MN load cell.	0.24	Normal	2	0.12
<i>r</i>	Repeatability friction test (standard deviation)	3.3	Normal	1	3.3
<i>R</i>	Reproducibility between tests (standard deviation)	0.6	Normal	1	0.6
u _c	Combined Uncertainty	-	-	-	3.37
u _e	Expanded Uncertainty (k=2, 95% confidence)	-	-	-	6.74

3.3 Uncertainty Estimates for Pin-on-Disc Friction Rig

Because of the geometry of the Pin-on Disc Friction rig, direct *in-situ* calibration of the load measurement system to follow the traceability route to the NMS, used for the Big Friction Rig, has not been possible to date. However, a bench comparison with a calibrated load cell has been undertaken to provide a spot check, and thus a nominal value of +/- 1% has been used in the uncertainty budget below based upon the manufacture's specification for the load cells. Since the uncertainty associated with the load cells is appreciably less than that due to the repeatability of the test results, it is unlikely that errors in the load cell uncertainties will have a significant affect on the overall uncertainty estimate. A typical example of recorded raw data from the Pin-on-Disc rig is shown in [Figure 9](#).

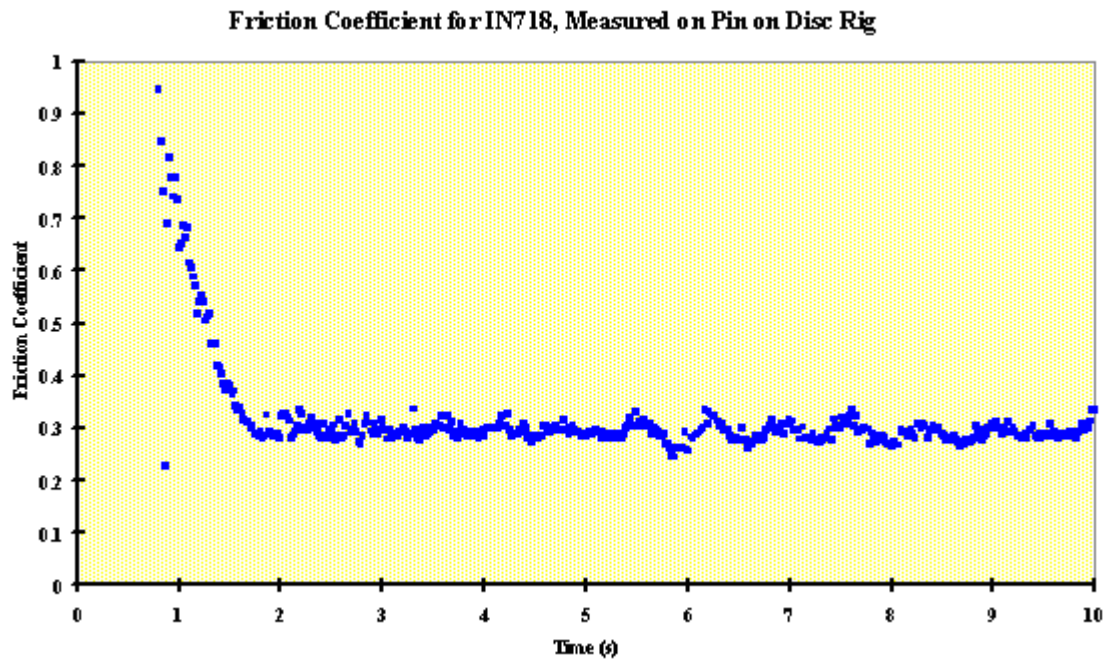


Figure 9. Typical example of a friction curve measured using the Pin-on Disc Rig. Results of repeat tests are shown in Figure 10 for IN 718 at 400°C at 60mm/s under a nominal axial stress of 80 MPa.

The various sources of uncertainty are listed in [Table 3](#) and the Combined and Expanded Uncertainties are calculated using the conventional root mean square technique.

