

Measurement Good Practice Guide No 27

Measuring Flow Stress in Hot Plane Strain Compression Tests

Revised – Summer 2002

A J Lacey⁺, M S Loveday*, G J Mahon**, B Roebuck*, C M Sellars⁺
and M R van der Winden⁺⁺

*NPL Materials Centre,
National Physical Laboratory

**Alcan International Ltd, Banbury, UK

⁺Dept of Engineering Materials, University of Sheffield

⁺⁺Corus Group, Ijmuiden, The Netherlands

Abstract

This document has been produced to complement the Measurement Good Practice Guide No 3 which describes current best UK practice for measuring hot flow stress in metallic materials using Hot Axisymmetric Compression (HAC). This Guide is applicable to hot (isothermal) plane strain compression (PSC) tests at medium to high rates of strain (10^{-3} to 10^2 s⁻¹) at deformation temperatures below the solidus. Technical input to the document has been provided by a steering group comprising academic researchers, representatives of industrial users and producers of a wide range of engineering materials. An experimental programme was conducted during the preparation of this document to underpin the procedures in this guide.

It is anticipated that, in due course, a further version of this document will be produced which, in principle, could form the basis of a CEN or ISO Standard.

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National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW

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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.

These guidelines are largely based on the collective experience gained at various organisations. In particular much of the technical development of correction factors has been based on research undertaken at The University of Sheffield over many years under the leadership of Prof. C M Sellars. A software package has been developed by the University of Sheffield to perform the different types of correction described in this GPG.

For convenience the authors of these guidelines have been listed in alphabetical order.

Further Information

For further information on *Materials Measurement* contact the Materials Enquiry Point at the National Physical Laboratory:

Tel: 020 8943 6701

Fax: 020 8943 7160

E-mail: materials@npl.co.uk

Website: www.npl.co.uk

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Measuring Flow Stress in Hot Plane Strain Compression Tests

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Executive Summary

These guidelines were prepared within the *Materials Measurements Programme*, an underpinning materials measurement research activity financed by the UK Department of Trade and Industry.

It describes a method for measuring the hot flow stress in metallic materials at medium to high rates of strain (10^{-3} to $\times 10^2$ s^{-1}), in plane strain compression (PSC) at deformation temperatures below the solidus (Figure 1).

The guidelines recommend good practice to minimise levels of uncertainty in the measurement process. The development of the procedure has been supported through tests on type 316 Stainless Steel at 1050-1150 °C and an aluminium alloy, AA5052, at 300 °C to 500 °C at strain rates ranging up to 100 s^{-1} .

Important work on the testing methodology for PSC was undertaken by Sellars et al, (1976). Other recent informative publications concerning the methodology of plane strain compression testing are by, Timothy et al (1991), Duckham & Knutsen (1998) and by Silk and van der Winden (1999). Finite Element Studies to support the development of the Guide were conducted by S M Mirza at the Universities of Sheffield and Leeds, and latterly of MERL Ltd. Technical contributions on ringing were provided by T Rehrmann (IBF RWTH, Aachen) and the document was reviewed by the EC SMT project group TESTIFY chaired by Y Chastel (CEMEF, Nice, France).

This document is a revision of the original GPG published in April 2000. 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 further version of this document will be produced which, in principle, could form the basis of a BSI, CEN or ISO Standard.

Industrial Members of Project Advisory Group

Dr P Atack	VAI Ltd
Dr J W Brooks	QinetiQ, Farnborough
Dr M G Brooks	Corus Group (Redcar)
Mr G Durrant	Rolls Royce (Derby)
Dr J Fletcher	Consultant (Sheffield)
Dr B J Glassey	Rolls Royce (Derby)
Prof A W D Hills	Consultant (Sheffield)
Dr Z Husain	Corus Group (Rotherham)
Dr P M Ingham	Corus Group (Rotherham)
Dr P Lee	Corus Group (Port Talbot)
Dr G J Mahon	Alcan International (Banbury)
Mr J. Middleton	Firth Rixon, Sheffield
Dr P F Morris	Corus Group (Rotherham)
Mr G Snape	Confederation of British Metalformers (Birmingham)
Dr S Price	Forgemasters (Sheffield)
Mr N Richardson	Servotest Ltd, Feltham
Dr A Riddick	Instron Ltd, High Wycombe
Mr C J Startin	Incotest (Hereford)
Dr M R van der Winden	Corus Group (Netherlands)

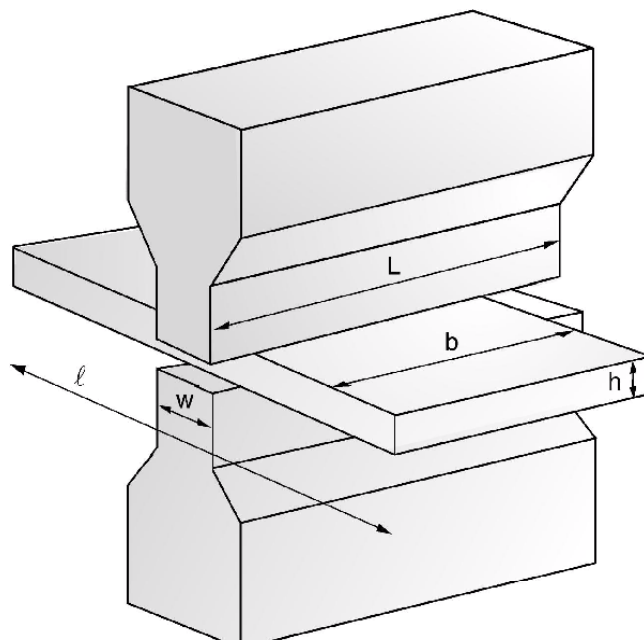


Figure 1 Schematic diagram of plane strain compression test.

1 Test Rationale

Industry and academia need repeatable and reproducible hot flow stress test data for modelling, for process deformation strategies and for correlation with microstructural evolution studies.

Internationally, for these applications, the three most commonly used types of hot deformation test are (i) axisymmetric compression, (ii) plane strain compression and (iii) torsion.

A good practice guide has been written for axisymmetric compression tests (Roebuck et al, 1997) that will be re-issued in revised form in 2002. These guidelines are concerned with plane strain compression.

Plane strain compression testing was first proposed by Orowan (1943) as a modified compression test which could simulate material flow behaviour experienced during rolling.

Plane strain compression testing has since been used to determine the true yield stress of a material compressed between smooth parallel dies, Watts & Ford (1952 & 1955). More recently extensive investigations have been undertaken to compare results between different laboratories using different designs of plane strain compression testing machines, but standardising the principle testing parameters, Shi et al (1997a & b). The technique is especially employed to generate material property data under conditions and constraints similar to those encountered in plate and strip rolling. The methods of analysis were validated using commercial purity aluminium and Al alloys containing 1% Mn and 1% Mg. It was shown that to determine true stress-strain data from the raw load displacement data required corrections for zero offset, machine compliance, extrusion of lubricant, increase in testpiece breadth and friction. It was noted that the frictional forces between the anvils and testpiece surfaces were critically dependent upon the type of lubricant as well as the surface conditions of the tools and the re-heating conditions used (Shi et al 1997a).

The accuracy of FE models depends strongly on the applied constitutive equations describing material behaviour during deformation. Strain-stress relations, accounting for friction and lateral spread, can be obtained from experimental load – displacement plane strain compression curves. However, the constitutive equations obtained in this way can be different for various initial specimen geometries. According to slip line field theory, it has been shown in recent modelling work at the University of Sheffield, Mirza and Sellars (2001), that for nominally constant strain rate the local strain rate in the slip

line field varies for different initial specimen geometries. These variations of local strain rate and local strain contribute to differences of the flow stress level obtained for different initial thickness of the specimen. It is important to take this geometry effect into account to obtain the true flow stress of the investigated material. The variations in strain and strain rate within the testpiece clearly have a significant influence on the evolution of microstructure. Future work is planned to investigate this aspect of plane strain compression testing in a range of engineering materials.

A new software package, Turtle Max, has been developed to allow the user complete experimental data processing, from origin correction to calculation of isothermal stress-strain curves and slip line field strain and strain rate correction.

In hot forming processes the workpiece generally experiences a wide range of strain rates, usually covering several orders of magnitude. The absolute values depend very much on the particular hot forming process, but strain rates of between the limits 10^{-4} and 10^3 s^{-1} can occur. These guidelines are targeted at providing a reliable test method to cover as wide a strain rate range as possible, and are at present being validated in a research programme covering a strain rate range of 10^{-2} to 10^2 s^{-1} .

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

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

2 Scope

2.1 General

- 2.1.1 These guidelines are intended for use with metallic materials.
- 2.1.2 These guidelines apply to plane strain compression tests on rectangular testpieces of a specified geometry shown schematically in Figure 1.

*This Guide does not cover channel die compression tests, quenching rates or microstructural studies, however many of the general principles would be applicable. These topics may be addressed in further Good Practice Guides.**

- 2.1.3 These guidelines apply to metal working deformation temperatures below the solidus of the material in question.
- 2.1.4 These guidelines apply to deformation strain rates in the range 10^{-3} to 10^2 s⁻¹, relevant to industrial forging and rolling processes.

Notes

- (1) *The guidelines have been supported by tests over a strain rate range from 10^{-2} to 100 s⁻¹ on type 316 Stainless Steel and Aluminium alloy AA5052 but are nevertheless still recommended for a wider range of strain rates and materials.*
- (2) *For the measurement of stress relaxation curves it is essential to have a knowledge of the compliance of the testing machine.*

* *Text in italics provides additional comment on topics addressed in the document.*

2.2 Outline of Procedure and Conditions of Testing

These guidelines for conducting hot plane strain “isothermal” compression tests contain 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.
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.

