Measurement Good Practice Guide No 3

Measuring Flow Stress in Hot Axisymmetric Compression Tests

Revised – Summer 2002

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Abstract

This document is a revised version of the November 1996 issue of (BPG)003 which describes good UK practice for measuring hot flow stress in metallic materials. It is applicable to hot (isothermal) uniaxial axisymmetric compression tests at medium to high rates of strain (10^{-4} to 10^{2} s^{-1}) at deformation temperatures below the solidus. Technical input to the document has been provided by a steering group containing academic researchers and representatives of industrial users and producers of a wide range of engineering materials. An experimental and modelling programme has been conducted during the preparation of the document to underpin the procedures in the guide. It is anticipated that, in due course, a version of this document could form the basis of a BSI, CEN and ISO Standard.

ISSN 1368–6550

Revised Summer 2002

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Acknowledgements

The guidance and advice of the project industrial advisory group (IAG) has underpinned the development of this good practice guide (GPG). This guide was produced as part of the *Materials Measurement* programme, a programme of underpinning research supported by the Department of Trade and Industry and co-ordinated by the National Physical Laboratory.

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Previously published as part of the Good Practice in Measurement Series
NPL-CMMT (GPG)003: February 1997

Measuring Flow Stress in Hot Axisymmetric Compression Tests

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Foreword

These guidelines were prepared within several projects supported by Materials Measurements and Processing Programmes, underpinning materials measurement research activities financed by the UK Department of Trade and Industry.

The Guide describes a method for measuring the hot flow stress in metallic materials at medium to high rates of strain (10^{-4} to 10^{2} s^{-1}), in axisymmetric uniaxial compression at deformation temperatures below the solidus. The guidelines recommend good practice to minimise levels of uncertainty in the measurement process. The procedure has been supported by modelling work at the IRC for Computer Aided Engineering, University of Wales, Swansea and experimental tests at NPL, the IRC and the University of Sheffield on Al alloy 5052, Nimonic 901 and 316 stainless steel at a range of temperatures and strain rates, including at rates of strain greater than 10 s^{-1}.

Additional work to further validate the best practice document was supported through a European collaborative project on test methods for modelling the metal working process and the document was reviewed by this EC SMT project group, TESTIFY, chaired by Y Chastel (CEMEF, Nice, France). Technical contributions on ringing and temperature rises during high rate tests were also provided by T Rehrmann (IBF RWTH, Aachen).

This document is a revision of the original GPG published in 1998. The changes reflect additional knowledge acquired through the detailed application of FE models to the PSC test and through further experimental work at higher rates of strain to examine the effect of test system ringing and deformational heating. The revised GPG is structured to include the analytical approach in the original GPG as well as the more accurate test analysis based on FE models.

It is anticipated that, in due course, a version of this document could form the basis of a BSI, CEN and ISO Standard.

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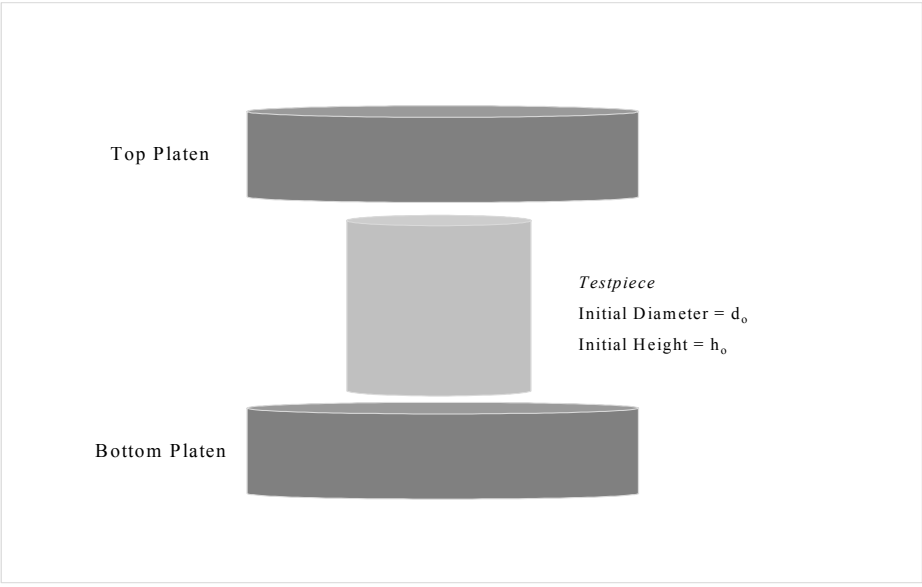


Figure 1 Schematic diagram of axisymmetric compression test.

1 Test Rationale

There is a requirement for repeatable and reproducible hot compression test data which can provide validated data for modelling, for process deformation strategies and for correlation with microstructural evolution studies (Oh et al,1992; Kopp et al, 1993 and 2001; Evans and Scharning, 2002). In hot forming processes the workpiece generally experiences a range of strain rates, with mean values over several orders of magnitude. The absolute values depend very much on the particular hot forming process, but typical strain rates of between 10^{-4} and 10^{2} s^{-1} can occur. These guidelines are targeted at providing a reliable test method to cover this strain rate range, and have been supported by tests in a range of 10^{-1} to about 200 s^{-1}. Strain rates in this regime are of interest to research groups developing models for the machining process where there are equivalent requirements for high quality data.

Internationally the three most commonly used types of hot deformation test are axisymmetric compression, plane strain compression and torsion. At present, there are no standards in place for any of these tests. These guidelines are concerned with axisymmetric compression. A similar document for good practice in plane strain compression tests, GPG No 27 [Lacey et al (revised 2002)], has also been written to complement this Guide.

In order to perform tests which provide accurate and reliable data the test conditions must be specified precisely, particularly concerning the following items:

- Geometry and surface finish of the testpiece
- Temperature distributions
- Temperature measurement
- Heating rates, soaking conditions
- Testpiece microstructure
- Oxidation
- Calibration procedures (including machine stiffness effects)
- Anvil materials and surface finish
- Lubrication
- Barrelling
- Strain/displacement measurements
- Data analysis/models

These guidelines provide a structured approach to enable the potential sources of uncertainty to be better controlled.

A quantitative analysis of the test has been conducted at the IRC in Computer Aided Engineering at the University of Wales, Swansea to investigate the effects of friction, strain rate temperature, testpiece volume and strain using a fully coupled finite element procedure. The work has been published (Evans and Scharning, 2001) and some of the issues raised are discussed in Appendix D.

The key findings were:

- Systematic errors are largely due to the presence of frictional forces and deformational heating effects
- The magnitudes of the errors are governed by the material properties and the test conditions
- Parameters describing testpiece geometry and volume, friction factor, test temperature, strain rate and strain are all important, but friction and testpiece geometry are of most significance. Strain and strain rate are of intermediate and testpiece volume and test temperature least importance, respectively.

2 Scope

2.1 General

1.1 These guidelines are intended for use with metallic materials.

1.2 These guidelines apply to "isothermal" uniaxial axisymmetric compression tests on cylindrical testpieces of a specified geometry.

1.3 These guidelines apply to deformation strain rates in the range 10^{-4} to 10^{2} s^{-1}, relevant to industrial forging and rolling processes.

1.4 These guidelines apply to hot metal working deformation temperatures below the solidus of the material in question.

Notes

(1) The guidelines have been supported by finite element modelling studies at the University of Wales, Swansea (IRC in Computer Aided Engineering) where parameters such as testpiece geometry, friction and deformation conditions have been systematically changed.

(2) The guidelines have also been supported by experimental measurements at the University of Wales, Swansea (IRC in Computer Aided Engineering), University of Sheffield (USEM) and NPL on an Al alloy, 5052; on 316 stainless steel and a nickel alloy, Nimonic 901, over a range of temperatures and strain rates.

2.2 Outline of Procedure and Conditions of Testing

These guidelines for conducting hot axisymmetric "isothermal" compression tests contain a number of basic steps (Figure 2):

1. Manufacture testpiece to chosen geometry.
   Decide on testpiece values for each test parameter.

2. Calibrate test system for load, displacement and temperature.

3. Install testpiece in system.
   Choose heating profile, and lubrication type.

4. Deform testpiece at specified temperature and strain rate.
   Measure changes in load and displacement (speed) and temperature.

5. Remove testpiece from system, quench or slow cool in an agreed predetermined manner.

6. Analyse and report data.

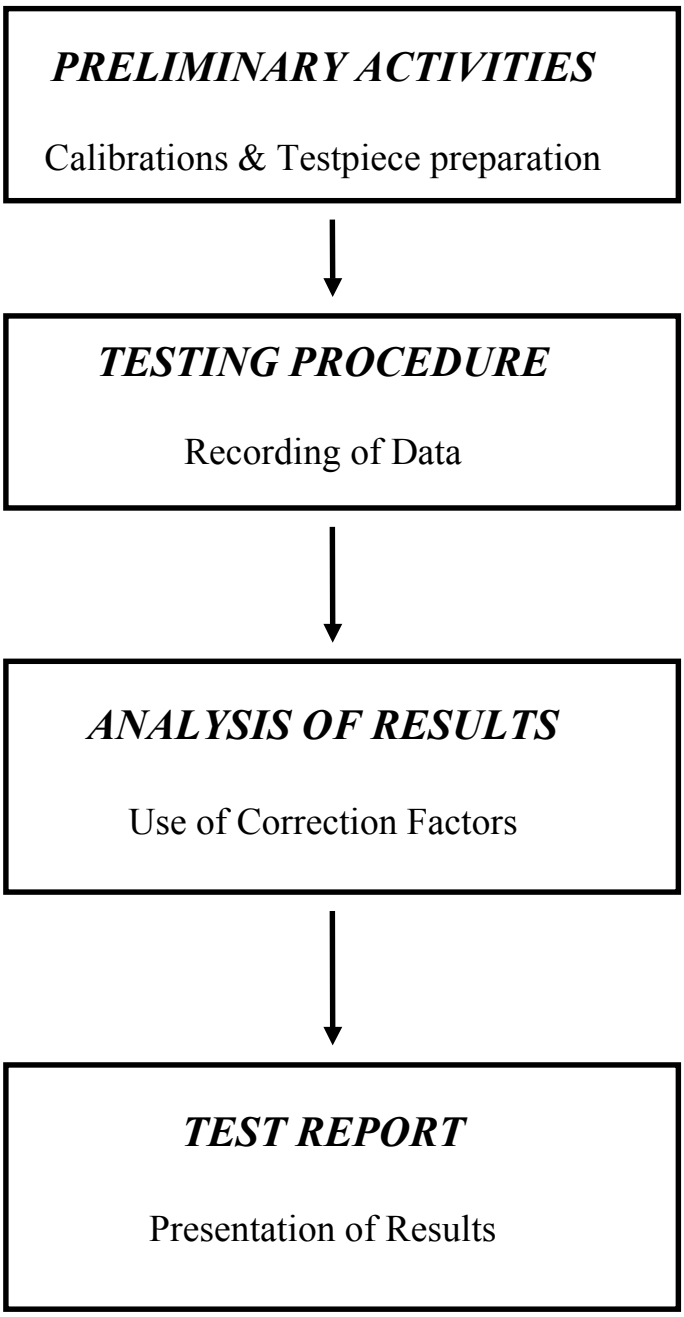


Figure 2 Schematic - Outline of Procedure.