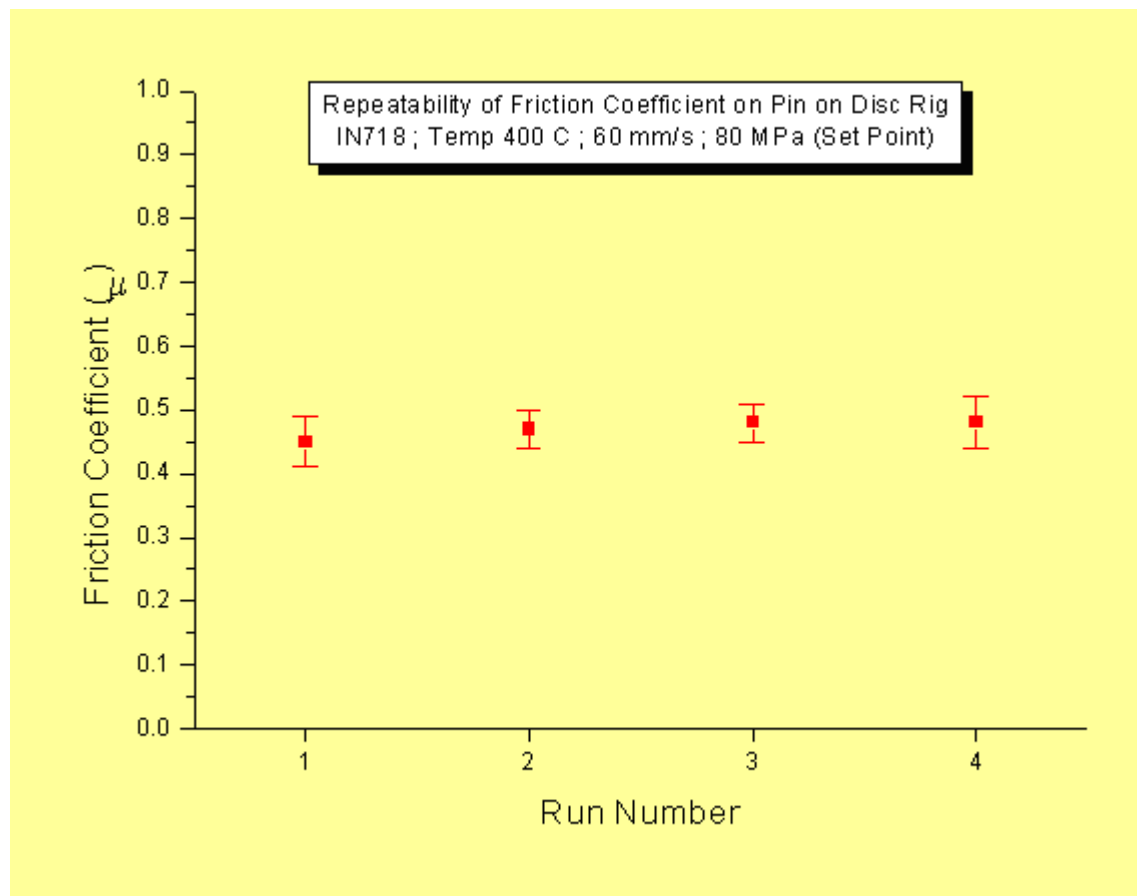


Figure 10. Repeat tests on the Pin on Disc friction rig.

Table 3. Uncertainty Budget for Pin on Disc Friction Rig.

Symbol	Source of Uncertainty	Value +/- %	Probability Distribution	Divisor	Ui(y) +/- %
$U_{e\text{ cal}}$	Specification of 1kN horizontal strain gauge load cell	1	Rectangular	$\sqrt{3}$	0.577
U_{std}	Specification of 1kN piezo electric axial load cell.	1	Rectangular	$\sqrt{3}$	0.577
r	Repeatability friction tests (standard deviation)	7.45	Normal	1	7.45
R	Reproducibility between tests (standard deviation)	1.5	Normal	1	1.5
u_c	Combined Uncertainty	-	-	-	7.64
u_e	Expanded Uncertainty ($k=2$, 95% confidence)	-	-	-	15.3

4 Discussion

The measurement uncertainties estimated above are summarised in [Table 4](#). for two techniques developed at NPL for the measurement of friction coefficients, μ , and for the Cockcroft-Male ring test which is used for the determination of a friction factor, m .

Table 4 Summary of Friction Measurement Uncertainties

Test Method	Measured Parameter	Uncertainty * + /- %
Big Friction Rig	μ	7
Pin on Disc Friction Rig	μ	15
Cockcroft-Male Ring Test (without oxide)	m	28
Cockcroft-Male Ring Test (with oxide)	m	56

* at the 95% confidence level

The estimated uncertainties for the various tests are presented schematically in [Figure 1](#), where the uncertainties are shown as error bars for a nominal friction value of 0.45.

It should be noted that in the calculations for uncertainty for friction coefficients using the two NPL techniques an allowance was made for the errors associated with a series of repeat measurements; in the case of the Cockcroft-Male tests no such allowance was made because suitable data was not available to the authors at the present time. Thus the measurement uncertainty values presented here for the Cockcroft-Male test are likely to be an underestimate.

5 Conclusions

It has been shown that the new friction measurement techniques developed under the DTI funded programme are significantly more accurate than the traditional Cockcroft-Male ring test and can thus provide more reliable data for use in hot forging process control and modelling.

6 Acknowledgement

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7 References

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