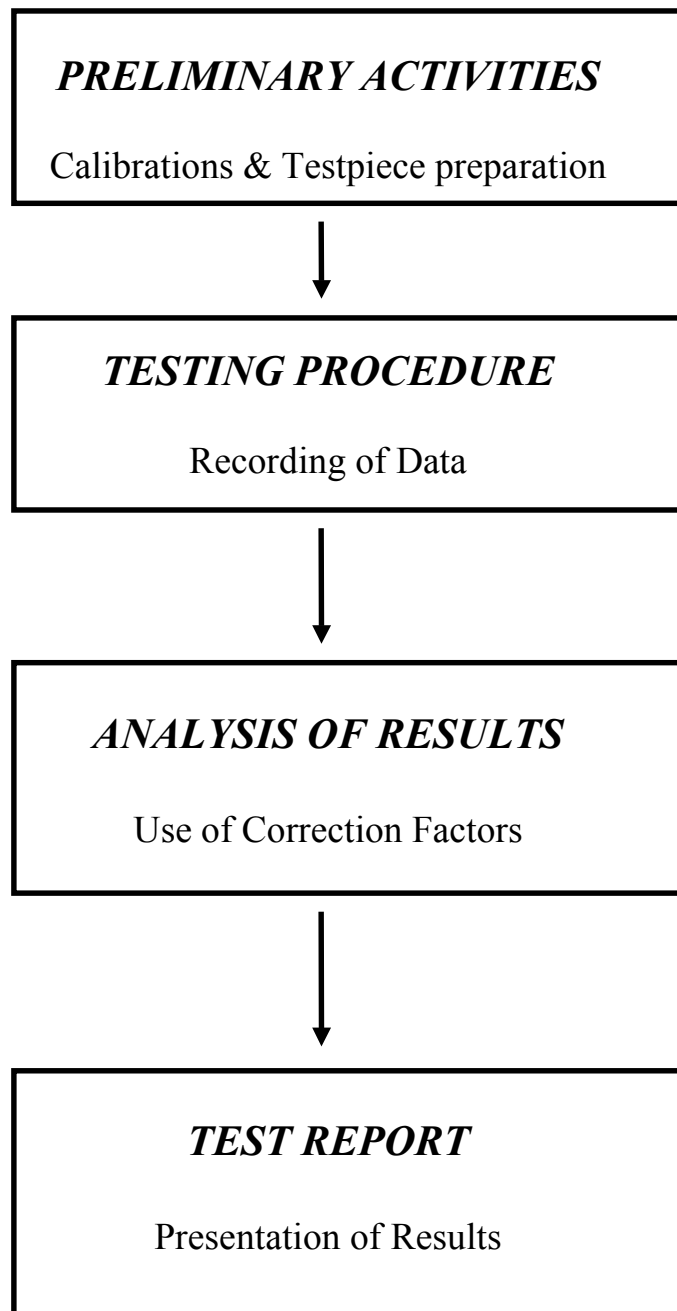
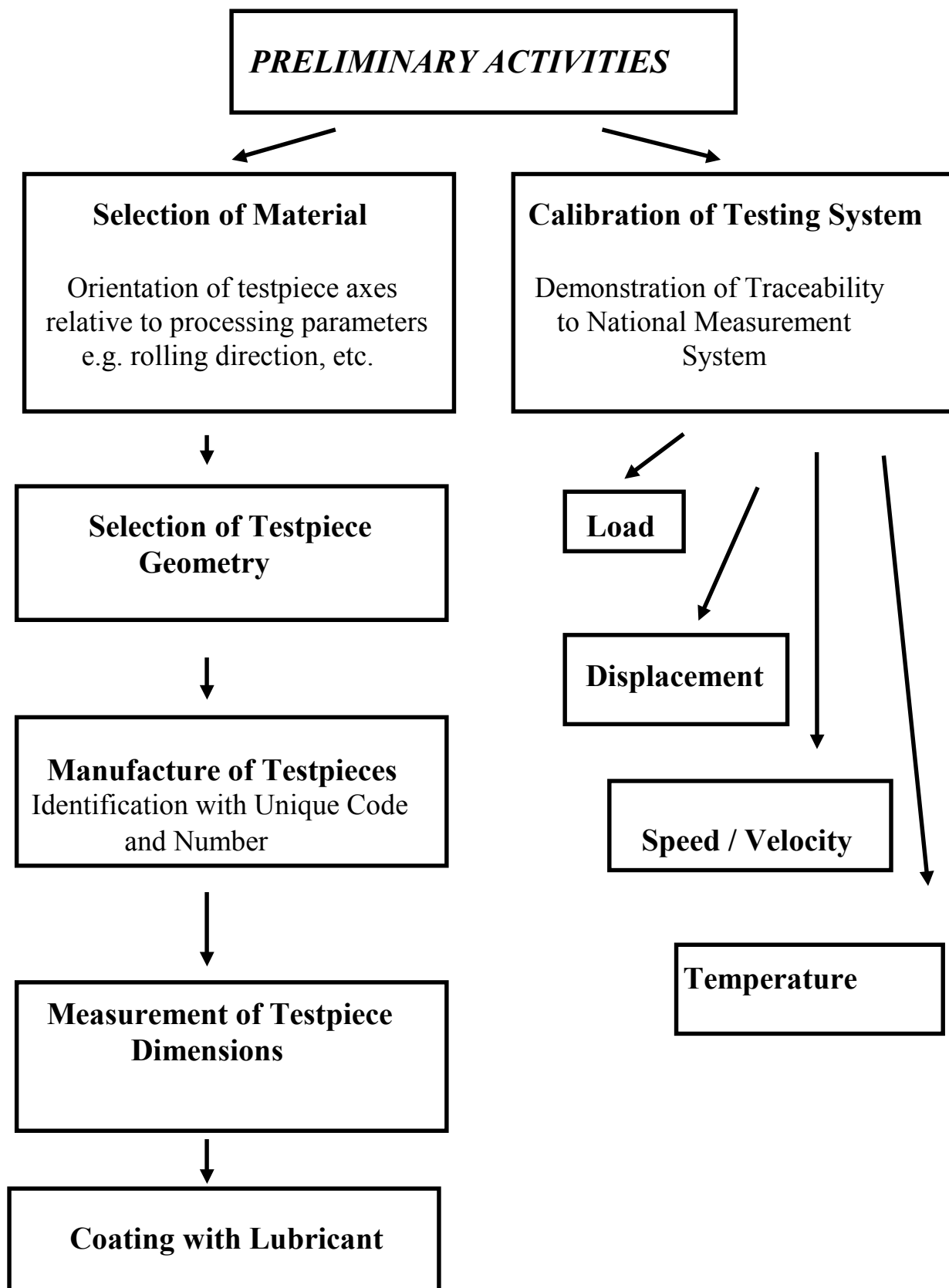
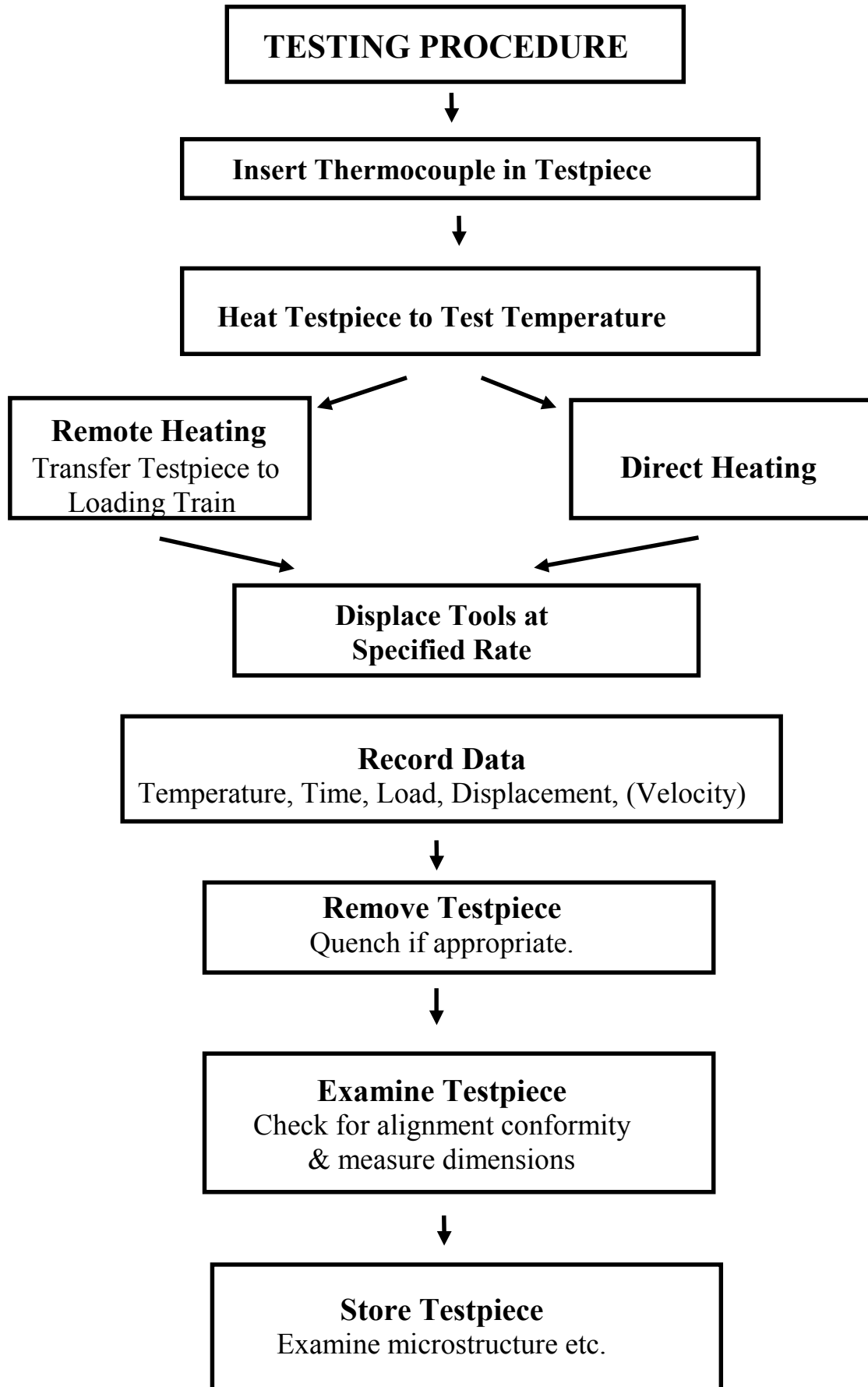
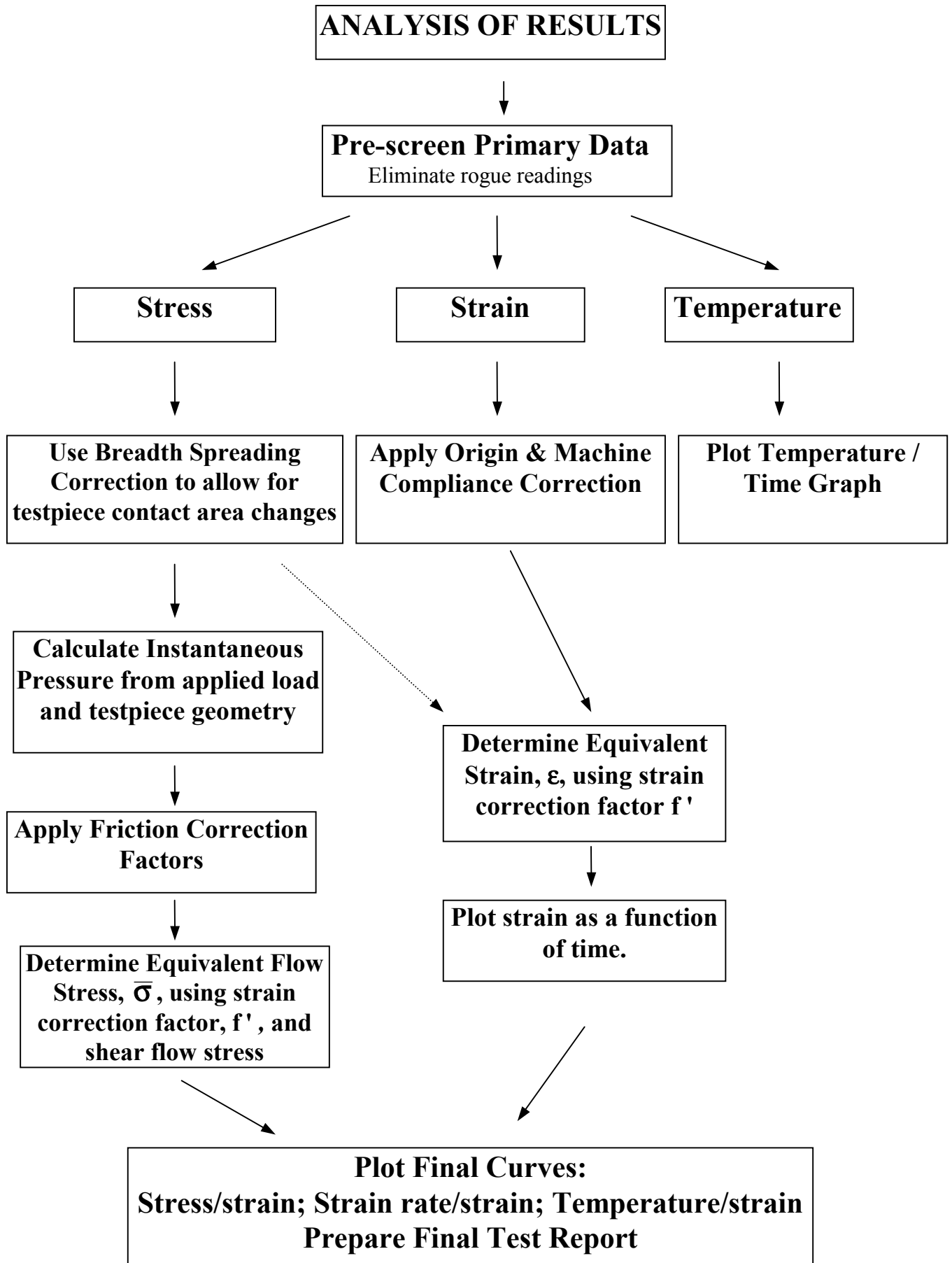