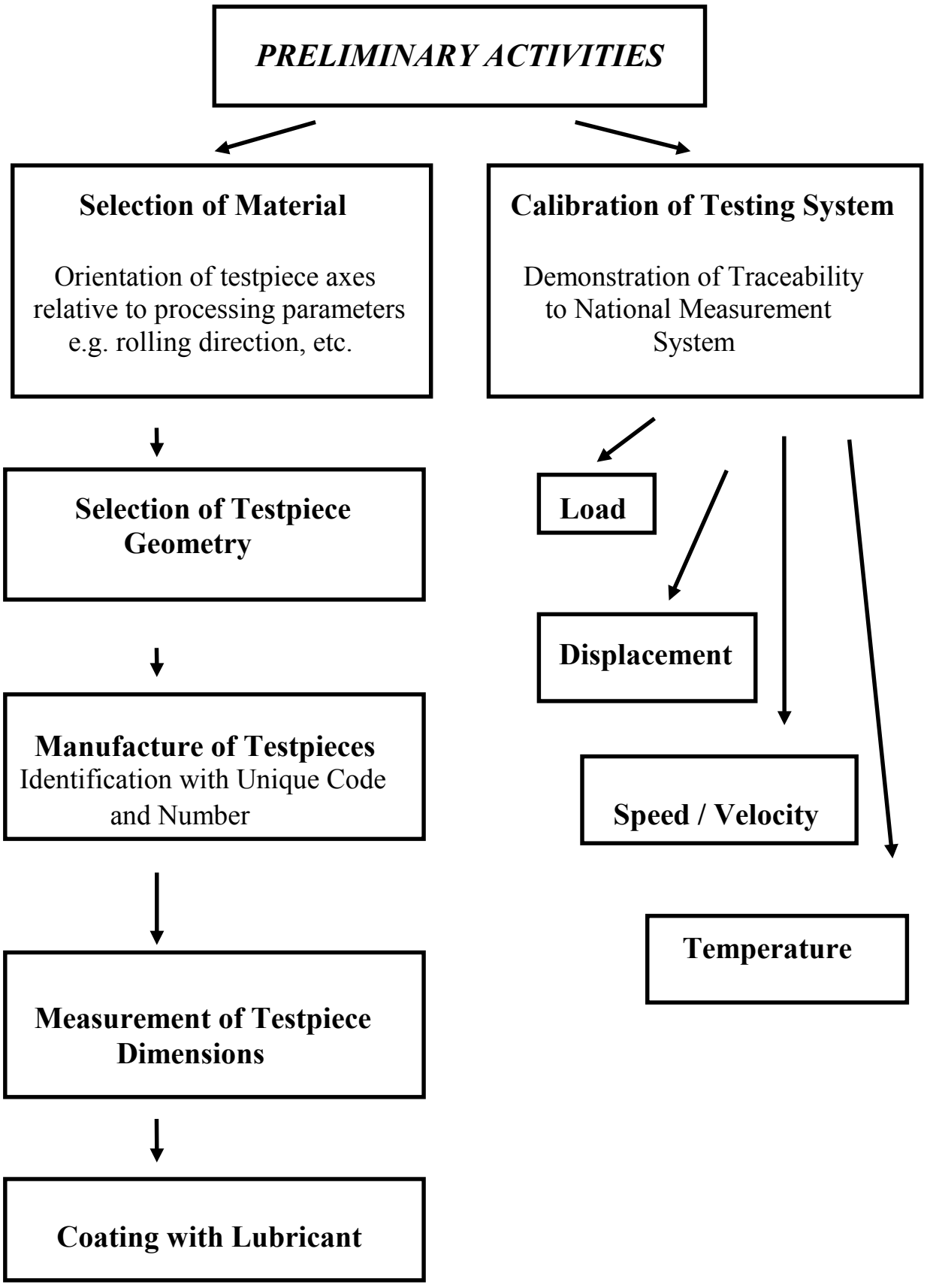


Figure 2 Continued

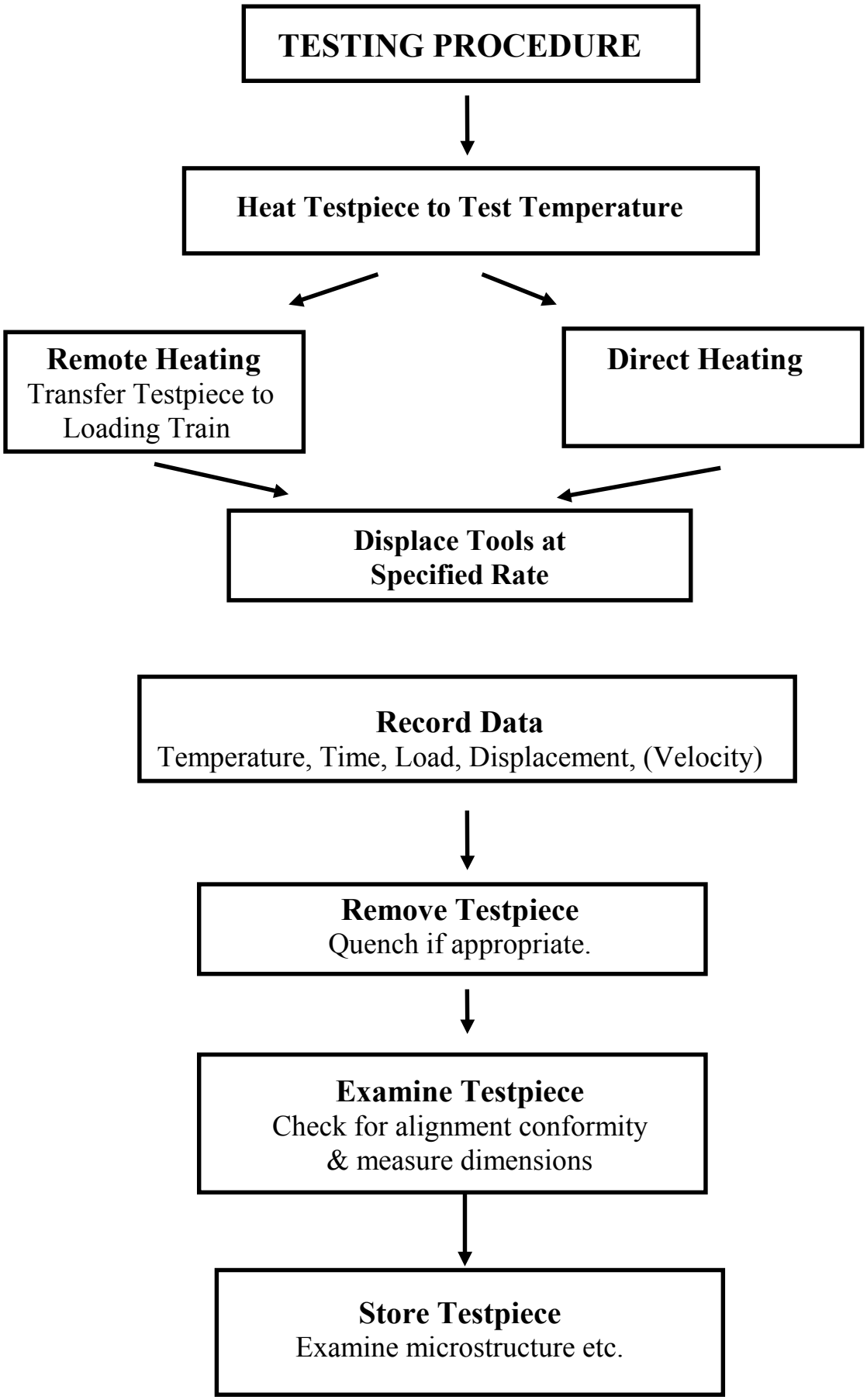
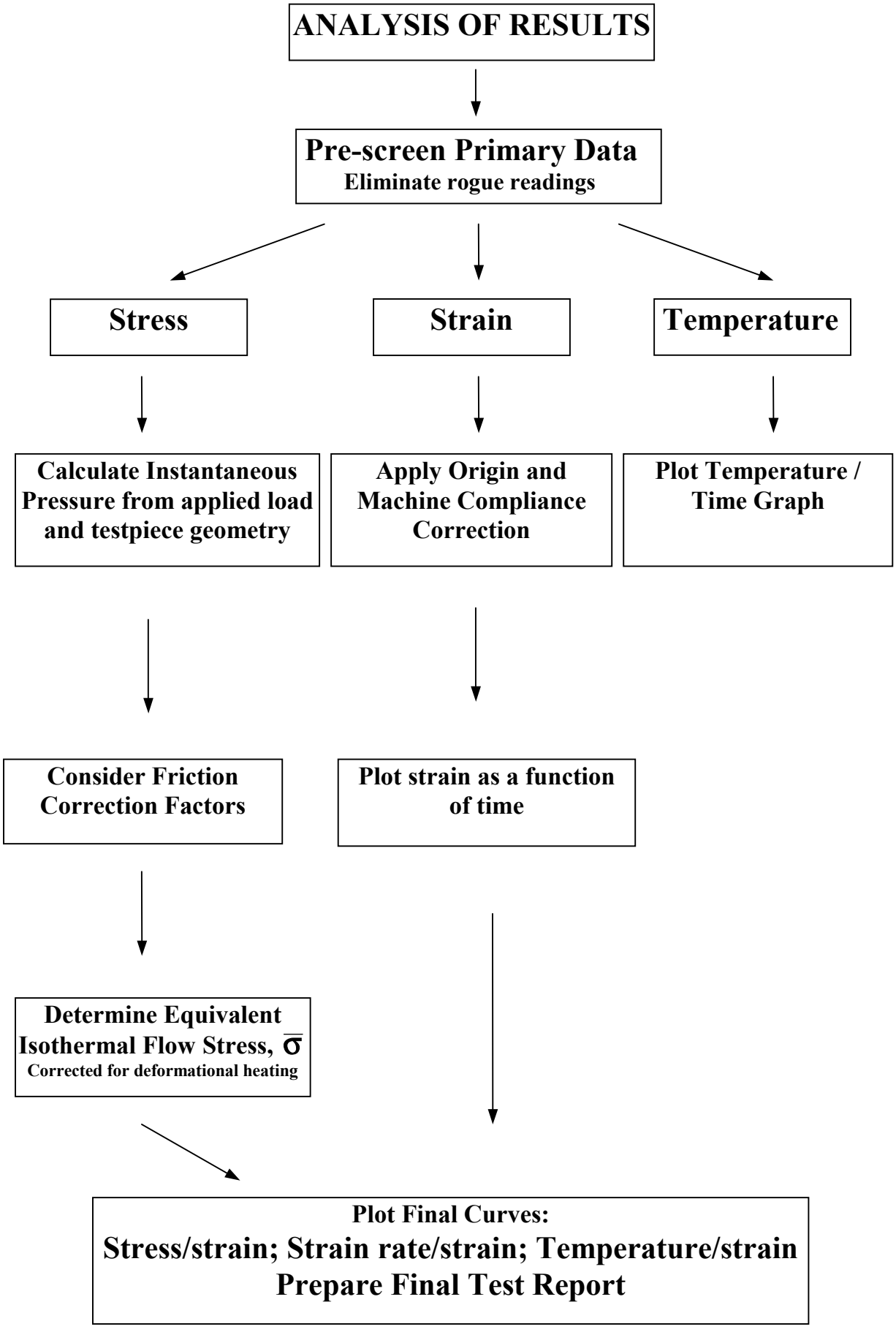


Figure 2 Continued


ANALYSIS OF RESULTS
Pre-screen Primary Data
Eliminate rogue readings
Stress
Strain
Temperature
Calculate Instantaneous Pressure from applied load and testpiece geometry
Apply Origin and Machine Compliance Correction
Plot Temperature / Time Graph
Consider Friction Correction Factors
Plot strain as a function of time
Determine Equivalent Isothermal Flow Stress, σ̄
Corrected for deformational heating
Plot Final Curves:
Stress/strain; Strain rate/strain; Temperature/strain
Prepare Final Test Report

3 Symbols and Units

For the purpose of these guidelines the following nomenclature shall apply:

Symbol		Designation	Units
ε		True strain at intermediate time	-
ε_a		Axial true strain	-
ε_d		Diametral true strain	-
ε_f		Total applied true strain at end of test	-
$\dot{\varepsilon}$		Strain rate at intermediate time	s^{-1}
	$\dot{\varepsilon}_a$	Average strain rate for whole testpiece	s^{-1}
	$\dot{\varepsilon}_\ell$	Local strain rate at a defined position on testpiece	s^{-1}
r_o		Radius of undeformed testpiece	mm
h_o		Height of undeformed testpiece	mm
h		Testpiece height at intermediate time	mm
h_f		Final testpiece height	mm
	Sh_f	Standard deviation of 4 measurements of the final height	mm
d_o		Diameter of undeformed testpiece	mm
d		Diameter of testpiece at intermediate time	mm
	d_ℓ	Local diameter at defined position at intermediate time	mm
d_f		Final testpiece diameter	mm
	Sd_f	Standard deviation of 4 measurements of the final diameter	
	d_{fmax}	Maximum diameter of deformed testpiece	mm
	d_{fmin}	Minimum diameter of deformed testpiece	mm
	$d_{f\ell}$	Final diameter - defined at local position	mm
A_o		Area of undeformed testpiece	mm^2
A		Area of testpiece at intermediate time	mm^2
	A_ℓ	Area of testpiece at locally defined position	mm^2
A_f		Area of deformed testpiece	mm^2
	$A_{f\ell}$	Area at defined position after deformation	mm^2
B		Barrelling coefficient	-
S		Shear coefficient	-
O_v		Ovality coefficient	-
H		Height coefficient	-
D_R		Testpiece aspect ratio	-
T		Average temperature of testpiece	^oC
F		Force (load) applied to testpiece	N
F_ε		Force at intermediate true strain ε	N
F_t		Force at intermediate time	N
R		True stress at intermediate time	$N\ mm^{-2}$
	$R = $	F/A	$N\ mm^{-2}$
	$R_f = $	F/A_f (true stress at end of deformation)	$N\ mm^{-2}$
R_ε		True stress at an applied true strain of ε	$N\ mm^{-2}$
	$R_\varepsilon = $	F_ε/A	$N\ mm^{-2}$
	$R_{\varepsilon\ell} = $	F_ε/A_ℓ (true stress at defined position, ℓ)	$N\ mm^{-2}$

4 Definitions

4.1 Stress, Strain and Displacement

Determination of the state of stress is necessary for the analysis of plastic deformation in metals. The state of stress at a point may be determined by calculating the stresses acting on three mutually perpendicular oriented planes passing through the point. When determining the complete state of stress at a point, O, it is found that on one plane the normal stress increases as the angle of the plane is increased until a maximum is reached, whilst the shear stress on the same plane decreases to zero. This plane of maximum normal stress and zero shear stress is called the Principal Plane and the normal stress acting on the plane, the Principal Stress. There are also Principal Strains associated with these stresses. A diagram showing the orientation of plane and axes relative to the point O is given in Figure 3. Thus the stress system at a point can be represented by three principal stresses, σ_1, σ_2, *and* σ_3, *which control the yielding behaviour of the metal and which give rise to the associated principal strains* ε_1, ε_2 *and* ε_3. *In the axisymmetric compression test* ε_1 *and* ε_2 *are the strains in the direction perpendicular to the length (see Figure 3) and in an ideal test (no barrelling) are equal to* $-\varepsilon_3/2$ *where* ε_3 *is the length strain.*

For further information concerning stress - strain relationships see Dieter (1989) or Harris (1983)

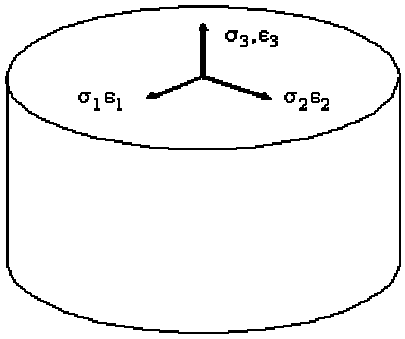


Figure 3 Schematic illustration of stress and strain axes relative to testpiece.

4.2 True Strain (ε)

The natural logarithm of the ratio of the height at an intermediate time (h) divided by the initial height (h_o).

$$\varepsilon = \ln(h / h_o) \qquad (1)$$

4.3 Diametral True Strain (ε_d)

The diametral true strain measured at a defined position along the testpiece, e.g. usually the mid-height.

$$\varepsilon_d = \ln(d / d_o) \quad (2)$$

4.4 Strain Rate ($\dot{\varepsilon}$)

Rate of change of true strain.

Can be measured globally, ε_a (ie an average for testpiece), or locally, ε_ℓ (at a defined position), from diametral strain measurements.

4.5 Load (F)

Force (F) applied to the testpiece.

4.6 Diameter (d)

The diameter of the undeformed testpiece (d_o) is calculated from an average of measurements of the diameter at four positions (see Appendix A) at the midpoint of the testpiece.

The diameter of the deformed testpiece (d_f) is also calculated from an average of measurements of the diameter at four positions at the midpoint of the testpiece (see Appendix A). If the deformed testpiece is oval in cross section, two of these diameters correspond to the minimum and maximum values. The other two are measured at 45^o to the maximum and minimum diameter axes (see Appendix A).

The maximum diameter is d_{fmax}.
The minimum diameter is d_{fmin}.

4.7 Height (h)

The height of the deformed testpiece is calculated from an average of measurements at four positions. One measurement should be taken at the centre point of the top and bottom surfaces and three more at the edge each separated by about 120^o.

The initial height is h_o.
The final height is h_f.

A proforma is provided in Appendix A for recording measurements of testpiece dimensions.

4.8 Cross Sectional Area (A)

The area of the undeformed testpiece (A_o) is given by

$$A_o = \pi d_o^2 / 4 \tag{3}$$

and the area of the deformed testpiece (A_f) is given by

$$A_f = \pi d_f^2 / 4 \tag{4}$$

where d_o and d_f are measured at the testpiece midpoint.

The area calculated from the measured diameter should be recorded in the test report - see suggested proforma in Appendix B.

The diameter of the testpiece can also be measured locally (d_ℓ or $d_{f\ell}$) during the test using a diametral clip gauge or other measurement method. In this case if the local position is not at the midlength the Area of the testpiece is given by

$$A_\ell = \pi d_\ell^2 / 4 \quad \text{during the test, (locally)}$$

$$\text{or} \quad A_{f\ell} = \pi d_{f\ell}^2 / 4 \quad \text{at the end of the test, (locally)}$$

where the local position must be reported if different from the midlength.

4.9 True Stress (R)

Force (F) at any time during the test divided by the cross sectional area (A) of the testpiece at that any intermediate time.

$$R = F/A \tag{5}$$

True stress at the end of deformation is defined as R_f (= F/A_f) and locally as R_ℓ (= F/A_ℓ).

4.10 Alignment

The geometrical conformance between the loading axes of the test machine.

Departure from conformance, ie lack of parallelism between loading platens, will result in non-uniform deformation. A valid test is one in which deformation is applied uniformly to the testpiece. The shape of the testpiece must be measured after the test to confirm the validity or otherwise of the test.

4.11 Aspect Ratio (D_R)

The testpiece aspect ratio (D_R) is the ratio of the height to the diameter of the undeformed testpiece.

$$D_R = h_o / d_o \quad (6)$$

The recommended value for D_R is 1.5, but any value in the range 1-2 can be used. The value of D_R must be included in the test report.

Sometimes aspect ratio is quoted as the ratio of radius/height (r_o/h_o). For convenience, a conversion table for specific values is given.

r_o/h_o	h_o/d_o (D_R)
1.0	0.5
0.75	0.67
0.5	1.0
0.375	1.33
0.33	1.5
0.25	2.0

4.12 Shape Coefficients

An important aspect of these guidelines is the use of shape measurements on the deformed testpieces to confirm the validity or otherwise of the test data. For example, if barrelling is greater than a specified amount the flow stress data will be significantly in error.

It is thus recommended that a number of shape measurements are made on the testpiece following deformation. Testpieces can be cleaned using grit blasting to remove dried lubricant and scale if necessary. The shape measurements are defined as follows:

4.12.1 Barrelling Coefficient (B)

The barrelling coefficient (B) is defined as

$$B = \frac{h_f d_f^2}{h_o d_o^2} \quad (7)$$

B is the ratio of the final volume of the testpiece, calculated from the final height and final diameter measured at the midlength of the testpiece, divided by the initial volume. Barrelling is caused by friction at the testpiece/platen interfaces and temperature gradients. Excessive amounts can give rise to large uncertainties in the flow stress measurement. B increases in value for increasing amounts of barrelling.

4.12.2 Ovality Coefficient (O_v)

The ovality coefficient (O_v) is defined as the ratio of the maximum to the minimum diameters of the deformed testpiece.

$$O_v = d_{fmax} / d_{fmin} \quad (8)$$

Ovality can occur through effects of texture and microstructure on the deformation behaviour, particularly for hexagonal close packed metals and alloys. A measurement of ovality is a useful parameter to record in these cases.

4.12.3 Height Coefficient (H)

The height coefficient (H) is the ratio of the standard deviation of four measurements of height of the deformed testpiece measured at the centre and at about 120^o intervals on the edge divided by the average height of the deformed testpiece.

$$H = Sh_f / h_f \quad (9)$$

If H is equal to or greater than 0.04 the test is invalid.

H gives an indication of the parallelism of testpiece deformation.

To measure the height of the testpiece it is recommended that a flat-ended micrometer is used with a spindle diameter of about 5 mm. To measure at the testpiece edges the midpoint of the micrometer spindle should be aligned with the edge of the testpiece.

For example, following deformation of a 15 mm long testpiece (see Appendix A).

a) $h_5 = 7$ *mm (centre)* $h_7 = 6.94$ *mm (edge)*
$h_6 = 7.06$ *mm (edge)* $h_8 = 6.90$ *mm (edge)*

NB $h_1 - h_4$ *are the height measurements prior to deformation.*

Therefore

h_f = *6.98 mm, and H is 0.01. The test is valid.*

b) h_5 = *7 mm (centre)* h_7 = *6.6 mm (edge)*
h_6 = *7.3 mm (edge)* h_8 = *6.8 mm (edge)*

h_f = *6.93 mm, and H is 0.04. The test is invalid.*

4.12.4 Shear Coefficient (S)

It is possible that the centre line of the testpiece, following deformation, may shear. The shear coefficient quantifies the amount of shear and is obtained by tracing the shape of the testpiece and measuring the angle, θ, between the centre line in the undeformed testpiece and the centre line in the deformed testpiece. The shear coefficient, S, is given by

$$S = \tan \theta \qquad (10)$$

If S is greater than 0.175 (i.e. $\theta \geq 10^o$) then the test is invalid.

4.12.5 Non-uniform Shapes

Unusually shaped testpieces can sometimes result from the deformation process because of material inhomogeneity, large grain size, texture or temperature inhomogeneities. These shapes are not easy to define using regular coefficients. However, it is necessary to decide whether the resulting shapes are a result of poor testing practice or a consequence of intrinsic material characteristics such as texture or coarseness of structure.

4.13 Friction (μ)

The coefficient of friction parameter is μ.

This should be determined for the lubrication and test conditions by testing specimens of different initial geometries.

5 Testpieces

The testpiece is usually obtained by cutting/machining a cylindrical sample from a larger product form. The size of the testpiece is a compromise between being large enough to be representative of the microstructure of interest but not too large as to present problems in non-uniformity of temperature or in machine capacity during deformation.

5.1 Preparation of Testpieces

Machining should be such as to minimise residual stresses and changes in local microstructure close to the surface. Spark machining (EDM) can be used first of all to blank the testpiece shape from a larger block if necessary and even to form the final shape of the testpiece provided the surface quality is good and provided the metallurgical structure of the material is not changed.

It is good practice to examine the microstructure of the testpiece close to the surface of the testpiece following manufacture, following the specific heating profile prior to testing and following deformation.

The identity and orientation of the testpiece with relation to the original material stock should be recorded. Reference to BS EN-ISO 3785 (Designation of testpiece axes) is recommended.

5.2 Shape, Dimension and Measurement

After machining the testpiece dimensions should be measured with a tolerance of ± 0.02 mm on each individual measurement of d and h (Section 4.6 and 4.7). The diameter should be taken as the average of four measurements and should be measured at the midpoint of the testpiece. Each of the individual measurements of diameter should be separated by approximately 45^o and an average taken (APPENDIX A). The height, h_o, should be taken as the average of four measurements - at the centre and at three points on the circumference (edge) separated by approximately 120^o (APPENDIX A). The ends of the undeformed testpieces should be perpendicular to the longitudinal direction within ± 0.2^o and should be parallel to within ± 0.02 mm.

The recommended aspect ratio (D_R) of the testpiece is 1.50. (Section 4.11). Testpieces with D_R in the range 1.2 - 1.8 can be used but the ratio must be quoted in the test report.

In a previous validation exercise [Roebuck (1996)] two axisymmetric compression (AC) geometries with D_R values of 1.50 were predominantly used:

d_o = 8 mm	*and*	d_o = 10 mm
h_o = 12 mm		h_o = 15 mm

These are within the range of widely used geometries and are recommended for typical test machines and test temperatures.

5.3 Surface Quality

It is more important to protect the surface of the testpiece from oxidation than to specify a surface finish to a required standard. There are several options eg plating, inert atmosphere or vacuum testing, the use of glass etc.

The final arbiter of test validity is the geometry of the deformed testpiece. Provided that the dimensional coefficients are within the prescribed values then the test will be deemed to be valid, irrespective of the initial quality of the surface of the testpiece.

5.4 Lubrication

Good lubrication is vital to conducting valid hot axisymmetric compression tests. It is essential to keep barrelling to a minimum to ensure that the measured flow stresses are representative of the material behaviour. Friction effects can in some instances be corrected for (see section 7.6) but a value for the friction coefficient must be known.

Cavities (grooves or recesses) in testpieces are sometimes used to retain lubricants. They are undesirable if the initial part of the stress/strain curve is required to be measured.

Some recommended lubricants are summarised in a separate Measurement Note (Lord and Loveday (2001)).

5.5 Microstructure

In planning the required tests it is important that some consideration be given to the scale of the microstructure with respect to that of the testpiece. For example, uniformity of deformation would be unlikely if the testpiece diameter contained less than about 10 grains. Examination of testpiece microstructure after the test can provide information for microstructure evolution models.

Heating rates and holding time at temperature can affect the microstructure of the material or the integrity of the lubricant and therefore should be carefully controlled and recorded.

6 Apparatus

For historical reasons current practice in the UK encompasses a number of different types of machine although most are servohydraulic. Machines are available that apply load to the testpiece either using servohydraulic actuators, or using mechanical methods, e.g. cam plastometers. In addition the testpiece may be heated

- *in a radiant element muffle furnace*
- *by inductive methods*
- *by an AC or DC electric current*

For this reason these guidelines recommend only that the test machine be calibrated for load, displacement and temperature measurement and that the calibrations are traceable. There is no formally recommended type of test machine.

The apparatus required for the test requires some form of heating to be applied to the testpiece, usually a furnace, but alternatives such as an induction coil or direct heating using an electrical current are allowed.

6.1 Alignment

For the purpose of this Good Practice Guide, alignment refers to the geometrical conformance between the loading axes of the test machine.

Tests should be carried out on a machine which has good lateral rigidity and accurate alignment between the testpiece tools, (platens). The machine loading can be hydraulic or electromechanical.

Departure from conformance, ie lack of parallelism between loading platens, will result in non-uniform deformation. A valid test is one in which deformation is applied uniformly to the testpiece. The shape of the testpiece must be measured after the test to confirm the validity or otherwise of the test.

It is difficult to specify in absolute terms the necessary minimum lateral misalignment of the platens, since the effect of misalignment is dependent upon the maximum strain to which the testpiece is subjected, ie if the testpiece is only compressed a small amount then a greater misalignment may be tolerated than if the testpiece is compressed until the platens are in close proximity.

6.2 Strain Rate Control

It is recommended that tests are performed in true strain rate control. Constant tool speeds can be used as an alternative. In the latter case the nominal strain rate of the test is defined from the tool speed at the start of the test. Whichever method is used must be specified in the test report.

The machine should have a sufficient response rate to achieve adequate control of the test.

Ideally tests should be performed in true strain rate control. The use of test machines with constant tool speeds introduces an additional uncertainty due to the variation of strain rate with applied strain. For example, in a test at a tool speed of 0.1 m s^{-1} on a 10 mm long testpiece the strain rate varies from 10 s^{-1} to 15 s^{-1} as the testpiece length reduces from 10 to 6 mm (ie deformation to a true strain of about 0.5). For this reason the test report requires a plot of strain rate vs true strain irrespective of the mode of control.

In examining machine performance in strain rate control the position of the measurement device must be considered and noted in the report. The optimum method is direct measurement across the platens/tools. Other options include the stroke transducer or diametral transducer. If a stroke transducer is used machine compliance must be measured and corrected. Diametral transducers can give misleading data if there is non-uniform ovality following deformation.

6.3 Load Measurement and Calibration

The force measurement system shall be verified at intervals not exceeding one year. Calibration should be carried out in accordance with BS EN ISO 7500-1 'Metallic materials—Verification of static uniaxial testing machines - Part 1: Tension/ Compression Testing Machines'

For high rate testing consideration may need to be given to the dynamic response of the load cell (and extensometer); this has been covered elsewhere, [Dixon, 1995 and Albright, 1995]. For conventional load cells it was shown that for frequencies less than ~20 Hz, i.e. (compression tests lasting more than ~50 ms, and strain rates less than about 10 s^{-1} on testpieces initially about 15 mm in height), the error introduced by using a static load calibration would be less than ~1%. For faster tests, dynamic load calibration should be considered [Dixon, 1995].

6.3.1 Dynamic Calibration

For higher rate tests it can be argued that it is more appropriate to calibrate the force measurement system dynamically at rates comparable to those used during testing. However, at present there is no standard in place for this process although considerable background research has been conducted in the topic of fatigue testing and a new British Standard

BS 7935-1:2000 "Method for Constant Amplitude Dynamic Force Calibration – Part 1: Calibration of non-resonant uniaxial dynamic testing systems" is shortly to be published even though it refers to another document BS 7935-2 "Static and Dynamic Calibration of Force Proving Devices" that has not yet been drafted. Also there is no infrastructure for traceable measurements back to the NPL primary system.

A separate NPL Measurement Note that includes comment on traceability issues has been written – High Temperature Flow Stress Measurements: Quality and Traceability Issues (Loveday 2002).

6.3.2 Load Cell Ringing

At higher rates of test it is possible for the test frame and testpiece to vibrate and the transducers attached to the machine to measure load and displacement frequently register their vibration superimposed on the true signal. This is called ringing. An example of ringing in the load signal is shown in Figure 4.

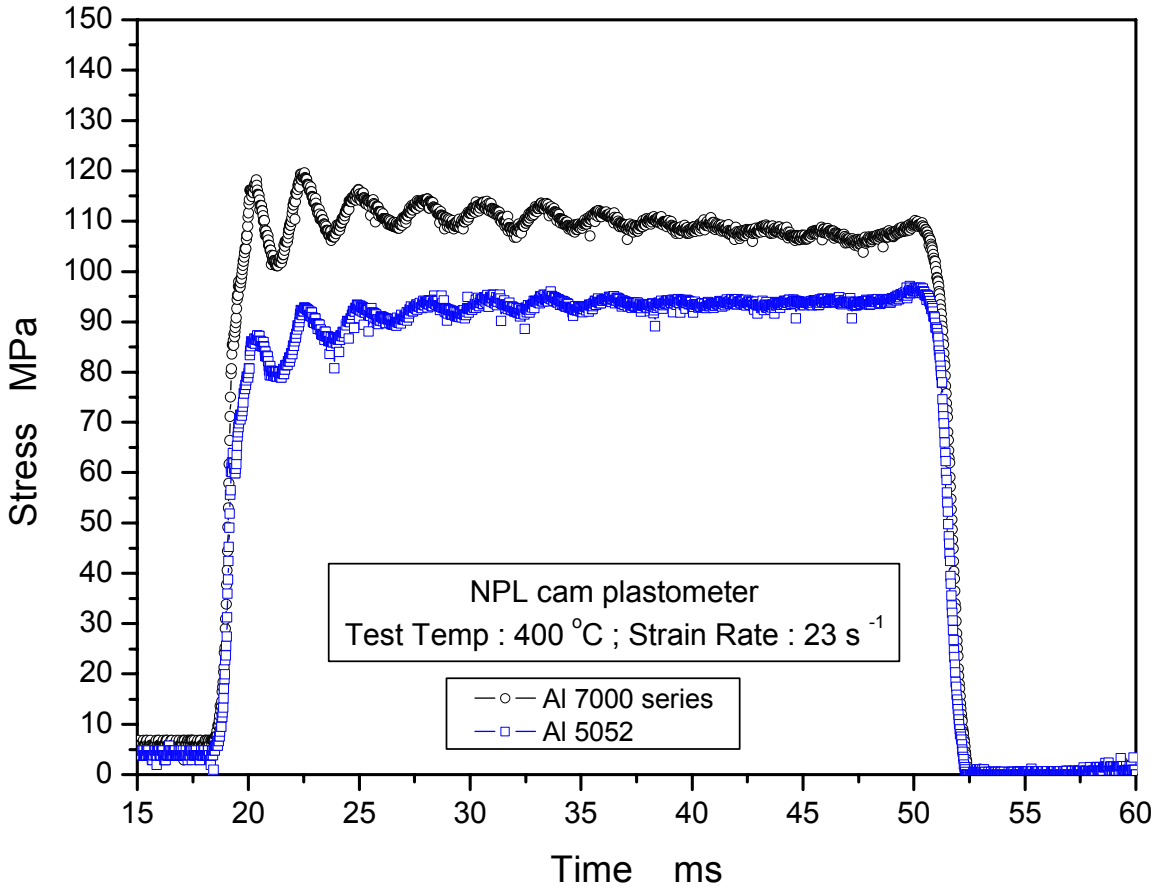


Figure 4 Load cell ringing.

Systematic tests were conducted to examine this effect and a software tool was developed for analysing the time dependence of the transducer signals and thus providing a means to correct the data.

A separate Measurement Note has been written to summarise the ringing experiments and describe the software tool, Load Cell Ringing in High Rate Compression Tests (Roebuck et al, 2002).

6.4 Platens

An important aspect of the test system is the use of platens which are strong enough to sustain the loads required for hot deformation and which will not react with the testpiece and lubrication at the test temperature. Platens should have a fine ground surface.

Some recommended platen materials are listed in a separate Measurement Note (Lord and Loveday (2001)).