Figure 2 Schematic - Outline of Procedure.







3 Symbols and Units

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

Note: The testpiece dimensions are measured at Room Temperature, either before, or after the test as applicable. For the purposes of analysis, the dimensions are corrected to compensate for expansion to the test temperature.

Symbol	Designation	Units*
δ	Tool displacement	mm
δ'	Corrected tool displacement	mm
ϵ	Thickness strain	-
$\epsilon_1, \epsilon_2 \text{ \& } \epsilon_3$	Strain tensors (see section 4.1.1)	-
$\bar{\epsilon}$	Equivalent strain	-
ϵ_f	Total applied strain at end of test	-
$\dot{\epsilon}$ or $\bar{\dot{\epsilon}}$	Strain rate (thickness or equivalent)	s ⁻¹
$\bar{\sigma}$	Equivalent stress	N mm ⁻²
$\sigma_1, \sigma_2 \text{ and } \sigma_3$	Stress tensors (see section 4.1.1)	N mm ⁻²
k	Shear flow stress	N mm ⁻²
b_o	Breadth of testpiece before deformation	mm
b	Breadth of testpiece at intermediate time corrected for spreading	mm
b_f	Final average breadth of testpiece (see Appendix A)	mm
f' and f	Strain correction factors (see Appendix G)	-
h_o	Height (thickness) of undeformed testpiece (average of 5 measurements see Figure 2)	mm
h	Testpiece height at intermediate time	mm
h_f	Final testpiece height (see Appendix A)	mm
l	Length of testpiece	mm
l_R	Testpiece length ratio (l/w)	-
\bar{p}	Average pressure at intermediate time	N mm ⁻²
w	Width of platens	mm
S_{h_o} and S_{h_f}	Standard deviation of 5 measurements of the thickness (height) of the testpiece	mm
A_o	Area of undeformed testpiece between platens ($A_o = wb_o$)	mm ²
A	Area of testpiece at intermediate time ($A = wb$)	mm ²
A_f	Final area of deformed testpiece between platens	mm ²

B_R	Testpiece breadth ratio (b_o/w)	-
C_b	Testpiece breadth spreading coefficient (Appendix D)	-
C_h	Testpiece height coefficient	-
F	Force (load) applied to testpiece	N
H_R	Testpiece height ratio (h_o/w)	-
L	Length of anvil	mm
S	Shear coefficient	-
T_o	Nominal temperature of test	°C
T	Temperature of testpiece at intermediate time	°C
z_o	A position in the tool width relevant to friction conditions (see Appendix H)	-
μ	Coefficient of friction	-

*** $1 \text{ N mm}^{-2} = 1 \text{ MPa}$**

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 minimum 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 plane strain compression test ϵ_3 is the thickness strain. ϵ_2 is the strain in the direction of the breadth (see Figure 1) and in an ideal test (no spreading) is equal to zero (hence plane strain) and ϵ_1 is the length strain.

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

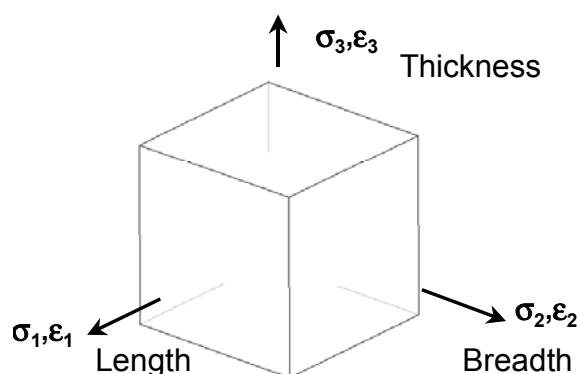


Figure 3 Schematic illustration of stress and strain axes relative to PSC testpiece.

4.1.1 Thickness Strain (ϵ)

The thickness strain, ϵ , is the natural logarithm of the ratio of the thickness at an intermediate time, h , divided by the initial thickness, h_0 :

$$\epsilon = \ln (h/h_0) \quad (1)$$

Thus, $\epsilon = \epsilon_3$ and is negative, which indicates compression.

4.1.2 Equivalent True Strain ($\bar{\epsilon}$)

Equivalent true strain, $\bar{\epsilon}$, is defined by (see Appendix G).

$$\bar{\epsilon} = \frac{2}{\sqrt{3}} (\epsilon_2^2 + \epsilon_2\epsilon_3 + \epsilon_3^2)^{1/2} \quad (2)$$

where $\epsilon_3 = \ln (h/h_0)$ and $\epsilon_2 = \ln (b/b_0)$.

4.1.3 Strain Rate ($\dot{\epsilon}$ or $\dot{\bar{\epsilon}}$)

Rate of change of thickness or equivalent true strain.

4.1.4 Strain Correction Factors (f and f')

It is necessary to convert thickness strain, ϵ_3 , into equivalent strain. For this purpose correction factors f and f' are defined as described in Appendix G.

4.1.5 Displacement (δ)

The linear distance moved by the platens.

Note: Displacement is often measured remotely from the platens, often at the back of the loading arm; under such circumstances it is necessary to correct the measured displacement for the machine compliance, see Appendix F.

4.1.6 Load (F)

Force, F , applied to the testpiece.

4.1.7 Pressure (\bar{p})

Force, F , at any time during the test divided by the cross sectional area, A , of the testpiece at any instant of time

$$\bar{p} = F / wb \quad (3)$$

4.1.8 Friction (μ)

The coefficient of friction parameter is μ .

4.1.9 Friction Position (z_0)

The position on the tool where friction conditions change from sliding to sticking (see Appendix H).

4.1.10 Equivalent Stress ($\bar{\sigma}$)

The equivalent stress, $\bar{\sigma}$, is defined as the pressure divided by two correction factors, one for friction (see Appendix H) - $(f_1\mu)$, and one for effective strain - f or f' (see Appendix G). Thus:

$$\bar{\sigma} = \bar{p} / (f_1(\mu) \cdot f) \quad (4)$$

4.2 Testpiece and Machine Dimensions

Note: The testpiece dimensions are measured at Room Temperature, either before, or after the test as applicable. For the purposes of analysis, the dimensions are corrected to compensate for expansion to the test temperature.

4.2.1 Testpiece Breadth (b)

Breadth of testpiece between anvils measured at the midpoint of the testpiece before the test as an average of three measurements (Appendix A, Figure A1). The initial breadth is b_0 , the intermediate breadth is b and the final breadth is b_f .

(See Appendix D for breadth spreading corrections)

4.2.2 Testpiece Height (h)

The height (thickness) of the deformed testpiece is calculated from an average of measurements at five positions (see Appendix A, Figure A1). One measurement should be taken at the centre point of the top and bottom surfaces and four more at the edges.

The initial thickness is h_0 , the intermediate thickness is h and the final thickness is h_f .

4.2.3 Platen Width (w)

Width, w , of the platen (anvils) in contact with the testpiece.

For calculations of pressure the width needs to be corrected for expansion at temperature (see worked example Appendix I).

4.2.4 Testpiece Length (ℓ)

ℓ is the testpiece length, see Figure 1.

To provide lateral constraint, the length of the testpiece, ℓ , shall be $> 3w$.

4.2.5 Platen Length (L)

Overall length of platen should be greater than $> 1.2 b_0$, see Figure 1.

4.2.6 Cross Sectional Area (A)

The area of the undeformed testpiece (A_0) is given by

$$A_0 = wb_0 \quad (6)$$

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

$$A_f = wb_f \quad (7)$$

where b_0 and b_f are measured on the testpiece as indicated in Appendix A.

A pro-forma for the test report is provided in Appendix B, for recording testpiece dimensions etc.

4.2.7 Testpiece Aspect Ratios

There are two critical aspect ratios which relate to the geometry of the testpiece used in the plane strain compression test. These ratios and recommended tolerances are given in Table 1.

Table 1 - Testpiece Aspect Ratios

Symbol	Title	Relationship	Preferred Values*	Permissible Values*
B_R	Breadth Ratio	$B_R = \frac{b_o}{w}$	5	≥ 2
H_R	Height Ratio	$H_R = \frac{h_o}{w}$	0.67	≤ 0.67
ℓ_R	Length Ratio	$\ell_R = \frac{\ell}{w}$	3	≥ 3

where b = testpiece breadth, h = testpiece height (thickness), ℓ = testpiece length and w = platen width.

*The value used shall be stated in the test report.

4.2.8 Shape Ratios

See Appendix A for worked example of thickness coefficient, C_h and Appendix D for breadth spreading coefficient, C_b .

5 Testpieces

The testpiece is usually obtained by cutting/machining a rectangular 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 load 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.

It is good practice to examine the microstructure of the testpiece close to the surface following a typical 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

Note: The testpiece dimensions are measured at Room Temperature, either before, or after the test as applicable. For the purposes of analysis, the dimensions are corrected to compensate for expansion to the test temperature.

After machining, the testpiece dimensions should be measured with a tolerance of ± 0.01 mm on each individual measurement of b_0 and h_0 (Appendix A and Figures 4 and A1). The faces of the undeformed testpieces should be perpendicular to the longitudinal direction within $\pm 0.2^\circ$ and should be parallel to within ± 0.01 mm. Testpieces shall have a ground or milled finish to better than $R_a = 1.25 \mu\text{m}$ (see BS 308, BS 1660 and BS EN ISO 1134).

The recommended testpiece breadth aspect ratio (B_R) is 5. Testpieces with B_R other than 5 can be used but the ratio must be quoted in the test report.

In the supporting practical work plane strain compression testpieces with B_R values of 3, 5 and 7 were tested. No problems were found in generating valid stress/strain curves even with a value for B_R of 3.

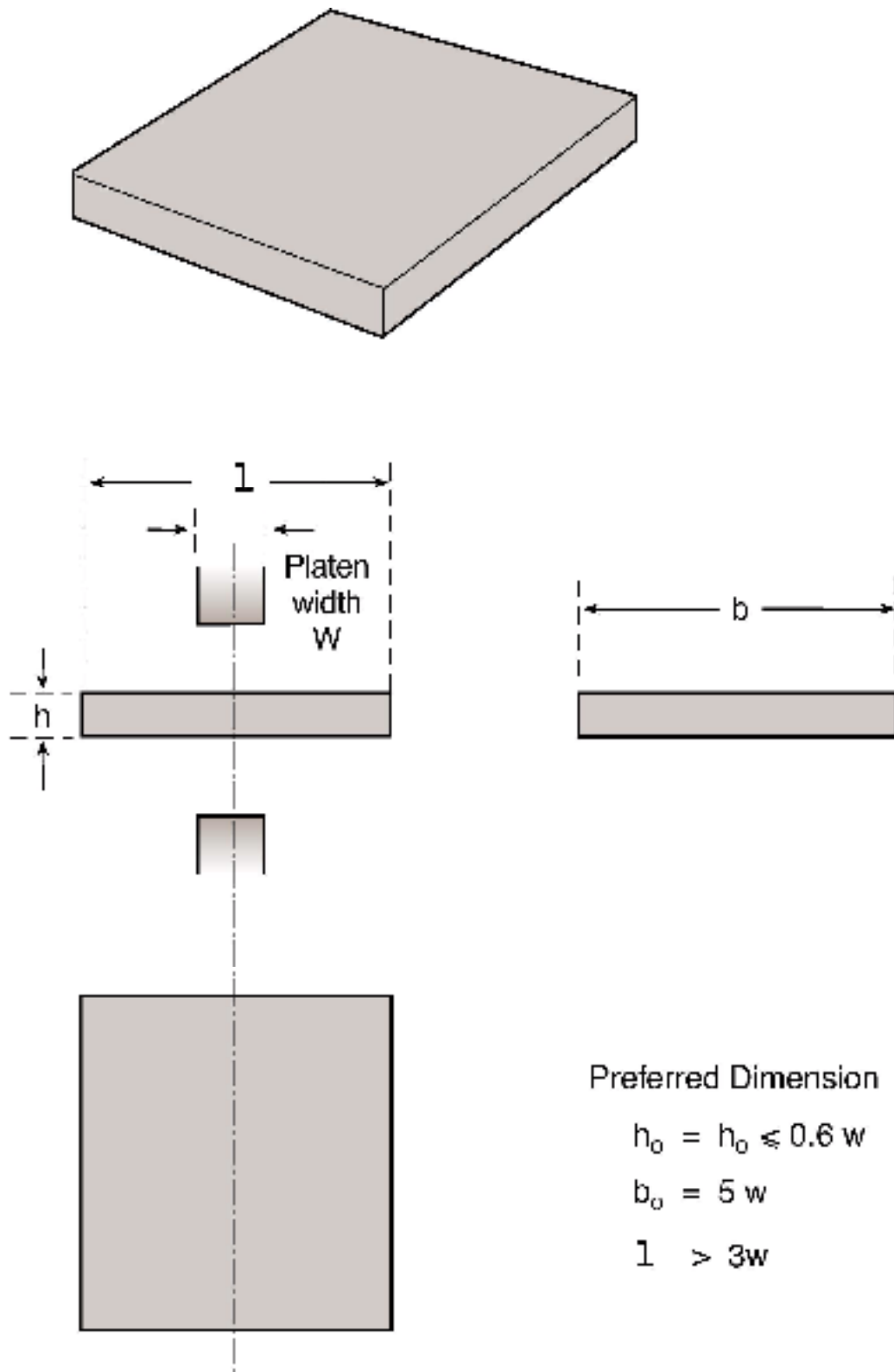


Figure 4 Schematic diagram of testpiece geometry [Also see Appendix A].

5.3 Surface Quality

For some materials it is more important to protect the surface of the testpiece from oxidation, since an interaction can occur with lubricants 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. However, in general, testpieces shall have a ground or milled finish, to better than $R_a = 1.25 \mu\text{m}$, (see BS 308, BS 1660 & BS EN ISO 1134).

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 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 thickness contained less than about 10 grains. Likewise, examination of the microstructure of the testpiece after deformation can provide information for microstructural 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, eg 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. It has been shown that asymmetric flow patterns may be observed in the material being compressed if the platens are mis-aligned [Duckham & Knutsen, 1998]. Nevertheless, the loads computed in FE modelling work to support

the development of this Guide were unaffected by misalignments up to 7%. However, for subsequent microstructural study, it is suggested that platens should be aligned such that lateral mis-match should be less than 1% of the width dimension of the platens.

6.2 Strain Rate Control

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

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

Ideally tests should be performed in equivalent strain rate control. The use of test machines with constant crosshead speeds introduces an additional uncertainty due to the variation of strain rate with applied strain. For example, in a test at a crosshead speed of 0.1 m s^{-1} on a 10 mm thick testpiece the strain rate varies from 10 s^{-1} to 50 s^{-1} as the testpiece thickness reduces from 10 to 2 mm (ie deformation to a equivalent strain of about 1.8). For this reason the test report requires a plot of strain rate versus equivalent 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. A desired method is direct measurement across the platens. If a stroke transducer is used, machine compliance must be measured and a correction applied. Other options include the use of a velocity meter.

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 $\sim 20 \text{ Hz}$, ie (compression tests lasting more than $\sim 50 \text{ ms}$, 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].

6.4 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 with deburred edges.

A separate Measurement Note has been written on suitable platen materials. J D Lord and M S Loveday, NPL MN(50), March 2001.

6.4.1 Platen Alignment

Platens should be aligned such that angular rotation, lateral offset and parallelism should all be less than 0.05 mm on a 50 mm length.

Following a PSC test it can sometimes be observed that the test piece is distorted resulting in either a U or a Z shape final geometry. This is due either to differences in the friction conditions at top and bottom interfaces or due to the lateral misalignment of the platens. FE models of the PSC test with different conditions were simulated to evaluate the effect of different conditions. Stainless steel type 316 specimen with 10 mm initial thickness was analysed at strain rate of 10 s^{-1} . Three different cases were analysed:

- (a) Different, but constant, coefficient of friction between top and bottom interfaces that results in a U shape. Results of the analysis are shown in Figure 5 with a friction coefficient of 0.15 for the top interface and 0.05 for the bottom interface.
- (b) Initial platen misalignment that produced Z shape. Results are shown in Figure 6 with an initial platen misalignment of 1mm.
- (c) Perfectly aligned platens, but with varying friction coefficient along the specimen width that also produces Z shape final specimen geometry. Analysis results with a friction coefficient that varies from 0.05 to 0.15 are shown in Figure 7.

Contours of instantaneous strain rates within the specimen are also shown in Figures 5-7. The unsymmetric strain rate distribution in all cases within the specimen is a consequence of the unsymmetric conditions at platen-specimen interfaces.

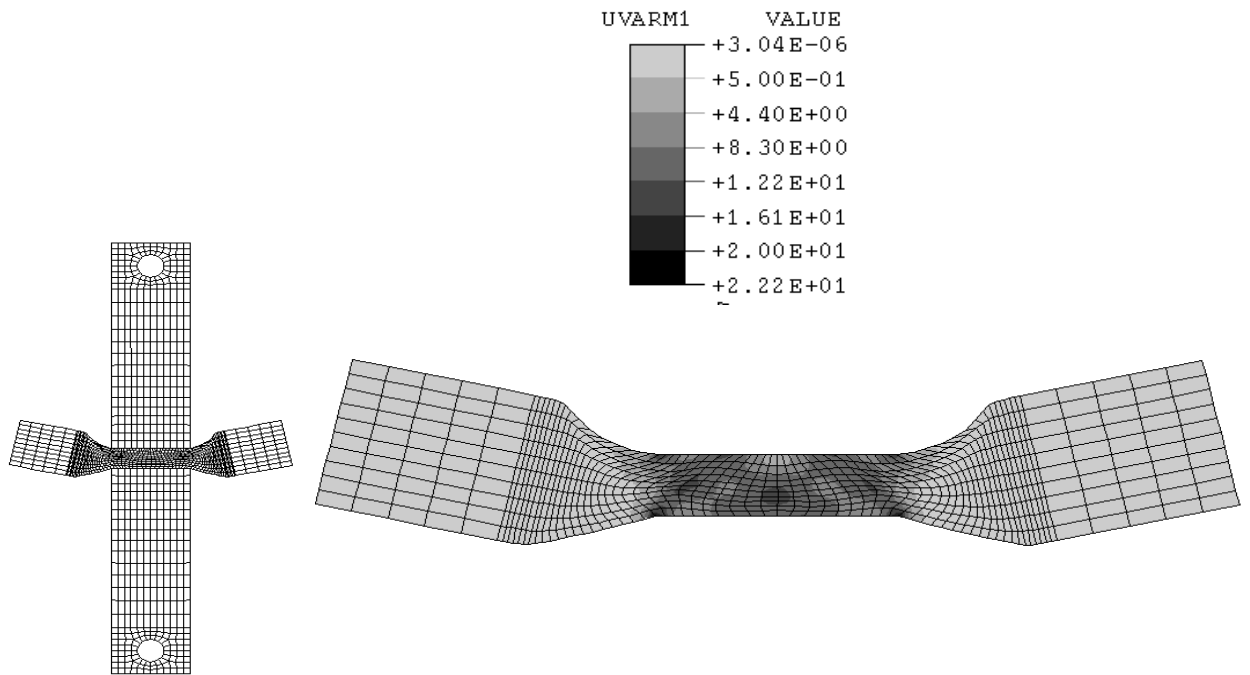


Figure 5 U shape deformed specimen with different friction coefficients at the top and bottom tools at strain of 1.