6.5 Displacement Measurement and Calibration

Strain measurement systems should be calibrated at intervals not exceeding one year, to BS EN 10002-4 (1995), class 0.5 or better. However, for most practical hot compression tests test machine crosshead/tool displacements are used. These should be corrected for machine compliance effects (section 7.6.1).

Issues of dynamic calibration are commented on in a separate Measurement Note on Quality and Traceability Issues (Loveday 2001).

6.5.1 Longitudinal Strain

For most purposes, crosshead/tool displacement is used to measure longitudinal strain, generally via an LVDT dial gauge or other transducer attached to the crosshead or platens. The LVDT must be calibrated and verified at intervals not exceeding one year, traceable to National Standards. Corrections for machine stiffness should be made in accordance with the procedure in section 7.6.1.

6.5.2 Diametral Strain

Diametral clip gauges, LVDTs or linescan cameras can be used to measure diametral strain during the test. They should be positioned at the mid-point of testpiece height. The choice of instrument is determined by their response time and the strain rate of interest.

Clip gauges should be calibrated to BS EN 10002-4 (1995) as described above and should have a fast response to capture the strain data.

It is not necessary to correct for machine compliance when diametral strain is being measured.

The location of the system should be included in the test report.

6.6 Temperature Measurements, Control and Calibration

6.6.1 General

The uniformity of temperature along the testpiece should be checked before every series of tests that introduces major changes to the test system geometries or new platen types and lubricants, and also at regular intervals not exceeding 1 year. In addition, a verification should be carried out when any part of the temperature measuring system has been submitted to major repairs or adjustments.

When using embedded thermocouples it is important to ensure that the system is earthed and that thermocouple poles at the recording device are floating. Also when induction or resistance heating methods are used the existence of stray induced and rectified voltages can normally be detected by examining the behaviour of the thermocouple voltage when the heating current is switched on or off.

Thermocouple tolerances should be agreed with the manufacturer and user. During compression testing, the pressure of mechanical stress may cause variation in the thermocouple characteristics. The accuracy of thermocouples can be affected by radio interference from induction coils. It is recommended therefore that they are not used as the only measurement system when induction heaters are used, and perhaps should be cross-referenced to pyrometry measurements or embedded thermocouples calibrated separately.

The BSI Thermocouple Reference Tables should be consulted for converting thermocouple voltages to their measured temperatures. The tables are based on IPTS-68 (Int. Practical Temp. Scale of 1968) in accordance with BS 4937: Pt.2: 1973. The thermocouples should have a resolution of at least 1 ^{o}C and an accuracy of $\pm$ 2 ^{o}C. They must be verified at intervals not exceeding one year over the complete working temperature range, traceable to National Standards by a documented method (BS 1041. Part 4: 1992). The thermocouple must be calibrated in accordance with BS 1041 Part 4: 1992 (pages 18-19). Two chapters (six – A R Colclough and seven – M P E Desvaux) in "Measurement of High Temperature Mechanical Properties of Materials" [Loveday et al, 1982] provide useful background reading.

There is a need to recommend tolerances for acceptable temperature gradients within the test system and for the temperature of test. The variation in indicated temperature from point to

point within the testpiece and the deviation from the specified test temperature should not exceed the values given in Table 1. Additional modelling work at the IRC in Computer Aided Engineering, University of Wales, Swansea, (see Appendix C) has allowed Table 1 to be constructed based on an uncertainty of about ± 2% in the flow stress. Table 1 provides values for the allowable precision and spread of temperature within a testpiece required to achieve this level of uncertainty.

Table 1 – Initial Temperature Tolerances*, ^{o}C

Test temperature, T	Temperature variation^{+}, ^{o}C	Precision^{++}
T < 600	± 2	± 2
900 > T > 600	± 4	± 3
T > 900	± 6	± 4

$^{+}$ Variation is defined as the difference between the measured temperature of the test (usually at the centre) and the mean temperature of the testpiece (obtained through calibration measurements of typical temperature variations).

$^{++}$ Precision refers to the nominal uncertainty of the temperature measurement on the testpiece associated with the indicating sensor (thermocouple, pyrometer, etc) including errors from all sources, nominally at the 95% confidence level.

* The term "initial tolerance" has been used since at very high strain rates inherent deformational heating may cause the temperature to deviate outside the specified tolerances during the test (see Appendix C).

6.6.2 Mean Temperature of Testpiece

In general, testpieces usually have only one thermocouple attached. It is therefore necessary to validate the testpiece temperature distribution using a testpiece instrumented with an array of thermocouples as recommended below.

6.6.3 Time Dependent Temperature

Rapid deformation of the testpiece can cause the testpiece temperature to rise. The magnitude of the temperature rise will depend upon the material being tested and its associated thermal properties, the thermal properties of the platens and the rate of deformation of the testpiece. Preliminary measurements with fully instrumented testpieces may be necessary to determine the magnitude of this effect

This can be done by using a number of thermocouples at different positions inserted or attached in the testpiece (along its length) and at the platens. Subsequent tests can then be controlled using the furnace temperature provided that regular checks are made to ensure the calibration persists. Alternatively a system can be installed which uses contact thermocouples to the testpiece or thermocouples permanently in place within or close to the

deformation platens. Large errors can be introduced if thermocouples are not in intimate contact with the testpiece and platens. See Appendix C.

6.6.4 Furnaces

It is necessary to calibrate the test system so that the furnace and temperature profiles are known. This must be done at regular intervals not exceeding 100 tests or if a series of tests introduces new testpiece geometries, new platen types or new lubricants.

This can be done by using a number of thermocouples at different positions in the furnace, in contact with the testpiece (along its length) and at the platens. Subsequent tests can then be controlled using the furnace temperature provided that regular checks are made to ensure the calibration persists. Alternatively a system can be installed which uses contact thermocouples to the testpiece or thermocouples permanently in place within or close to the deformation platens. Large errors can be introduced if thermocouples are not in intimate contact with the testpiece and platens.

6.6.5 Direct Heating

For direct heating methods (using electrical resistance) it is necessary to have contact thermocouples in place for each test or to use pyrometry. Pyrometric measurements should be treated with care. Accurate values for the emissivity of the testpiece and for platens must be known and readings can be affected by background radiation. Again, calibration experiments should be performed to establish the variation of temperature along the testpiece height, because this is inevitable with resistance heating methods. It is an additional source of uncertainty. The frequency of calibration should be the same as that described in 6.5.1 for furnaces.

For direct heating the use of surface thermocouples can possibly lead to significant inaccuracies if it is assumed that this represents the bulk temperature. Some form of calibration for radial temperature may be required.

6.7 Data Recording

A system capable of collecting and storing data should be used. The frequency of the system should be such that finite changes in load, cross head velocity and displacement with time can be measured, with at least 10 data points for each interval of 0.1 true strain. For a typical test at a strain rate of $1s^{-1}$, this means a sampling rate of 100 Hz.

7 Testing Procedure

The procedure for conducting hot, axisymmetric, isothermal uniaxial compression tests contains a number of basic steps.

1. Manufacture testpiece to chosen geometry.
   Decide on testpiece numbers for each test parameter.

2. Calibrate test system for load, displacement and temperature.

3. Install testpiece in system.
   Heating profile, lubrication.

4. Deform testpiece at specified temperature and strain rate.
   Measure changes in load and displacement.

5. Remove testpiece from system, quench or slow cool in an agreed predetermined manner.

6. Analyse and report data.

These guidelines provide a methodology to address these basic elements.

7.1 Testpiece Manufacture

Calculate the approximate maximum stress required to deform the chosen testpiece size, if necessary from a series of preliminary exploratory tests. Choose a testpiece geometry which will ensure that the load capacity of the test machine is adequate to maintain sufficient force at the required strain rate **to the maximum value of applied strain of the test**. Manufacture sufficient testpieces for the required study to the guidelines in Section 5.

Plating, although sometimes costly, can be beneficial in minimising surface oxidation prior to the test. The plating must be crack free, hard chromium plating in accordance with BS 4641.

7.2 System Calibration

The test system must be calibrated regularly for load, displacement and temperature, including documentation of the calibration procedure as described in section 6. If equipment is moved or damaged and repaired it must be recalibrated before re-use.

7.3 Testpiece Installation

Ensure machine anvils (platens) are clean and flat.

It is necessary to examine platens frequently to ensure no serious damage has developed on their surfaces. Remachine at regular intervals if necessary. It is good practice to have a number of sets of interchangable platens available so that clean platens can be used regularly.

Alignment of the platens should be checked at intervals not exceeding 100 tests. Alignment can be checked by using a suitable strain gauged compression cylinder (following the procedure described in prEN 3988:1995 - Test Methods for Metallic Materials. Constant Amplitude Strain-Controlled Low Cycle Fatigue Testing (ASTM E1012)), or by a dial gauge indicator. The platens should be parallel to within ± 0.2^{o}.

Include details of the heating profile to the temperature of the test and the dwell at temperature prior to the test in test report.

Because the test requires the testpiece to be heated to the temperature of test, including a period at temperature before the deformation process, it is necessary to understand how the microstructure of the testpiece changes with heating profile so that significant changes are minimised in, for example, grain size during the heating profile of the test prior to deformation. For steels it is also necessary to define the heating profile to the temperature of test since the heating rate through the transformation temperature may have an effect on the size of microstructural features.

Heat the testpiece to the test temperature as quickly as possible, either by installation directly into a hot furnace or by applying a temperature ramp. Record details of the heating rate. Hold at test temperature for a specified time before applying deformation loads.

7.3.1 Lubrication

Position the testpiece on the platens using appropriate lubrication and position thermocouples. **Unlubricated tests are not recommended.**

Lubricant can be applied directly to the platens or by coating the testpiece prior to testing.

7.4 Deformation

Apply a deformation load at the test temperature and strain rate to ensure that the final value of the true strain required by the test is achieved.

Measure the load and store the data at true strain intervals of 0.01 or less.

Measure the displacement or diameter and store the data at true strain intervals of 0.01 or less.

Measure the testpiece or nominal temperature and record the value, including observed tolerances (see Table 1).

Record the velocity of the crosshead throughout the test.

7.5 Testpiece Removal

For some tests it is necessary to measure changes in the test material microstructure after different amounts of deformation. It is thus necessary to quench-in the structure following the test.

For parallel studies of microstructural evolution.

- Remove the testpiece from the system and either quench or air cool if a furnace is used for the heating source. Record the method of cooling and a value for the cooling rate in the test report.
- If a resistance method is used, turn off the heating current. Record the method of cooling and a value for the cooling rate.
- If the cooling rate cannot be measured, specify the type of cooling used, for example, air, furnace or water quench.
- Report elapsed time between end of test and start of cooling process.

8 Analysis of Results

8.1 General

Document the results in a suitable test report. An example is given in Section 9 and Appendix B.

The results can be stored in tables in a documented report or as a computer file. If the latter method is used the file name must be documented in the test report.

Calculate the mean pressure (P) and the true strain (ε) values from the variation of applied load and displacement

$$P = \frac{4F}{\pi d^2} \tag{11}$$

$$\varepsilon = \ln(h / h_o) \quad \text{or} \quad = \ln(A / A_o) \tag{12}$$

8.2 Friction Corrections

An equation for applying corrections for friction is available, Dieter (1989), but a value for μ is needed. For example,

$$P = R \left[\frac{h}{\mu d}\right]^2 \left[\exp\left[\frac{\mu d}{h}\right] - \frac{\mu d}{h} - 1\right] \tag{13}$$

For low μ this can be simplified by expanding the exponential term:

$$P = R \left[1 + \frac{\mu d}{3h}\right] \tag{14}$$

A plot of the ratio of mean pressure/uniaxial stress (F/R) for different values of μ for both the full and simplified formulae is shown below for a compression testpiece deformed from an initial h/d_o of 1.5 to a true strain of about 0.5. Instantaneous values of h/d through the deformation test should be used to calculate the mean pressure/uniaxial stress ratio.

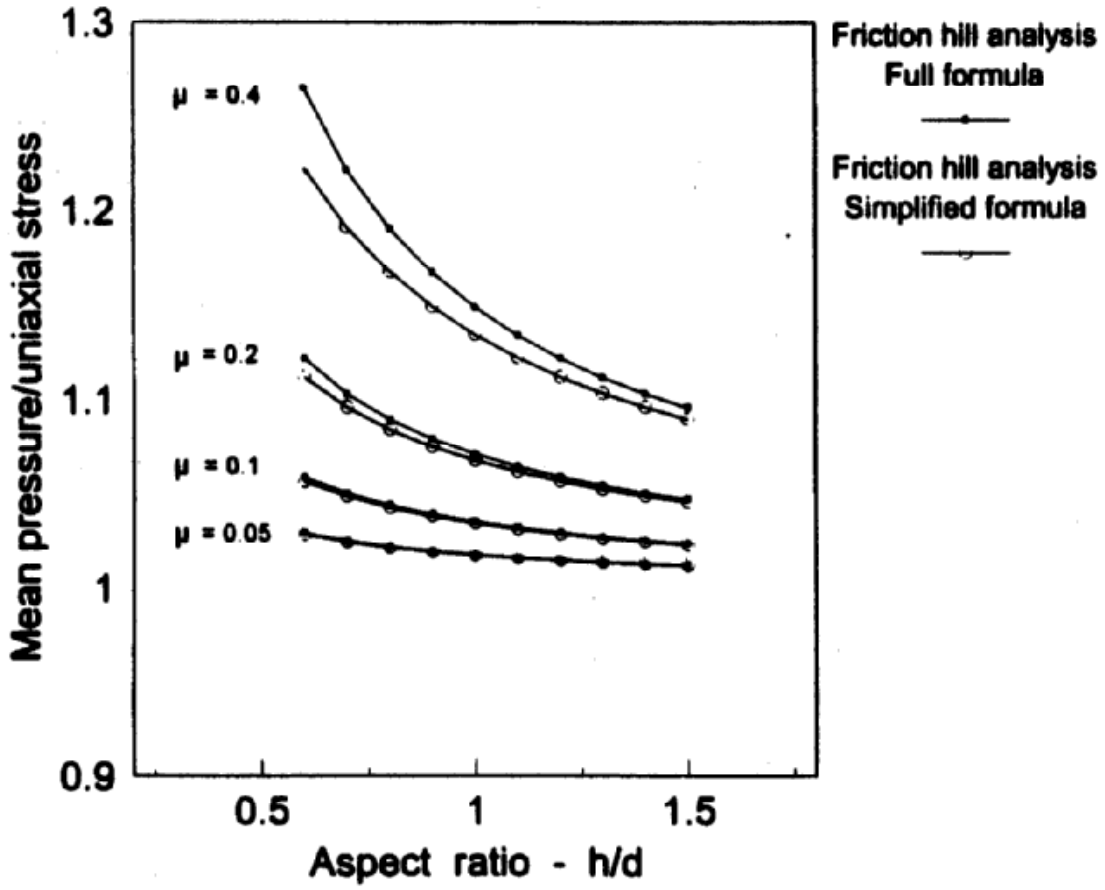


Figure 5 Mean pressure/uniaxial stress ratios.
Effect of friction on correction factors for calculating uniaxial stress data for different values of the coefficient of friction, μ, Dieter (1989).

8.3 Corrections for Test Machine Compliance

Measure the compliance (the slope of the displacement/load curve) of the test machine/platen setup at the temperature of the tests. Use this figure to correct the displacement measurements in subsequent deformation tests. Lengthwise strain measurement between the platens is the preferred method. Care must be taken to ensure the calibration of the measurement device is not affected by temperature.