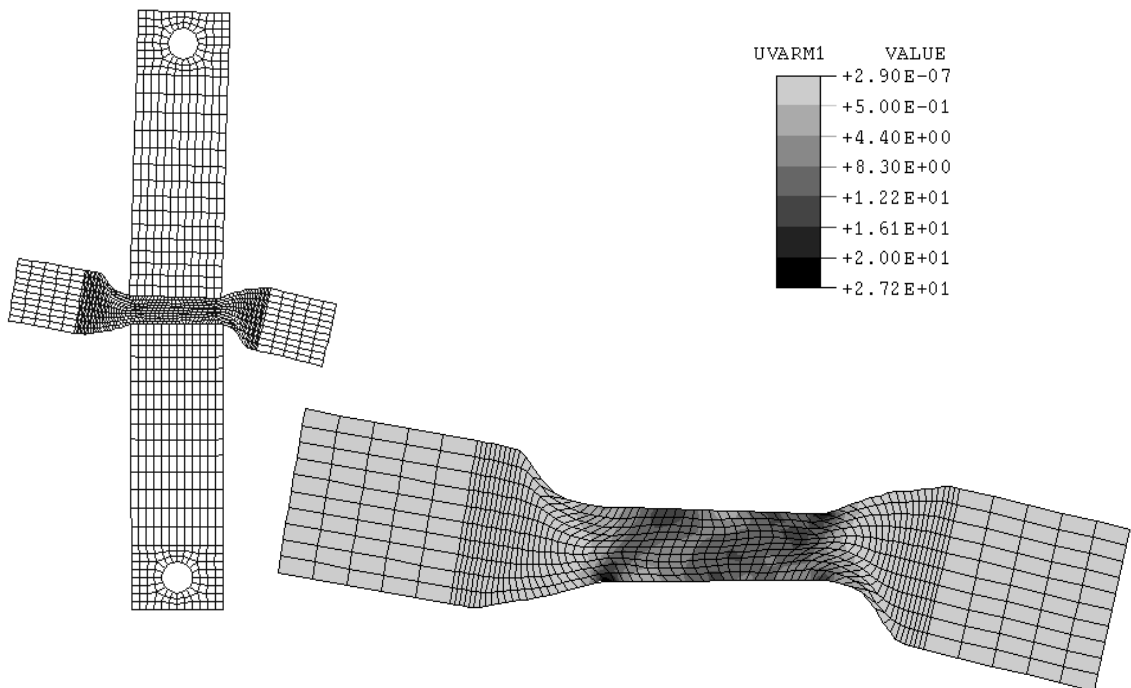


Figure 6 Z shape deformed specimen due to initial platen misalignment at strain of 1.

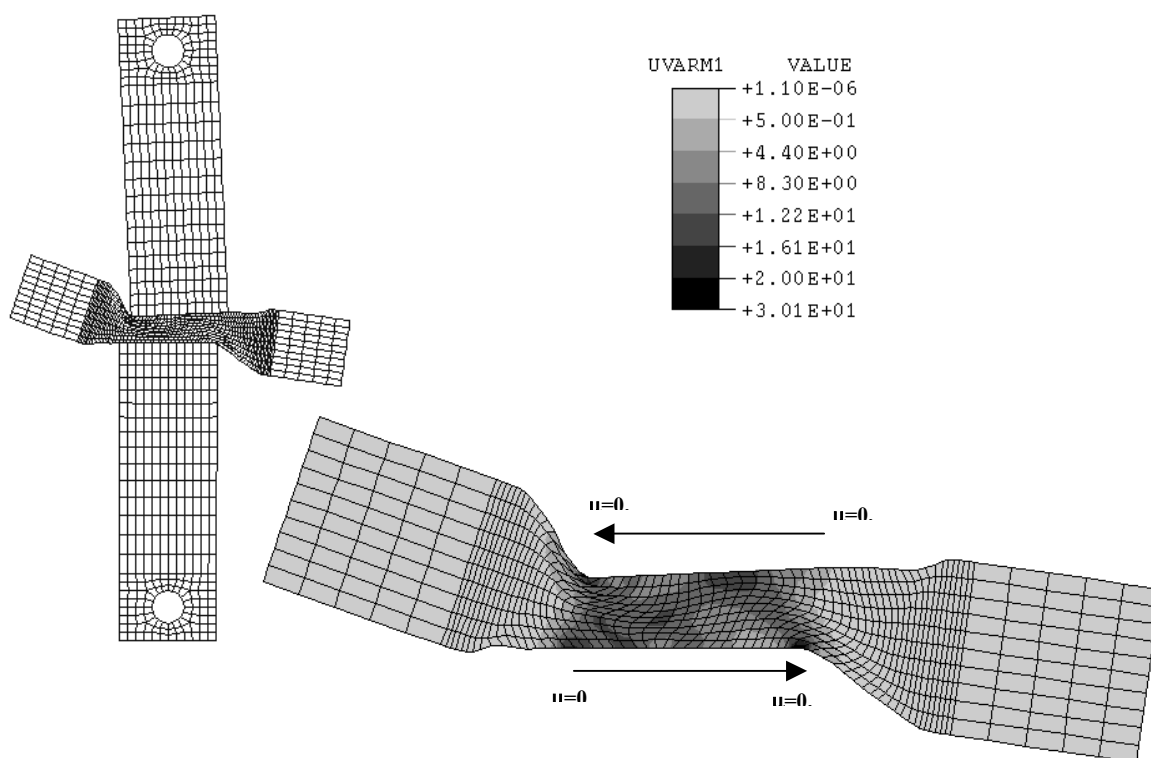


Figure 7. Z shape deformed specimen due to varying friction along the width of the platens, at strain of 1.

6.5 Lubrication

Good lubrication is vital to conducting valid hot plane strain compression tests. Friction effects can be corrected for (see section 8.6 and Appendix G) but a value for the friction coefficient must be known.

For some lubricants, e.g. glass, it may be necessary to make an allowance for the thickness of the lubricant coating; a displacement zero offset of up to 0.2 mm may be encountered.

A separate Measurement Note has been written on suitable lubricants. J D Lord and M S Loveday, NPL MN(50), March 2001.

6.6 Displacement Measurement and Calibration

Displacement 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 displacements are used. These should be corrected for machine compliance effects (section 8.4).

6.6.1 Thickness Strain

For most purposes, crosshead displacement is used to measure thickness strain, generally via a Linear Variable Differential Transformer (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 8.4.

6.7 Heating Systems

6.7.1 Radiant Furnaces

In many PSC testing machines, the testpiece is heated in an ancillary furnace and then rapidly transferred to the compression testing machine. It is necessary to calibrate the test system so that the furnace and temperature profiles are known.

6.7.2 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 and widths since it is an additional source of uncertainty. The frequency of calibration should be the same as that described in 6.7.1 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.

6.7.3 Inductive Heating

Some machines use Radio Frequency (RF) inductive heating of the testpiece. The frequency of calibration should be the same as that described in 6.7.1 for furnaces. In

addition, the usual safety precautions associated with generation of RF signals must be observed, e.g. warning to people with heart pacemakers, etc.

6.8 Temperature Measurement, Control and Calibration

6.8.1 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.

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 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 °C and an accuracy of ± 2 °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.

The variation in indicated temperature within the testpiece and the deviation from the specified test temperature should not exceed the values given in Table 2.

Table 2
Initial Temperature Tolerances*, °C

Test temperature, T °C	Temperature variation ⁺	Precision, ⁺⁺ °C
<i>Across testpiece thickness</i>		
< 600	12	± 2
600 < T < 900	18	± 3
> 900	24	± 4
<i>Across testpiece breadth</i>		
< 600	16	± 2
600 < T < 900	24	± 3
> 900	32	± 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).

Further comments on quality and traceability issues are given in an associated Measurement Note (M S Loveday, 2001).

6.8.2 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 in Appendix C.

6.8.3 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. Alternatively, validated computer models may be used to obtain complete temperature distributions [Foster, 1981; Hand et al 2000].

FE analysis of typical temperature rises resulting from deformation heating have been performed, Mirza and Sellars (2001). A 2D model of testpieces with an initial thickness of 10 mm and a tool width of 15 mm was evaluated at strain rates of 10-500 s⁻¹ and a friction coefficient of 0.1 for two materials – Al alloy AA5052 at 400 °C and 316 stainless steel at 1000 °C. The model was used to predict average and maximum temperature histories in the deformation zone. Average temperature rises for different strain rates in tests on the 316 stainless steel are shown in Figure 8.

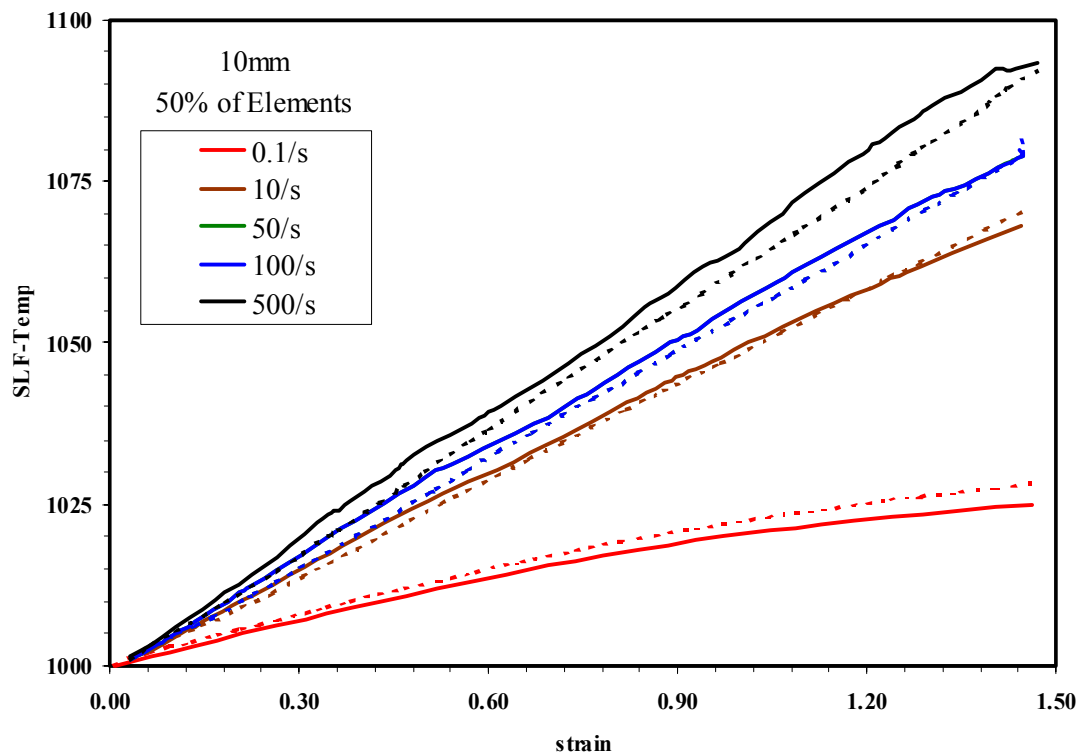


Figure 8 Average temperatures for 316 stainless steel for different strain rates.

However, this overall picture obscures the sometimes very large variation in temperature that develops across the testpiece, particularly in the slip line fields at high strain rates. Figure 9 shows temperature distributions that were calculated at a strain of 1.0 and strain rate of 5 s^{-1} in the 316 stainless steel.