If diametral measurements of strain are made it is not necessary to make this correction.

Conduct the compliance calibration with the top and bottom platens in direct contact at the temperature of interest. Load to a value equivalent to the maximum load to be expected in tests in the material/testpiece at the temperature of interest, unload and repeat to confirm validity of data. Displacement readings give a direct measure of compliance as a function of load.

8.4 Deformational Heating

At high strain rates the testpiece temperature increases by an amount which is dependent on the material of interest, the applied strain rate, deformation temperature and the materials work hardening characteristics. It is necessary to know when and how to correct for this effect. For example, at strain rates less than 0.2 s^{-1} for aluminium alloys a correction may not be necessary, but for steels at strain rates greater than 1 s^{-1} a correction should probably be applied.

If it is assumed that adiabatic conditions apply then a guide to the potential magnitude of the temperature rise is obtained from the load displacement curve (converted to equivalent pressure, p and equivalent strain ε). Thus, the mean temperature rise ΔT is given by

$$\Delta T = \int_0^{\epsilon} p d\varepsilon / C_p \rho \qquad (15)$$

where C_p and ρ are the specific heat and density respectively. Temperature rises of 30-40 ^oC are easily achievable for typical ferrous and non-ferrous alloys.

Further background information is given in Appendix C.

8.5 Repeatability Determination

If possible test two testpieces, taken from adjacent positions in the original material stock, for each condition to confirm repeatability.

Strictly, to ensure repeatability at least two testpieces for each condition of test should be tested. If the flow stresses from these first two tests, measured at applied true strains of 0.1 and 0.3, differ by more than 5% then a further test on an additional testpiece should be conducted.

In practice it is often too expensive to manufacture sufficient testpieces to meet this repeatability requirement. There are two possible practical approaches, therefore, to assist in ensuring consistency of testing.

(a) to use a reference material with known stress/strain characteristics, if possible similar in composition to the material to be tested, and to test this material before each new set of tests

(b) to complete a set of tests at different strain rates and temperatures and check for consistency through, for example, examination of the Zener Hollomon parameter or a fit to specified constitutive relations.

8.6 Test Validity Shape Determination

8.6.1 Uniform Shapes

The geometry of the testpiece should be measured following deformation to ensure that excessive barrelling has not occurred and that the deformation is uniform across the testpiece. In order that the test is declared valid, there must be uniformity of deformation, defined by quantifiable parameters and barrelling should be minimised. The extent of barrelling is a complex function of testpiece geometry and friction and cannot therefore be used as a means of estimating friction factors. However, if the recommended testpiece geometry is used (D_R = 1.50), and if B is measured to be greater than 1.10 it is likely that friction was high and the test results are to be considered invalid. For other testpiece geometries then Appendix D should be consulted. The barrelling coefficient is obtained from measurements of the diameter of the testpiece following deformation (Section 4.12).

For standard testpieces (D_R = 1.50) measure the barrelling coefficient, B (Appendix A). If it is greater than 1.10 then the test is invalid. For other geometry testpieces see Appendix D.

Measure the height coefficient, H. If it is equal to or greater than 0.04 then the test is invalid.

Following deformation the height of the testpiece should be measured at the centre and at three points on the circumference separated by 120^o. The average of these four measurements is the value for h_f. For the test to be valid the ratio of the standard deviation of the four measurements divided by the average should be less than 0.04.

8.6.2 Non Uniform Shapes

Measure the ovality coefficient, O_v, and report.

Measure the shear coefficient, S, and report. If it is greater than 0.175 then the test is invalid.

8.7 Data Presentation

Record plots of true stress, strain rate and temperature vs strain. Tabulate the maximum value of flow stress and at least two, specified values of applied true strain.

The measurement requirement is for data on the variation of uniaxial stress with applied true strain at constant strain rate and constant temperature. The results can be presented as a table of stress and true strain values obtained at specified values of applied strain or a graph of true stress against true strain. The results can be fitted to a constitutive equation if required, but if so the equation and method of fitting should be included in the report.

8.8 Assessment of Uncertainties

In 1994 an important new document was issued: 'Guide to the expression of uncertainty in measurement', published jointly by several authoritative standards bodies, namely BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML which is referred to here as the TAG4 Guide, after the ISO Technical Advisory Group 4 which drafted the document. It is a comprehensive document of over 90 pages based upon rigorous statistical methods for the summation of uncertainties from various sources. Its complexity has provided the driving force for a number of organisations to produce simplified versions of the TAG4 Guide, eg the National Institute of Science and Technology (NIST) in the USA, the National Measurement Accreditation Service (NAMAS) in the UK and the British Measurement and Testing Association, also in the UK. These various documents all give guidance of how to estimate uncertainty of measurement based upon an 'uncertainty budget' concept. A case study illustrating the estimation of uncertainty in creep testing, based upon the concepts given in the TAG4 Guide, is described in a paper by M S Loveday (1996).

The total uncertainty of a measurement is determined by summing all the contributing components in an appropriate manner. All the contributions must be quantified. At a preliminary evaluation stage a decision must be made as to whether some contributions are negligible and can be excluded from subsequent calculations. For most practical measurements in the materials field the definition of negligible may be taken as a component smaller than one-fifth of the largest component.

The TAG4 Guide categorises two types of method for evaluating the uncertainties, A and B. Method A determines uncertainties from repeat observations and provided sufficient readings are available, conventional statistical analysis can be used to determine the standard deviation S. Method B uses alternative means, eg tolerances specified in standards, measured data, manufacturers specifications, calibration certificates, and from some basic knowledge of a simple model of the relationship between the various components. A combined uncertainty is then derived from estimates of A and B.

8.8.1 Uncertainty Calculation

The hyperbolic sine expression that relates stress to strain rate and temperature can be analysed to give an indication of fractional uncertainties in flow stress due to fractional uncertainties in strain rate and temperature.

$$A[\sinh(\alpha\sigma)]^n = \dot{\varepsilon} \exp[Q/RT] = Z \text{ (Zener-Hollomon parameter)} \quad (15)$$

Evaluation of the hyperbolic sine expression for the dependence of flow stress on strain rate and temperature requires values for four constants, α, Q, n and A, for the materials being tested. Where possible, values for these constants have been extracted from published work [Roebuck and Brooks (1998)] for evaluation of the differential forms of the hyperbolic sine expression, since from expression (15)

$$\frac{d\sigma}{dT} = \frac{-Q}{\alpha n T^2 R}\tanh(\alpha\sigma) \quad \text{and} \quad \frac{d\sigma}{d\dot{\varepsilon}} = \frac{1}{\alpha n \dot{\varepsilon}}\tanh(\alpha\sigma) \quad (16)$$

Fractional changes in flow stress ($d\sigma/\sigma$) can thus be evaluated as a function of the fractional change in temperature or strain rate (dT/T) or ($d\dot{\varepsilon}/\dot{\varepsilon}$). If values for the constants in the hyperbolic sine relation between σ, $\dot{\varepsilon}$ and T [expression (15)] are known then uncertainties in flow stress can be estimated from uncertainties in temperature and strain rate.

$$\frac{d\sigma}{\sigma} = \frac{dT}{T}\frac{-Q}{nRT}\frac{\tanh(\alpha\sigma)}{\sigma} \quad \text{and} \quad \frac{d\sigma}{\sigma} = \frac{d\dot{\varepsilon}}{\dot{\varepsilon}}\frac{1}{n}\frac{\tanh(\alpha\sigma)}{\sigma} \quad (17)$$

Some typical results for an aluminium and a ferrous alloy are given in Figure 6.

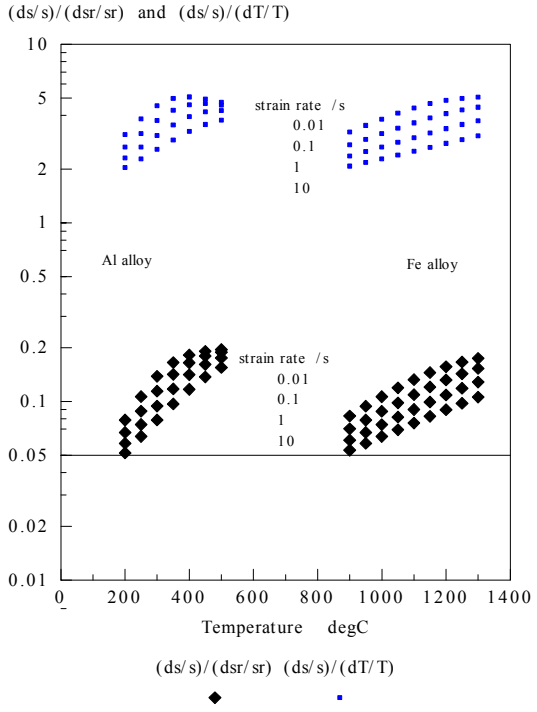


Figure 6 Temperature dependence of the fractional change in stress (ds/s) normalised by fractional change in strain rate (dsr/sr) or temperature (dT/T) for typical Al and Fe alloys for four strain rates (0.01-10 s^{-1}).

9 Test Report

It is recommended that the proforma given in APPENDIX B is used for the test report and shall contain at least the following information:

- Reference to this procedure
- Material type and condition
- Identification of the testpiece
- Location and direction of sampling of testpieces
- Type of testpiece (Aspect ratio, especially if not equal to 1.5)
- Preheating temperature profile
- Temperature and strain rate history of test
- Lubricant and platen materials
- Platen temperatures
- Results in tabular or computer file format, and graphs when required
- Validity assessment.

10 References and Other Related Procedural Documents

10.1 Papers

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Roebuck, B and Brooks, M. Flow Stress Measurements for Machining Modelling. NPL Report CMMT(A)123, July 1998.

Roebuck, B, Gee, M.G, Loveday, M.S. and Brooks, M. Load Cell Ringing in High Rate Compression Tests. NPL Measurement Note MATC(MN)18, May 2002.

10.2 Standards

BS EN 10002-2 Tensile Testing of Metallic Materials - Part 2: Verification of the force measuring system of the tensile testing machine.

BS EN 10002-4 Tensile Testing of Metallic Materials - Part 4: Verification of Extensometers used in uniaxial testing.

EN 150-3785 Designation of testpiece axes.

ASTM E1012 Metallic Materials - Constant Amplitude Strain-Controlled Low Cycle Fatigue Testing (pr EN 3988: 1995).

BS 1041 - 4: 1992 Temperature measurement.

EN 60584 - 1: 1993 Thermocouples - Part 1: Reference tables.

BS 1041 - 4: 1992 Guide to selection and use of thermocouples.

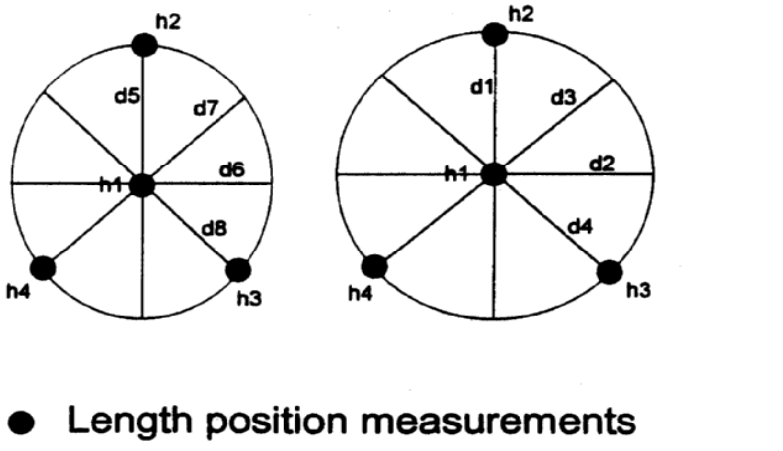
BS 1610 - 1: 1992 Materials testing machines and force verification equipment. Part 1: Specification for the grading of the forces applied by materials testing machines when used in the compression mode.

BS 7935-1: 2000 Method for Constant Amplitude Dynamic Force Calibration – Part 1: Calibration of non-resonant uniaxial dynamic testing systems.

Appendix A – Testpiece Geometries

Hot Uniaxial Axisymmetric Compression Tests
Test Geometry - Uniform Shapes

Testpiece and Material identification				
Dimensions	Diameter, mm		Height, mm	
Initial	d_1 d_2 d_3 d_4		h_1 (centre) h_2 (edge) h_3 (edge) h_4 (edge)	
Average	d_o		h_o	
Standard deviation	Sd_o		Sh_o	
Final	d_5 (d_{max}) d_6 (d_{min}) d_7 d_8		h_1 (centre) h_2 (edge) h_3 (edge) h_4 (edge)	
Average	d_f		h_f	
Standard deviation	Sd_f		Sh_f	



NB *Place testpieces on this grid to align maximum diameter with d, when calculating ovality and barrelling coefficients.*

Figure A1 Test geometries.

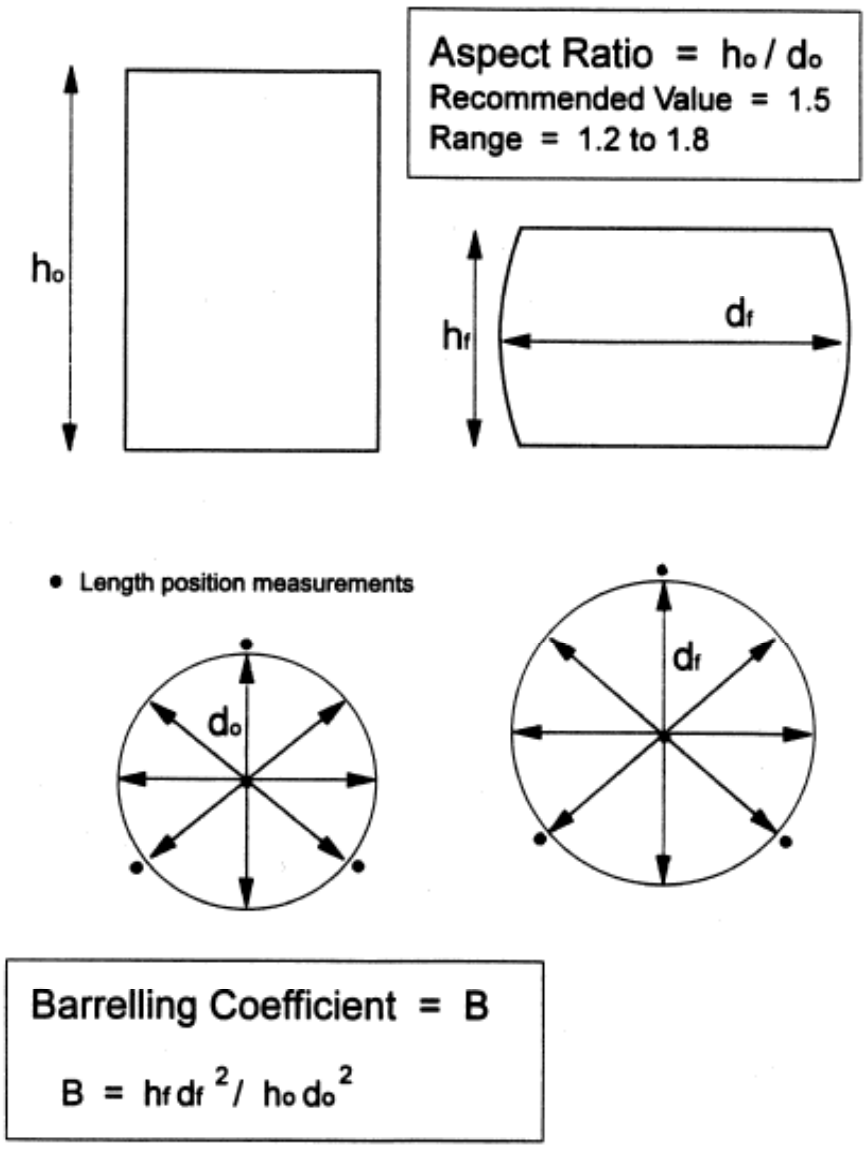


Figure A2 Axisymmetric compression geometries.

Appendix B – Reporting Proforma

Hot Uniaxial Axisymmetric Compression Tests

Test Report Number	
Computer File Number	

It is recommended that the test report is in tabular form as follows.

1. Material and testpiece information

Reference	Description		
Material	Source Identifier Composition Form Heat treatment		
Testpiece preparation	Orientation (relative) Method Geometry Aspect Ratio (D_R) Applicable standard(s)*	A*	
Testpiece information	Testpiece identification Testpiece height (initial), nominal Testpiece diameter (initial), nominal Cross-sectional area (initial), nominal Surface finish (comment on method of manufacture)		mm mm mm^2

A* refer to Measurement Good Practice Guide No 3 and others if appropriate.

2. Testing organisation

Organisation:- Name:- Date:-

3. Details of test procedure

Reference	Description	Value	Units/Notes
Test procedure	Type of test	Hot Axisymmetric Compression	
	Date of test		
	Applicable standard(s)*	A*	
	Test machine		
	Test environment		
	Temperature of test		^{o}C
	Heating rate to test temperature		^{o}C min^{-1}
	Time to test temperature before test		min
	Temperature variation (Table 1)		^{o}C
	Temperature uncertainty (Table 1)		^{o}C
	Platen material		
	Platen surface finish		
	Lubricant		
	Application Method		
	Cooling Method		
	Cooling Rate		^{o}C min^{-1}
	Elapsed time (end of test - cooling start)		min
	Alignment? - give details		
	Test control mode		
	Constant crosshead speed		
	True strain rate control		
	Rate of strain application		
	Nominal or true		s^{-1}
	Strain measurement method		
	- diametral (D)		
	- longitudinal (L)		
	Location of strain transducer		
	Displacement calibration method		
	Load calibration method		
	Temperature calibration method		
	Data collection method		
	- Sampling rate		
	Method of calculating results		
	- True stress		
	- True strain		

A* refer to Measurement Good Practice Guide No 3 and others if possible

4. Test Results

Reference	Description	Value	Units
Test results (individual values)	Maximum load Hot flow stress, R Maximum - at 0.1 true strain - at 0.3 true strain True strain - final value in test		N N mm^{-2} N mm^{-2} N mm^{-2}
Test validity	Initial height, h_o Final height, h_f Initial diameter, d_o Final diameter, d_f Height coefficient Ovality coefficient Barrelling coefficient Shear coefficient Validity - Yes or No		mm mm mm mm ≥ 0.04 is invalid - ≥ 1.10 is invalid ≥ 0.175 is invalid
Test results (full curves)	Record plots of: R vs ε $\dot{\varepsilon}$ vs ε T vs ε *at true strain intervals of at least 0.01*		

Appendix C: Temperature Measurement: Precision and Traceability

C.1 Introduction

Good temperature measurement and control are essential if reliable flow stress measurements are to be undertaken, and the results to be comparable with those measured elsewhere.

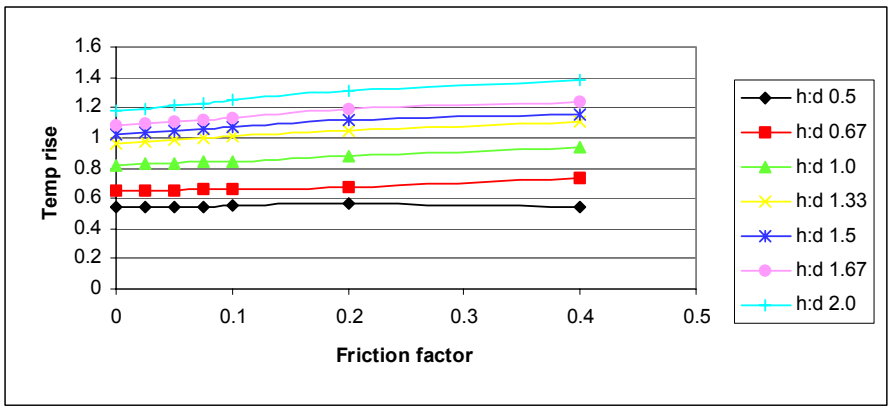
Attention must be paid to both the precision of the temperature measurement and the traceability to the National Measurement System (NMS). The following notes provide guidance as to how these objectives may be achieved.

C.2 Deformational Temperature Changes

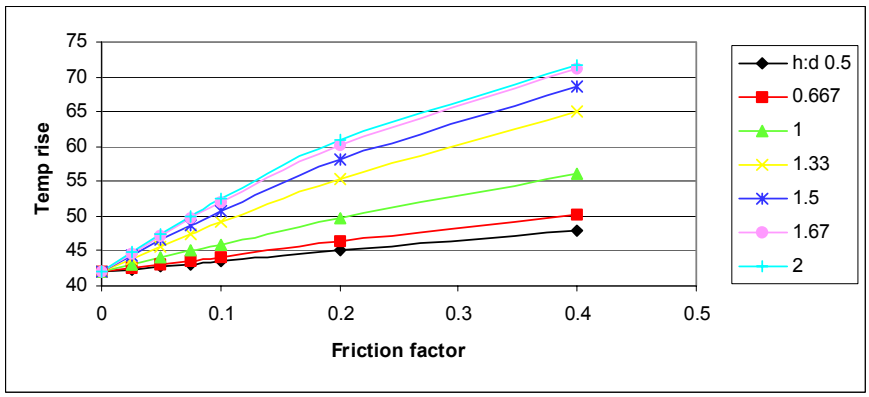
In the case of high strain rate testing, as encountered in hot compression tests, the temperature of the testpiece may rise during testing due to deformational heating. In practice it is rarely possible to provide adequate feedback control to compensate for this effect and maintain the testpiece at a uniform temperature. Thus, it is helpful to monitor the testpiece temperature throughout the test so that post testing analysis can be applied to compensate the flow stress measurements for temperature changes if required.

This effect has also been studied by FE analysis at the IRC in Computer Aided Engineering at University of Wales, Swansea using similar generic parameters for a Ni base alloy to those adopted for evaluating geometry (Appendix D) and temperature inhomogeneity (Appendix C6). Contour plots of temperature rise were generated for different test parameters and an example of temperature rise after a strain of 0.7 for different friction factors at different test strain rates and geometries is shown in Figure C.2.1. These correspond to the mean values of temperature within the testpiece. In practice temperature variations develop across the testpiece as can be seen in Figure C.2.2.

(a) Strain rate 0.01/sec



(b) Strain rate 10/sec



(c) Strain rate 1000/sec

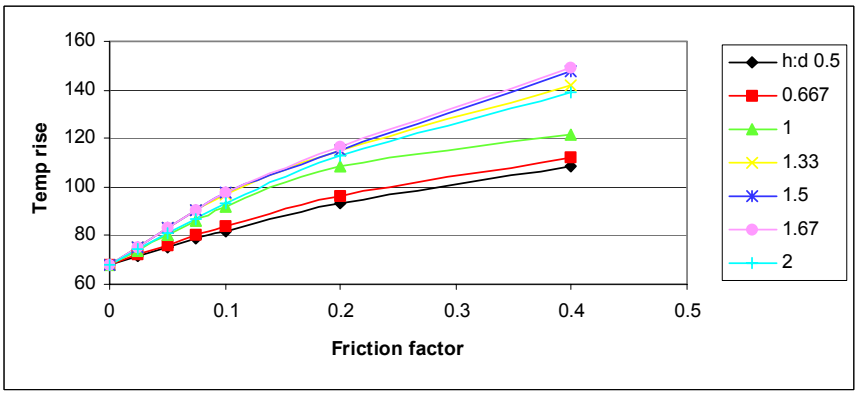


Figure C.2.1 Effect of friction factor on temperature rise for different testpiece geometries and strain rates.

10/s

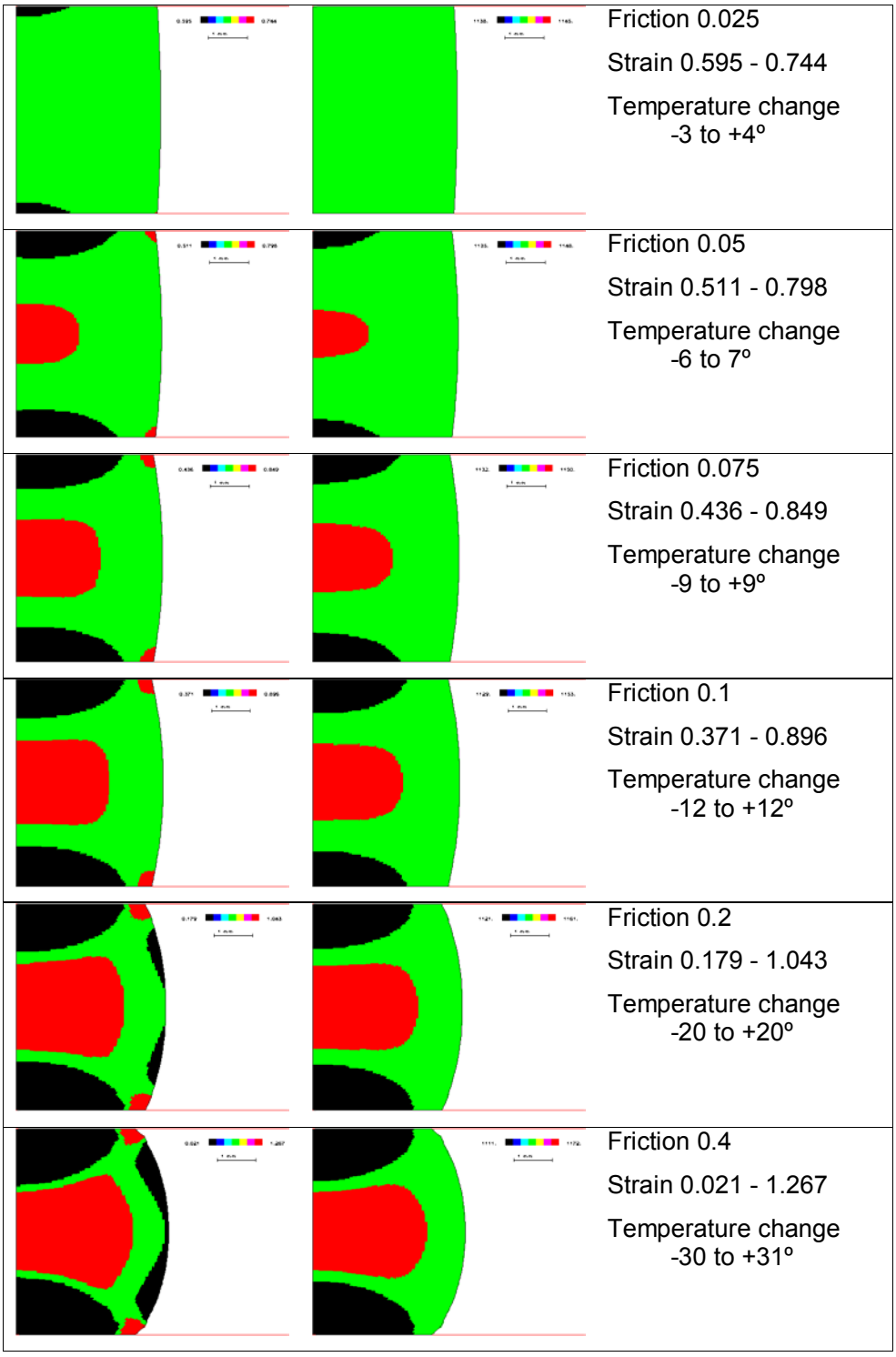


Figure C.2.2 Strain and temperature contours for h/d = 2 and strain rate of 10 s^{-1}

C.3 Traceability

In hot compression tests the temperature of the testpiece can be measured using thermocouple(s) rather than non contact temperature sensors. Depending upon the test temperature either base metal (Type K & N) or noble metal (Type R & S) may be used. Typically, a small hole, ~1.2 mm diameter is drilled into the testpiece and a 1 mm sheathed thermocouple inserted. It must be ensured that the thermocouple makes good contact with the testpiece and that it will not fall out when being manipulated. If the thermocouple is not in good contact, the thermal response is too slow. Although of course if the thermocouple is inserted in a hole, it is in a blackbody cavity and it will eventually record the correct temperature. Clearly, when the test is started, the testpiece deforms and eventually makes intimate contact with the thermocouple.

It is essential that the thermocouple and its recording system are fully calibrated and that traceability to the National Measurement System can be demonstrated. This may be achieved by comparison of the voltage output with that from a Certified Reference Thermocouple. Usually this is done in a separate calibration furnace, at a similar temperature to that to be used during testing. The calibration furnace should also have a similar depth of immersion to the furnace used in the testing machine. Further information concerning calibration of thermocouples is given elsewhere [Colclough & Robinson, 1982], Loveday [Creep Lab Manual].

A mobile calibration furnace, which can be positioned next to the testing machine is most useful. In this way the test thermocouples remain connected to their readout system and the entire temperature measurement system is thus verified. If the test thermocouples are disconnected from their readout system, then it is necessary to independently verify the readout system

C.4 Heating Systems

In general there are two types of heating systems used for hot compression testing, (a) heated furnaces, and (b) resistance (direct or induction) heating systems, e.g. Gleeble machines.

In the former type, the testpiece is heated in a furnace that surrounds the loading train. In this case the testpiece monitoring thermocouple must have sufficiently long trailing leads to accommodate the opening of the furnace. It helps to verify that the furnace has the capability of heating the testpiece uniformly to the desired temperature by using a special calibration testpiece which is instrumented with an array of thermocouples. As specified in Table 1, Section 6.6.1, the testpiece temperature should be within the specified tolerances at the start of the test.

In this situation it is necessary to independently verify that the upper and lower anvils in the loading train are also preheated to the test temperature, and that both anvils are at the same temperature. Because the upper and lower loading trains may not be identical they may have different heat loss characteristics. Thus it may be essential to have a means of independently controlling the temperature of the two parts of the loading train, e.g. a multi zone furnace may be necessary. Ideally, the upper and lower platens should incorporate independent temperature sensors. However, in the absence of such devices, it is necessary to demonstrate that the heat loss (or gain) to the upper and lower anvils from the testpiece are within specified tolerances. This can be demonstrated by using a special testpiece, instrumented with an array of thermocouples. Such a testpiece could either be a sandwich with a central thermal barrier (zirconia may be suitable) or a two layered testpiece which may be turned over to determine the heat loss to each anvil separately.

In the case of resistance heating of the testpiece, as undertaken in Gleeble machines, independent temperature control of the grips is not practical. However, it is still essential to demonstrate that the testpiece is heated uniformly within specified tolerances as indicated in Table 1, Section 6.6.1, at the start of the test. Good contact between the grips and both sides of the testpiece is essential if a uniform temperature is to be achieved. If the distribution in the testpiece is verified using a testpiece specially instrumented with an array of thermocouples, then it is essential that the surface finish and conditions (i.e. level of oxidation) are faithfully replicated when subsequently undertaking testing.