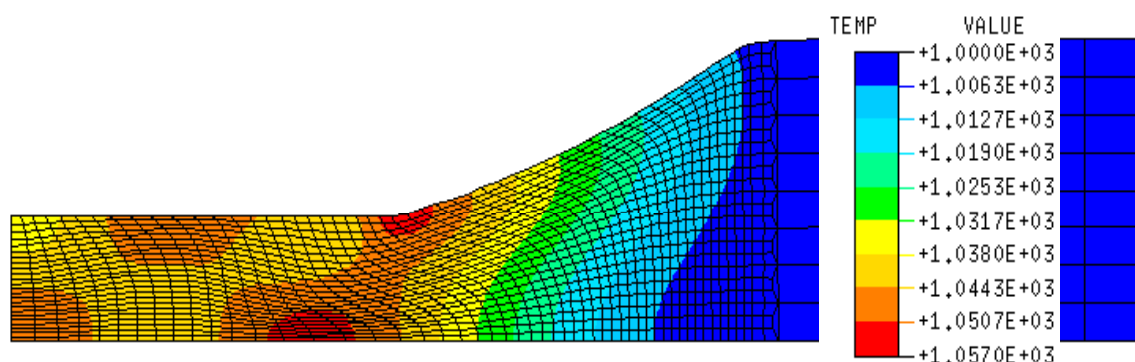


Figure 9 Temperature distributions following test at a strain rate of 5 s^{-1} in 316 stainless steel.

Detailed investigation of the model outputs indicated that the maximum temperatures occurred at the surfaces of the testpiece and could lead to localised melting at higher deformation temperatures (typically $500 \text{ }^\circ\text{C}$ for AA5052 and $1100 \text{ }^\circ\text{C}$ for 316 stainless steel). The results clearly show the importance of siting the measurement thermocouple in a known position.

6.9 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 such that ~ 1000 data points can be recorded covering the full deformation curve. Depending upon the rate of deformation, data sampling frequencies may range from 100 Hz - 10 kHz . For a typical test at a strain rate of 1 s^{-1} , this means a sampling rate of 100 Hz .

7 Testing Procedure

7.1 Testpiece Manufacture

Calculate the approximate maximum pressure required to deform the chosen testpiece size with the prevailing friction coefficient, 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 in accordance with the guidelines given in Section 5.

For some materials, e.g. steels, plating is essential for minimising surface oxidation and interactions with glass lubricants 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 tools (platens) are smooth and flat.

It is necessary to examine platens frequently to ensure no serious damage has developed on their surfaces and to minimise lubricant build-up. Re-machine at regular intervals if necessary.

Alignment of the platens is checked by examination of the testpiece after each test. The platens should be parallel to within $\sim \pm 0.1^\circ$ (i.e. typically ± 0.05 mm on a 50 mm breadth testpiece).

Include details of the heating profile to the temperature of the test and the dwell at temperature prior to the test in test report, since heating times can influence microstructure and oxidation.

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.

7.3.1 Lubrication

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

Lubricant is normally applied to the testpiece, but may also be applied directly to the platens.

7.4 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 cooling process.

8 Analysis of Results

8.1 General

Document the results in a suitable test report, as, for example, specified in Section 9. An appropriate Test Report Pro-Forma is also given in Appendix B.

It is necessary to make a number of corrections for the following issues:

- breadth spreading
- friction
- origin correction
- test system ringing (at higher rates of strain)
- machine compliance
- equivalent strain
- deformational heating

Details of the equations to be used for the various corrections are given in Appendices D-K, and a detailed worked example is given in Appendix K.

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.

8.2 Breadth Spreading Correction

Since the testpiece spreads laterally as it is deformed under load, it is necessary to make a correction for the spreading when calculating the instantaneous pressure. Details of the breadth spreading correction method are given in Appendix D.

8.3 Origin Correction

The zero reading of the displacement may need to be corrected for the thickness of the lubricant or non-linearity in the load/displacement curve at the start of the test. Details of the approach that may be used to correct for origin shift is given in Appendix E.

8.4 Corrections for Test Machine Compliance

Further information concerning the compliance correction is given in Appendix F. The procedure for applying a correction for the compliance (or stiffness) of the testing machine is sometimes referred to as Load-Elongation Compensation (or 'LEC').

8.5 Calculation of Equivalent Strain

From the displacement measurements recorded during the test, it is necessary to apply correction factors (given the symbol f) in order to determine equivalent strain, $\bar{\epsilon}$ (see Appendix G). In some machines, the control system will allow an approximate conversion of the displacements into equivalent strains “on line” during the test, followed by rigorous correction of the data “off line” after the test. As the processing speed of computers improves it maybe possible for rigorous corrections to be made “on line” during the test.

8.6 Friction and Friction Corrections

Friction was evaluated using an analytical approach in the initial version of this GPG, published in April 2000. Recent FE work at USEM has enabled a more accurate procedure to be adopted. However, for information, both approaches are retained in the GPG.

8.6.1 Analytical Approach

To determine the flow stress of the material, the pressure at intermediate time must first be calculated from the load at intermediate time. The force exerted by the ram F is converted to an average pressure \bar{p} using the breadth b and platen width w :

$$\bar{p} = F / wb \quad (8)$$

The shear flow stress or the equivalent flow stress can then be deduced from the pressure depending on whether the friction conditions are predominantly sliding friction, sticking friction, or a combination of the two. Sliding friction assumes a constant Coulomb friction coefficient, whereas sticking friction assumes the contact stress at the tool/specimen interface to be equal to the material flow stress in pure shear. Different friction conditions may occur in different regions of the contact area at the same time. In this case, it is assumed that the lubrication causes each type of behaviour to occur in distinct bands across the width of the specimen. Details are given in Appendix H.

8.6.2 Finite Element Models

FE analysis of the hot plane strain compression test was performed, Mirza and Sellars (2001), to investigate the effect of test parameters such as geometry, strain rate and friction in deformation. It was found that load deformation behaviour was independent of material and strain rate up to 50 s^{-1} , but friction and geometry were more important (Figure 10).

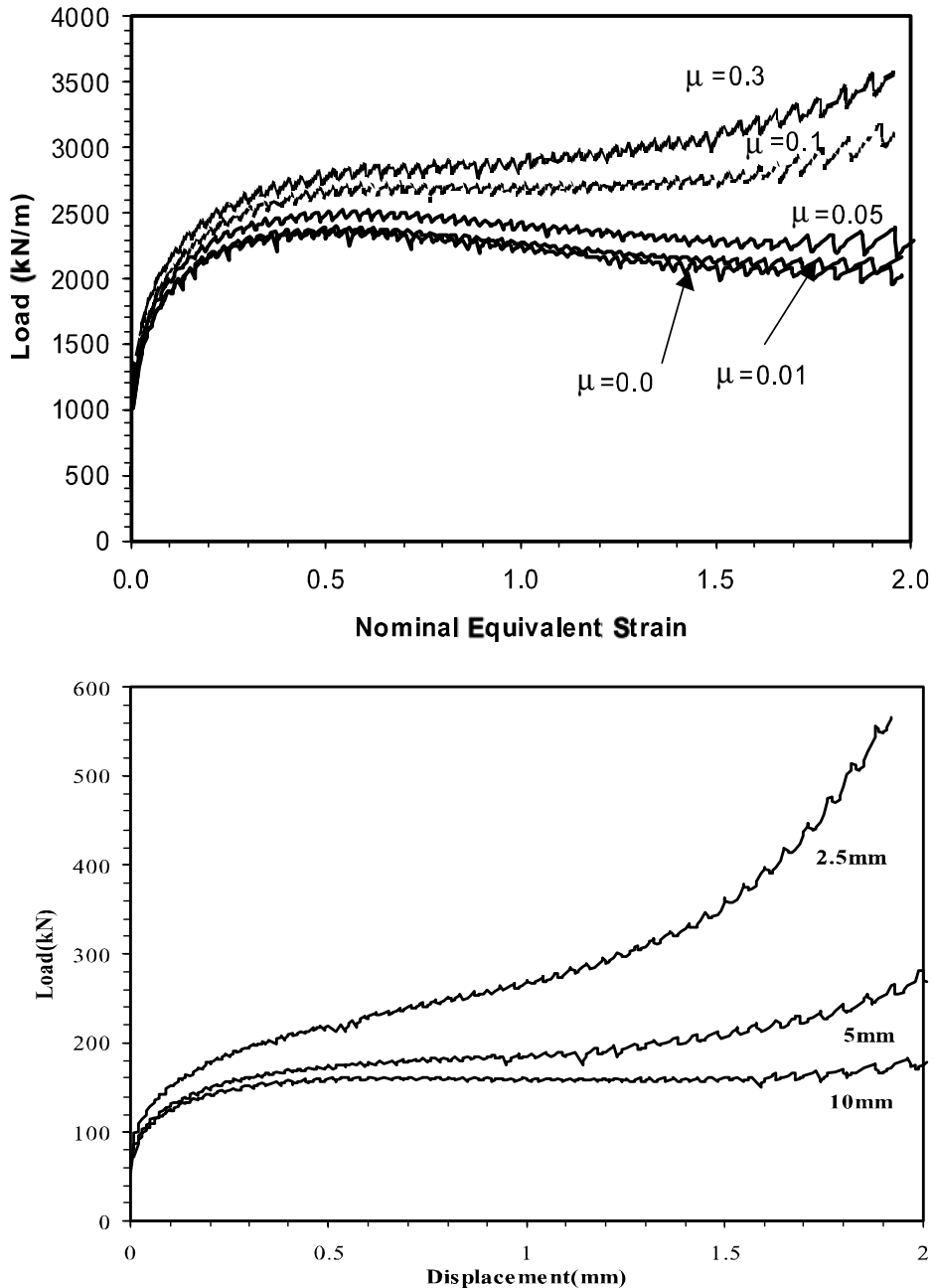


Figure 10 2D FE prediction of effects of friction coefficient and geometry (thickness) on load/strain behaviour.

Additional 3D FE modelling was conducted, Mirza and Sellars (2001), to investigate the influence on testpiece spread of specimen geometry and friction. It was found that spread was less sensitive to friction than it was to initial testpiece breadth (Figure 11). However, a more significant effect of friction was found in the curvature that developed on the sides of the testpiece in the thickness direction. Thus breadth should always be measured from either top or bottom contact faces.