C.5 Periods Between Re-verifications

Thermocouples from a single batch, together with the readout system, should be re-verified at periods of not less than 1 year as specified in Section 6.8.1. If new batches of thermocouples (or wire) are employed, then it is recommended that a sample thermocouple, together with the readout system is calibrated before undertaking further testing.

If any repairs are undertaken to the heating system, or if grips are changed in the loading train, then it is recommended that the relevant parts of the system are rechecked with a specially instrumented testpiece before undertaking further tests.

C.6 Temperature Inhomogeneity

A finite element study has been undertaken (Evans and Scharning, 2002) to evaluate the uncertainties in flow stress arising from two types (I and II) of temperature distribution in a cylindrical testpiece. In Type I the temperature was varied linearly from top to centre and from bottom to centre with top and bottom temperature identical. The central temperature

was higher than top and bottom. In Type II the distribution was linearly varied from bottom to top with the central temperature at the mean value. Variations in other parameters such as geometry, friction and total strain were also studied but these effects had less significance than those arising from the allowed temperature variations.

Temperatures were expressed as scaled temperatures, B, to make the calculations consistent with the FE studies of geometrical effects. For example, B was set at 0.83 T_m where T_m is the solidus temperature of a Ni alloy. The temperature variation (spread) was defined by the parameter α (scaled in the same way). Thus the difference between top and centre is 2α in Type I and α in the Type II experiments.

Figures C.6.1 and C.6.2 show the additional relative error in stress for a specified error in scaled temperature for testpiece geometries of r_o/h_o = 0.25 (h_o/d_o = 1.0) Type I and II distributions respectively. The effects are linear and relatively insensitive to friction factor and strain for Type I and very small for Type II.

Thus for Type I temperature variation α has to be kept to a value of less than about 0.004 (equivalent to about $\pm 4\ ^oC$ at T < 700 ^oC and $\pm 6\ ^oC$ for T > 1000) to maintain a flow stress uncertainty of about 2%.

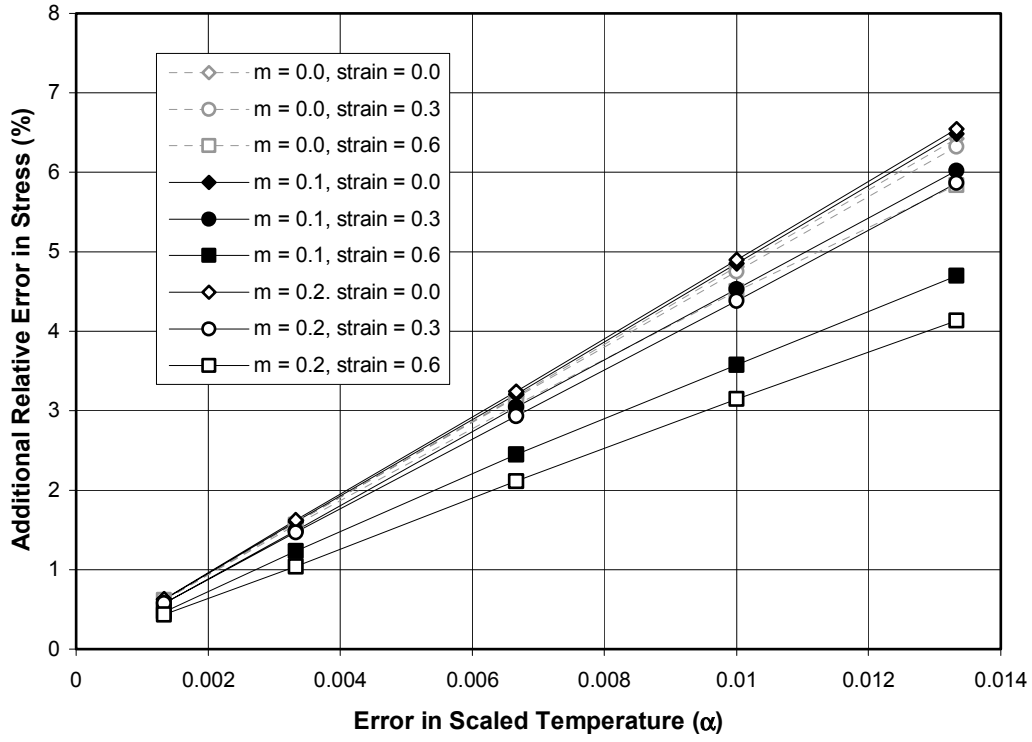


Figure C.6.1 *Variation in relative error in stress with temperature spread for Type I variation (r_o/h_o = 0.25, h_o/d_o = 2.0).*

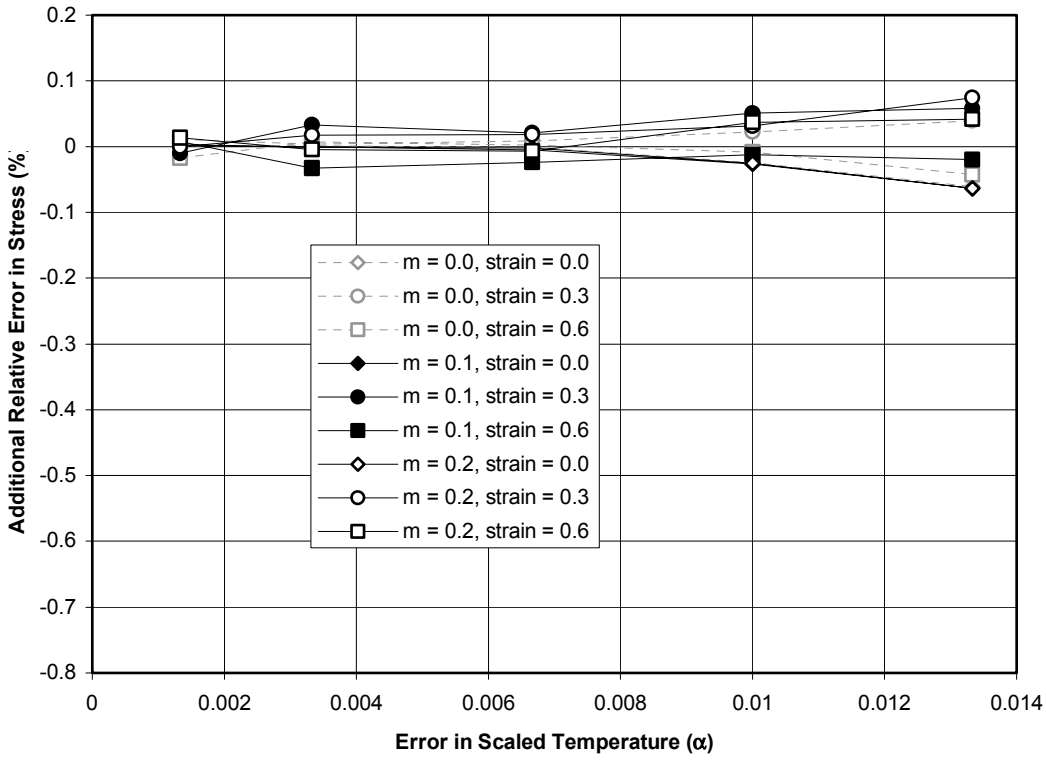


Figure C.6.2 *Variation in relative error in stress with temperature spread for Type II variation (r_o/h_o = 0.25, h_o/d_o = 2.0)*

An additional validation of these guidelines is provided by examining the typical change in flow stress with temperature on the hot working range of a number of representative materials. This is shown in Figure C.6.3. where stress uncertainty is calculated for the mid range of flow stress in the working temperature intervals given in Table C1 and percentage temperature difference is basd on the mid point of the working range. It can be seen in Figure C.6.3 that for a stress uncertainty of about 2% that the equivalent temperature difference is approximately 0.5-1% of the working range value.

Material	***Working range, ^oC***	***Mid range stress, MPa***
Al alloy 5082	*300-500*	*70*
C Mn steel	*900-1100*	*150*
Brass	*500-750*	*120*
Nimonic 901	*900-1100*	*250*
316 Stainless steel	*950-1050*	*200*

Table C1 Stress uncertainty calculation

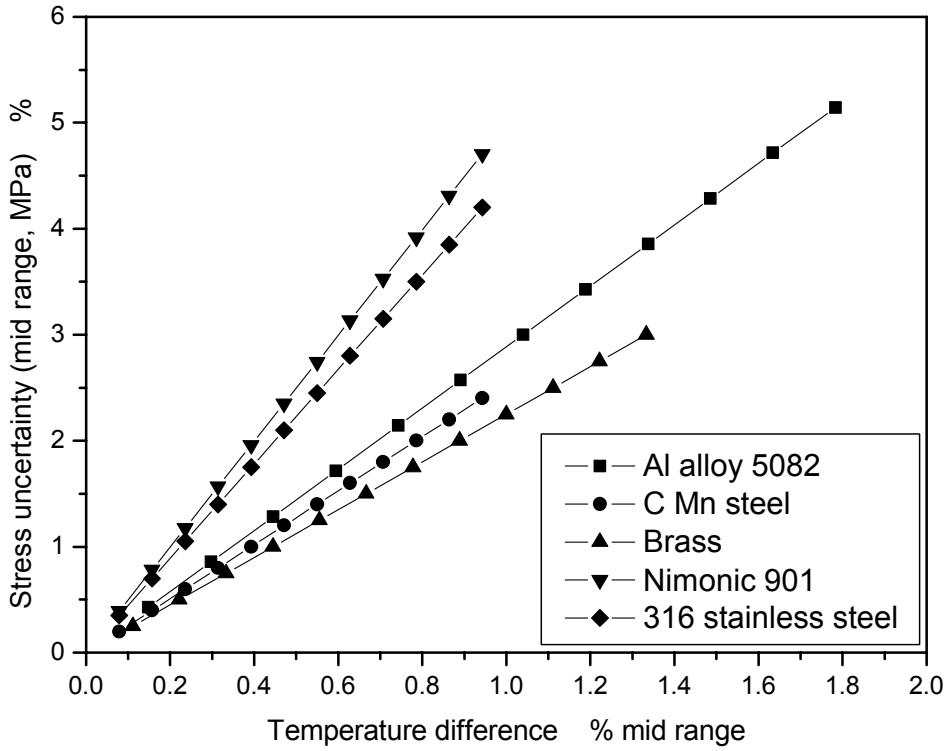


Figure C.6.3 *Stress uncertainty as a function of difference in temperature (normalised values)*

Appendix D : Finite Element Modelling – Geometrical Factors

D.1 Introduction

A finite element model was used to investigate various hot axisymmetric compression testing parameters, in particular the effects of friction and height to diameter ratio on the measured values of flow stress (Evans and Scharning, 2001).

The objective was to quantify the uncertainties associated with a variation in these parameters assuming the following constitutive relation between equivalent stress, $\bar{\sigma}$, and equivalent strain rate, $\dot{\bar{\varepsilon}}$:

$$A\left[\sinh\left(\alpha\bar{\sigma}\right)\right]^{n} = \dot{\bar{\varepsilon}}\exp\left[Q/RT\right] \qquad \text{(D1)}$$

with the following values for the coefficients used in preliminary evaluation trials.

$$A = 0.56\times10^{16}\ ; \qquad Q = 392289\ \text{kJ mole}^{-1}$$
$$n = 6.06\ ; \qquad \alpha = 0.00341\ \text{MPa}^{-1}$$

In later more detailed studies a wide ranging series of properties for a variety of engineering materials were used (Evans and Scharning, 2001). The Lagrangian finite element programme was mechanically and thermally coupled and used isoparametric eight-noded quadrilateral elements.

Typical outputs from the preliminary trials are shown in Figs D1-D3. Figs D1 and D2 show the effects of h/d for two different friction conditions compared with the theoretical behaviour and Figure D3 illustrates the difference between a test carried out under conditions of constant velocity compared with a test performed under constant strain rate. The effects of h_o/d_o and friction are summarised in a contour plot in Figure D4.

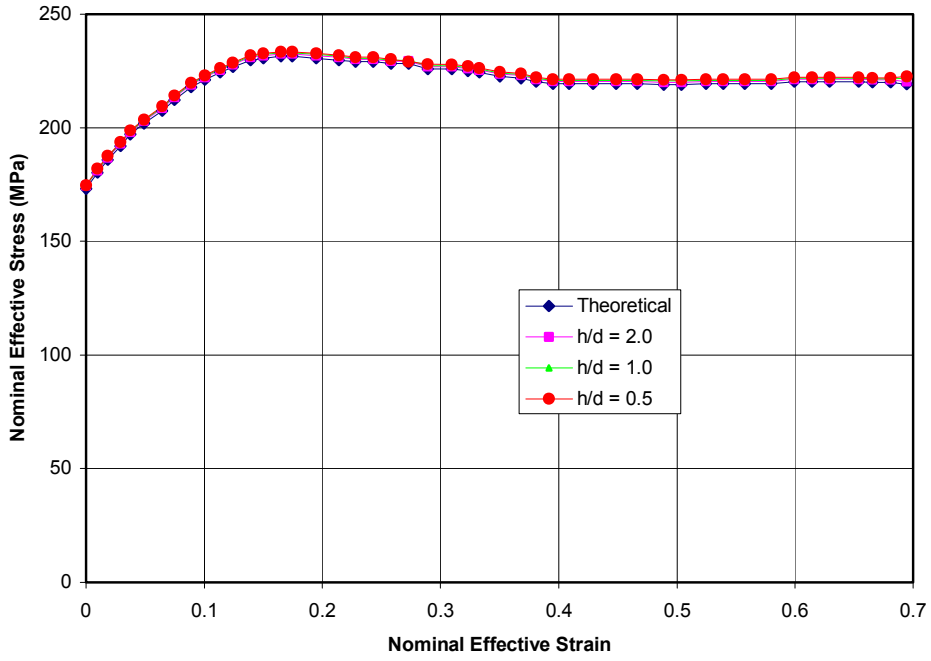


Figure D1 Effect of various h_o/d_o at a friction parameter of zero.

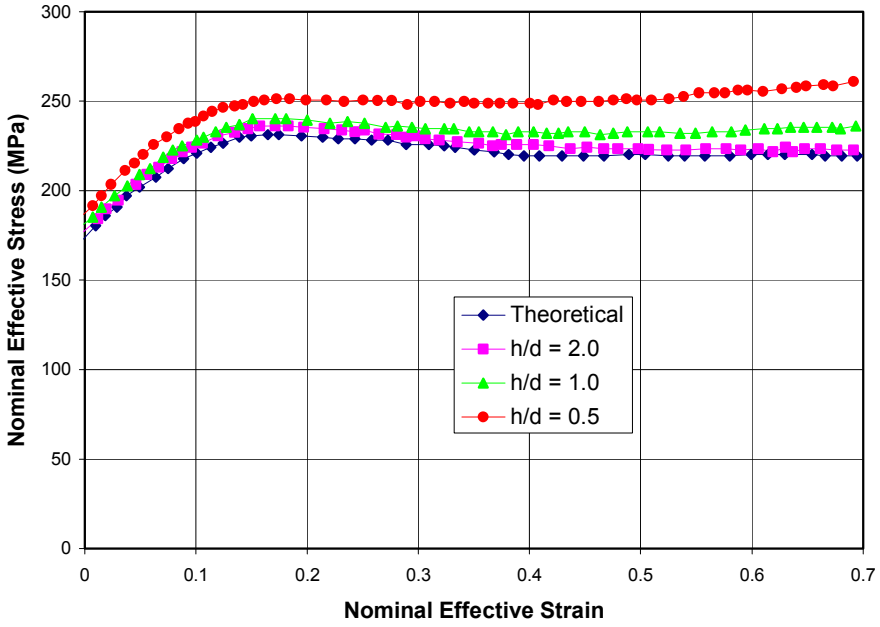


Figure D2 Effect of various h_o/d_o with a friction parameter of 0.2.