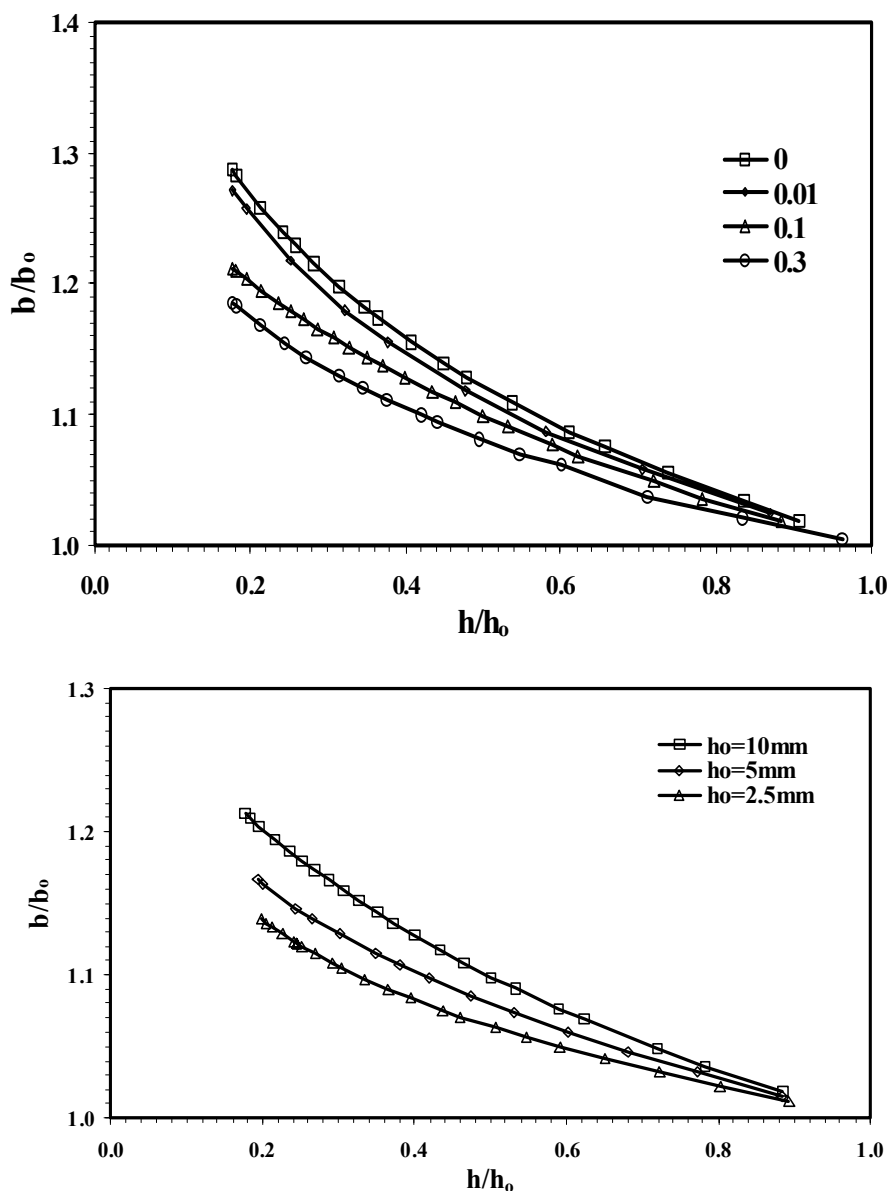


Figure 11 2D FE prediction of effects of friction and initial testpiece height on spread.

8.7 Flow Stress Corrections

Once all the corrections have been made the equivalent flow stress, $\bar{\sigma}$, of the material is then calculated, from the shear flow stress, k , using the same empirical correction factor as that used for strain, f . Thus:

$$\bar{\sigma} = \frac{2k}{f} \quad (12)$$

8.8 Deformational Heating Corrections

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

$$\Delta T = \int_0^{\epsilon} p d\epsilon / C_p \rho \quad (13)$$

where C_p and ρ are the specific heat and density respectively. Temperature rises of $30\text{-}40 \text{ }^\circ\text{C}$ are easily achievable for typical ferrous and non-ferrous alloys.

Further background information is given in Appendix I and in a PhD Thesis from the University of Sheffield [Foster (1981)] and in Hand et al (2000).

8.9 Test System 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 12, together with a plot that has been “filtered” to reduce the ringing amplitude.

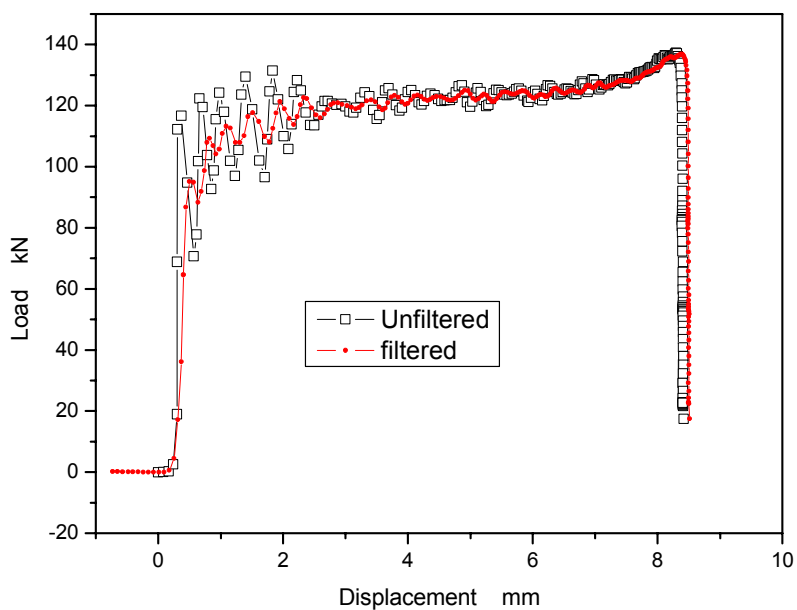


Figure 12 Load cell ringing.

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).

8.10 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 $\pm 3\%$ 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.*

8.11 Data Presentation

Record plots of $\bar{\sigma}$, $\bar{\dot{\epsilon}}$ and T_i versus $\bar{\epsilon}$. Tabulate values of flow stress at sufficient values of applied true strain to adequately describe the stress/strain curve.

The measurement requirement is for data on the variation of corrected flow stress with applied equivalent strain at constant strain rate and constant temperature. The results can be presented as a table of stress and strain values obtained at specified values of instantaneous applied strain rate and temperature or a graph of stress against strain. The results can be fitted to a constitutive equation if required. But this must be defined in the report if this is the case.

8.12 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.

A worked example of the analysis necessary for obtaining the correct data from a Plane Strain Compression Test is given in Appendix K.

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 ie orientation relative to the rolling or processing directions
- Dimension of testpiece (Aspect ratios, especially if B_R not equal to 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

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10.2 Standards

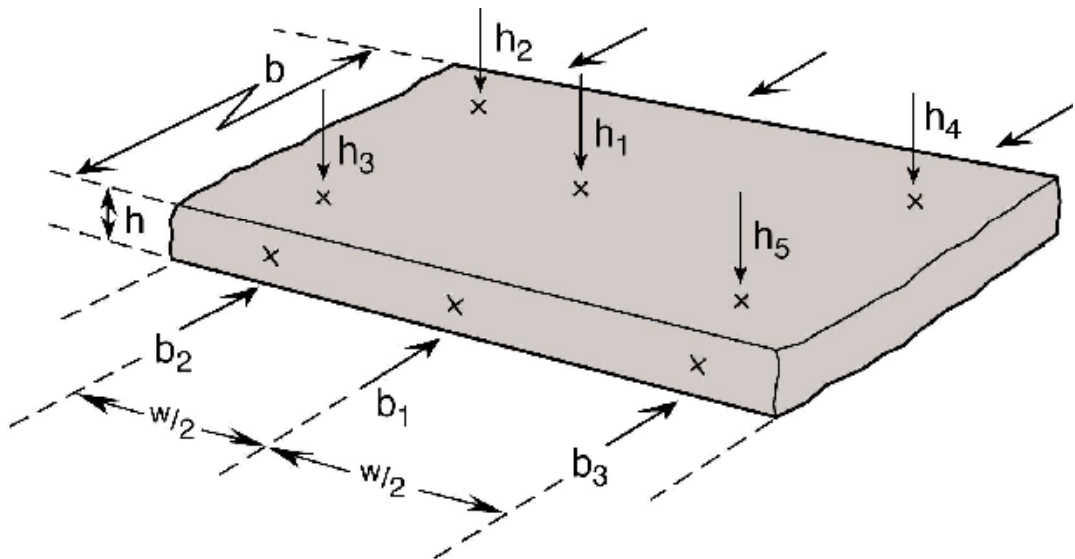
- BS EN ISO 1660: 1996 Technical drawings. Dimensioning and tolerancing of profiles
- BS EN-ISO-3785: 1995 Steel. Designation of testpiece axes.
- BS EN ISO 7500-1:1999 Metallic materials—Verification of static uniaxial testing machines - Part1: tension / Compression Testing Machines.
- BS EN 10002-4 Tensile Testing of Metallic Materials - Part 4: Verification of Extensometers used in uniaxial testing.
- ASTM E1012 Metallic Materials - Constant Amplitude Strain-Controlled Low Cycle Fatigue Testing (pr EN 3988: 1995).
- BS 308-2: 1992 Engineering drawing practice. Part2 - Recommendations for dimensions and tolerancing of size.
- BS 1041 - 4: 1992 Temperature measurement. Guide to selection and use of thermocouples.
- BS 1134 Assessment of surface texture.
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BS 1134-2: 1990 Guidance and general information.
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Appendix A: Hot Plane Strain Compression Tests

Testpiece Measurement Table

Testpiece identification	
Material	

Dimensions	Breadth, mm		Height, mm	
Initial	b_1		h_1 (centre)	
	b_2		h_2 (edge)	
	b_3		h_3 (edge)	
			h_4 (edge)	
			h_5 (edge)	
Average	b_o		h_o	
Standard deviation	S_{h_o}		S_{h_o}	
Final	b_f		h_6 (centre)	
			h_7 (edge)	
			h_8 (edge)	
			h_9 (edge)	
			h_{10} (edge)	
Average	-		h_f	
Standard deviation	-		S_{h_f}	



h = average of five readings
 b = average of three readings

Figure A1 Testpiece geometry before testing and approximate dimensional measurement positions.

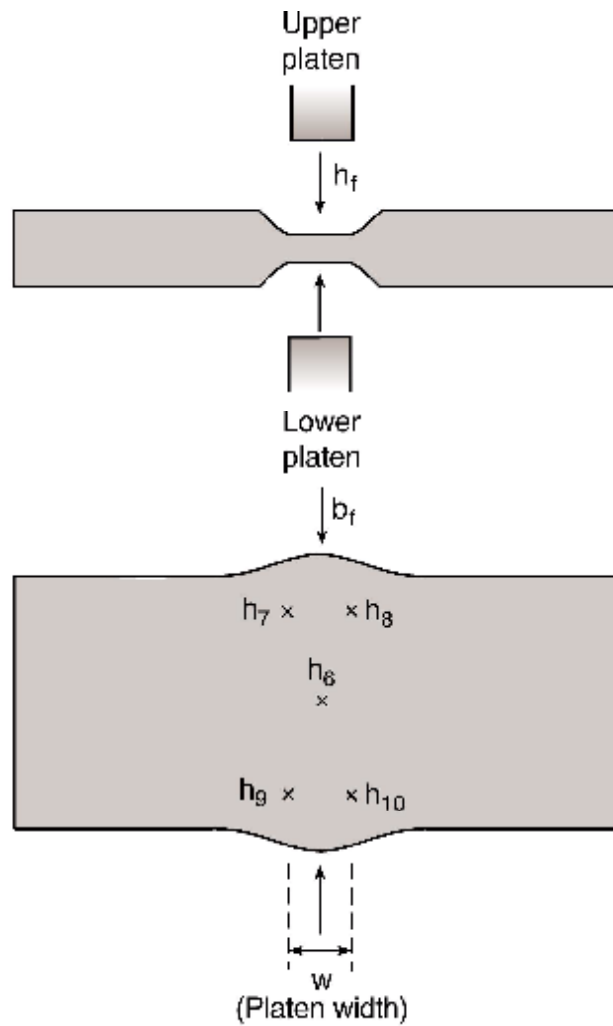


Figure A2 Schematic diagram of testpiece after testing and approximate dimensional measurement positions.