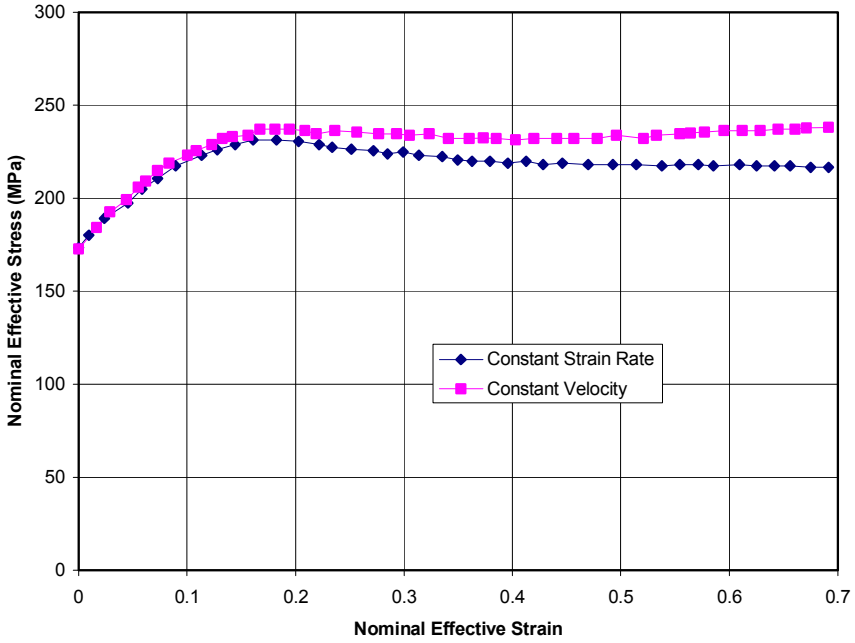


Figure D3 Comparison of a constant strain rate test with a constant velocity test at ε = 0.5.

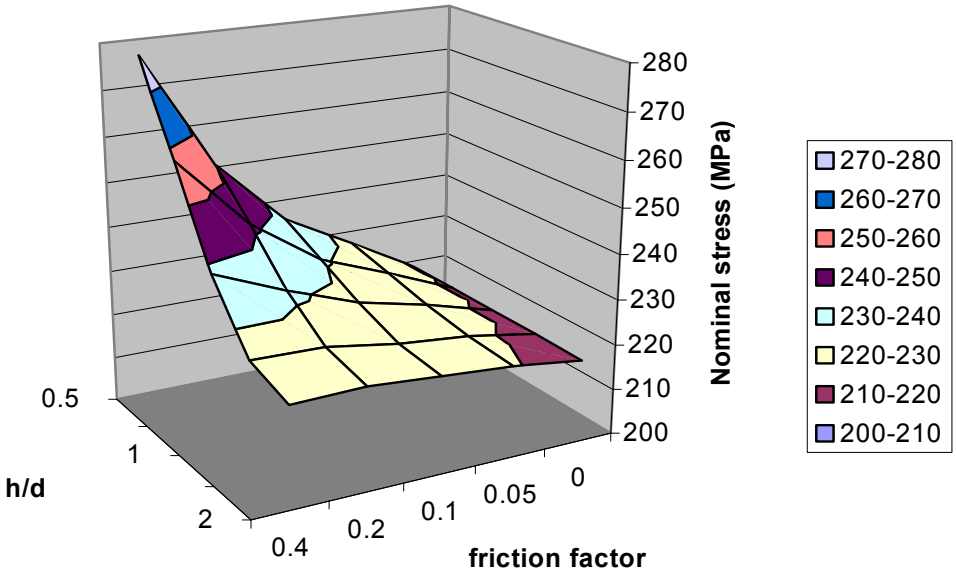


Figure D4 Contour plot of calculated flow stress values at a strain of 0.69 for different h/d and friction parameters.

D.2. Detailed FE Evaluation

The results of more detailed studies (Evans and Scharning, 2001) are shown in Figs D5 and D6. Figure 5 shows typical relative errors in stress as a function of strain that was calculated for strain rates of 0.01 and 100 s^{-1} and friction factors (m) of 0 and 0.4. Figure D5 shows that for:

zero friction, low strain rate	errors are small and steady with strain.
zero friction, high strain rate	errors increase (in negative direction) with strain.
high friction, low strain rate	large positive errors increasing with strain.
high friction, high strain rate	effects of heating and friction in opposition with complex behaviour observed.

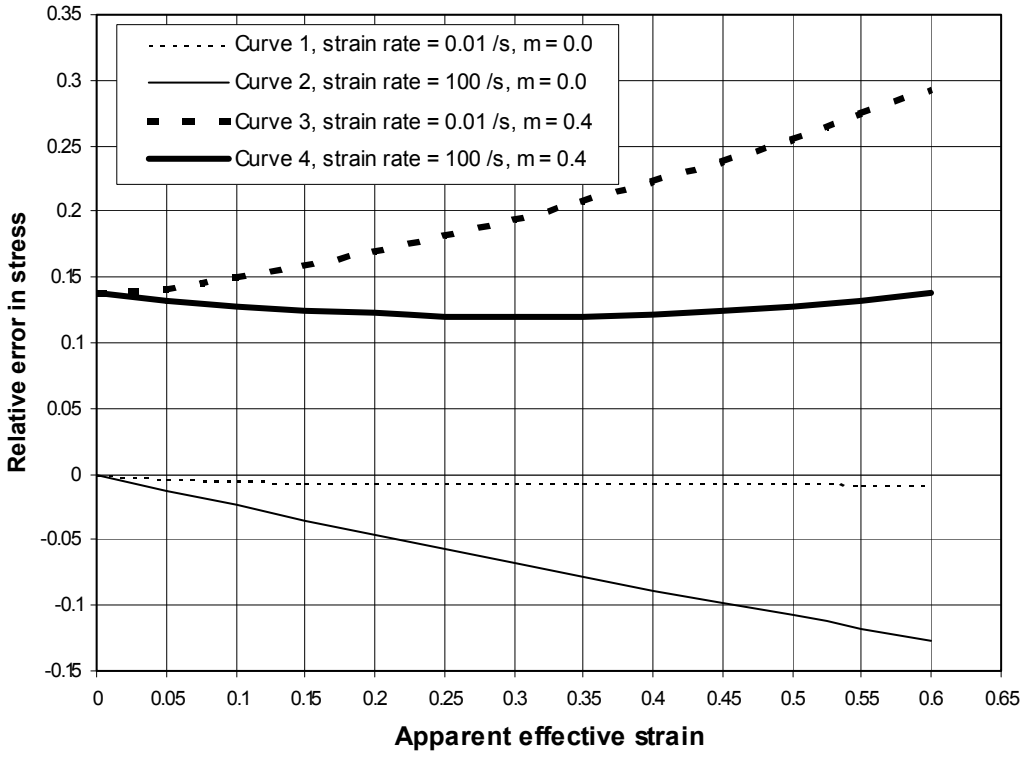


Figure D5 Relative errors in stress for different friction factors and strain rates.

Figure D6 shows typical relative errors in stress as a function of strain for different testpiece geometries showing that at higher values of friction the initial geometry has a significant effect.

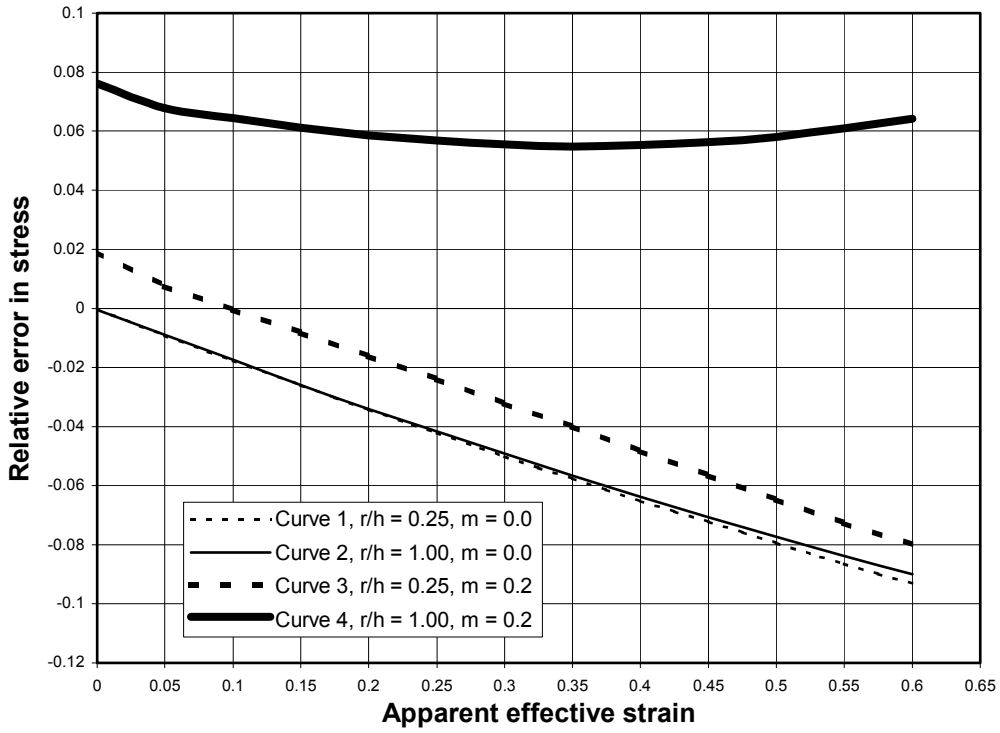


Figure D6 Relative errors in stress for different initial testpiece geometries.

The FE analysis was used to evaluate the effects of the following six parameters at seven levels (tabulated in Evans and Scharning, 2001).

Geometry (X_1)	Temperature (normalized) (X_4)
Volume (X_2)	Strain rate (X_5)
Friction factor (X_3)	Strain (X_6)

This evaluation allowed an interpolation function, ϕ, to be calculated by numerical analysis that represented the linear variation and interaction of the terms for these six parameters. Thus

$$\sigma_{corrected} = \sigma_{measured}/(1 + \phi)$$

where ϕ is calculated using appropriate values for X_1-X_6. These are usually well controlled, although some uncertainty exists for friction factor (X_3). The modelling studies were also used to assess the effects of friction factor on barreling coefficient (B). It was found

(Evans and Scharning, 2001) that the friction factor, m, is related to the square root of B (Figure D7).

$$m = \lambda (1 + \sqrt{B})$$

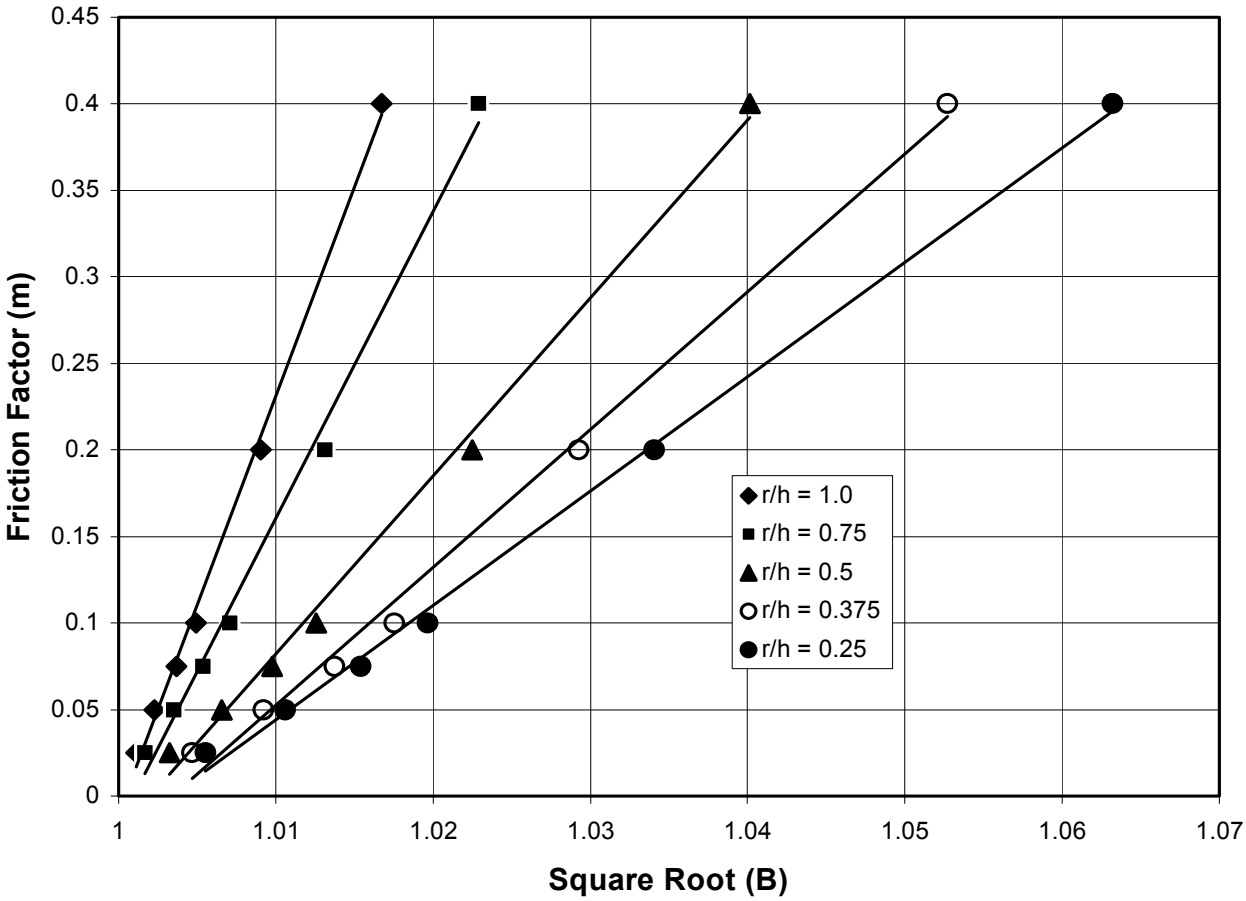


Figure D7 Typical barrelling coefficient dependence on friction factor for different testpiece geometries.

Figure D7 shows that for tall thin testpieces large values of B are obtained even for low friction. Whereas at the other extreme short fat testpieces give low values of B even for high friction.

Thus the use of a single value of barrelling coefficient as a validation test is not recommended for all test geometries.

D.3 Data Validation

Bearing in mind the complexities of the evaluation revealed by the FE analysis it is still useful to outline an algorithm for validating test data as follows:

- Set a limit for tolerance on flow stress uncertainty. A limit of ± 2% is reasonable.
- Calculate the friction factor from the testpiece dimensions.
- Estimate stress uncertainty along the stress/strain curve using test variables, friction factor and function ϕ. If it is less than the tolerance specified above then the test is valid.