A.1 Thickness Coefficient C_h Validity

C_h gives an indication of the parallelism of testpiece deformation. If $C_h > 0.04$ the test is invalid.

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 close to the testpiece edges the midpoint of the micrometer spindle should be aligned with the edge of the testpiece.

For example, following deformation of a 10 mm thick testpiece (see Appendix A).

$$\begin{array}{ll} a) h_6 = 6.95 \text{ mm (centre)} & h_9 = 6.90 \text{ mm (edge)} \\ h_7 = 7.06 \text{ mm (edge)} & h_{10} = 6.94 \text{ mm (edge)} \\ h_8 = 7.00 \text{ mm (edge)} & \end{array}$$

(NB $h_1 - h_5$ are the height measurements prior to deformation.)

Therefore

$$h_f = 6.97 \text{ mm, and } C_h \text{ is } 0.009. \text{ The test is valid.}$$

$$\begin{array}{ll} b) h_6 = 7 \text{ mm (centre)} & h_9 = 6.6 \text{ mm (edge)} \\ h_7 = 7.3 \text{ mm (edge)} & h_{10} = 6.8 \text{ mm (edge)} \\ h_8 = 7.2 \text{ mm (edge)} & \end{array}$$

$$h_f = 6.98 \text{ mm, and } C_h \text{ is } 0.041. \text{ The test is invalid.}$$

Appendix B Test Report Pro-forma

Hot Plane Strain 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) Geometry Aspect Ratio (B_R) Length Ratio (l_R) Height Ratio (H_R) Applicable standard(s)*	A*
Testpiece information	Testpiece identification Testpiece thickness (initial), nominal Testpiece width (initial), nominal Cross-sectional area under platens (initial), nominal Surface finish (comment on method of manufacture)	mm mm mm ²

A* refer to Measurement Good Practice Guide No 27 and other documents if appropriate.

2. Testing organisation

<p>Organisation:-</p> <p>Name:-</p> <p>Date:-</p>

3. Details of test procedure

Reference	Description	Value	Units/Notes
Test procedure	Type of test	Hot Plane Strain Compression	
	Date of test		
	Applicable standard(s)*	A*	
	Test machine		
	Test environment		
	Temperature of test		°C
	Heating rate to test temperature		°C min ⁻¹
	Time to test temperature before test		min
	Temperature variation (Table 1)		°C
	Temperature uncertainty (Table 1)		°C
	Platen material		
	Platen surface finish		
	Lubricant		
	<i>Application Method</i>		
	Cooling Method		
	Cooling Rate		°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		
Strain measurement method			
Location of strain transducer			
Displacement calibration method			
Load calibration method			
Temperature calibration method			
Data collection method			
- Sampling rate			
Method of calculating results			
- Equivalent stress			
- Equivalent strain			

A* refer to Measurement Good Practice Guide No 27 and others if possible

4. Test Results

Reference	Description	Value	Units
Test results (individual values)	Maximum load Hot flow stress, $\bar{\sigma}$ Maximum - at 0.1 true strain - at 0.3 true strain Thickness strain - final value in test		N N mm ⁻² N mm ⁻² N mm ⁻²
Test validity	Initial thickness, h_0 Final thickness, h_f Initial breadth, b_0 Final breadth, b_f Height coefficient, C_h ? Breadth spreading coefficient, C_b ?		mm mm mm mm - -
Test results (full curves)	Record plots of: \bar{p} versus δ $\bar{\sigma}$ versus $\bar{\epsilon}$ <i>at true strain intervals of at least 0.01</i> $\bar{\epsilon}$ versus t T versus t <i>at time intervals sufficient to give 500 data points for the test</i>		

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 the Plane Strain Compression Test, the temperature of the testpiece may rise during testing due to deformational heating, although in practice it is rarely possible to provide adequate feedback control to compensate for this effect and maintain the testpiece at a uniform temperature, however it is essential 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. The magnitude of such deformation temperature changes may be large as discussed by Hand et al 2000, see Figure C1.

C.3 Traceability

In plane strain compression tests the temperature of the testpiece is generally 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 plane strain compression testing, (a) preheating furnaces, and (b) direct heating system, e.g. Gleeble machines.

In the former type, the testpiece is preheated in a furnace that is separate from the loading train. The testpiece is rapidly transferred from the heating station into the loading station, usually using some form of automated manipulation. In this case the testpiece monitoring thermocouple must have sufficiently long trailing leads to accommodate the movement between the two positions. It is simpler to verify that the preheating 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 Section 6.8.1 the testpiece temperature should be within ± 10 °C ($T < 800$ °C) 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 two 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 direct 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 tolerances of $\pm 10\text{ }^{\circ}\text{C}$ ($T < 800\text{ }^{\circ}\text{C}$) as specified in Section 6.8.1 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.

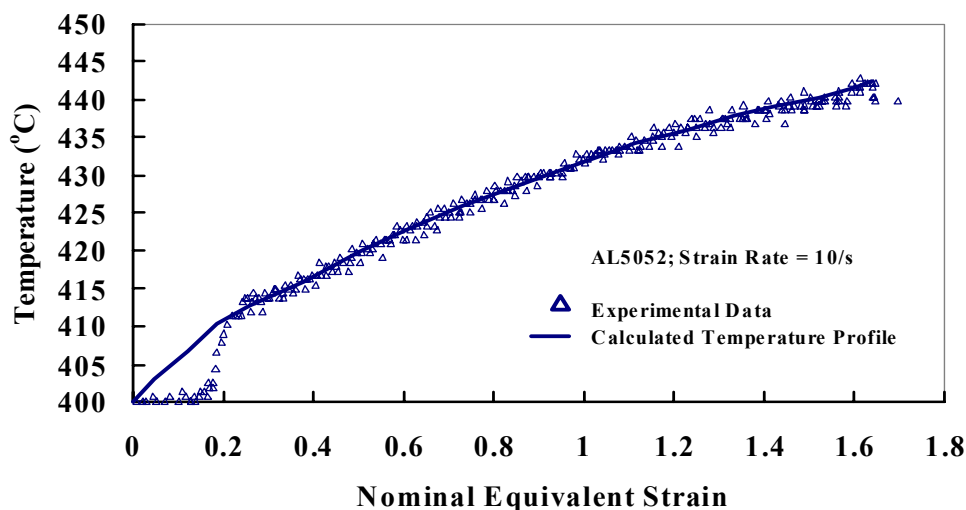


Figure C1 Deformational Temperature Change.

Appendix D Breadth Spreading Correction

D.1 Analytical Approach

A satisfactory empirical relationship was previously reported by Sellars et al (1976), which defined a ‘spread coefficient’ C_b from the specimen dimensions before and after a test.

$$C_b = \frac{(b_f / b_o) - 1}{1 - (h_f / h_o)^{0.5}} \quad (D1)$$

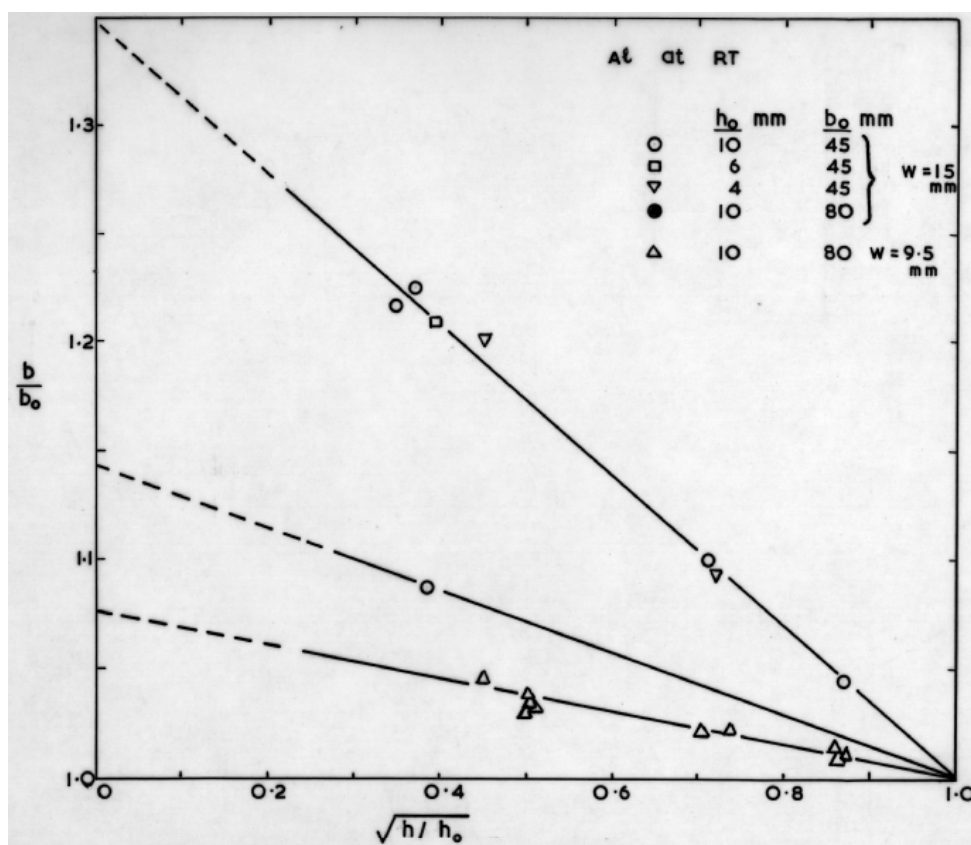


Figure D1 Increase in specimen breadth with deformation in plane strain compression tests at room temperature.

where b_f is the average breadth after deformation, b_o is the average breadth before deformation, h_f is the average thickness after deformation, and h_o is the average thickness before deformation.

More recently, Shi et al (1997a) indicated that the exponent in equation (D1) should be nearer 0.18 for aluminium specimens lubricated with graphite. Numerical analysis of a large number of aluminium specimens tested to different strains using water based graphite lubricants in place of the original oil based lubricants has required the exponent in equation (D1) to be modified to 0.18. Using the adjusted equation, the breadth at an intermediate time, b , is currently estimated using

$$b = b_o [1 + C_b - C_b (h/h_o)^{0.18}] \quad (D2)$$

For other materials, the optimum exponent should be determined, although as long as a consistent value is used in equations (D1) and (D2) the effect is relatively small, Figure D2.

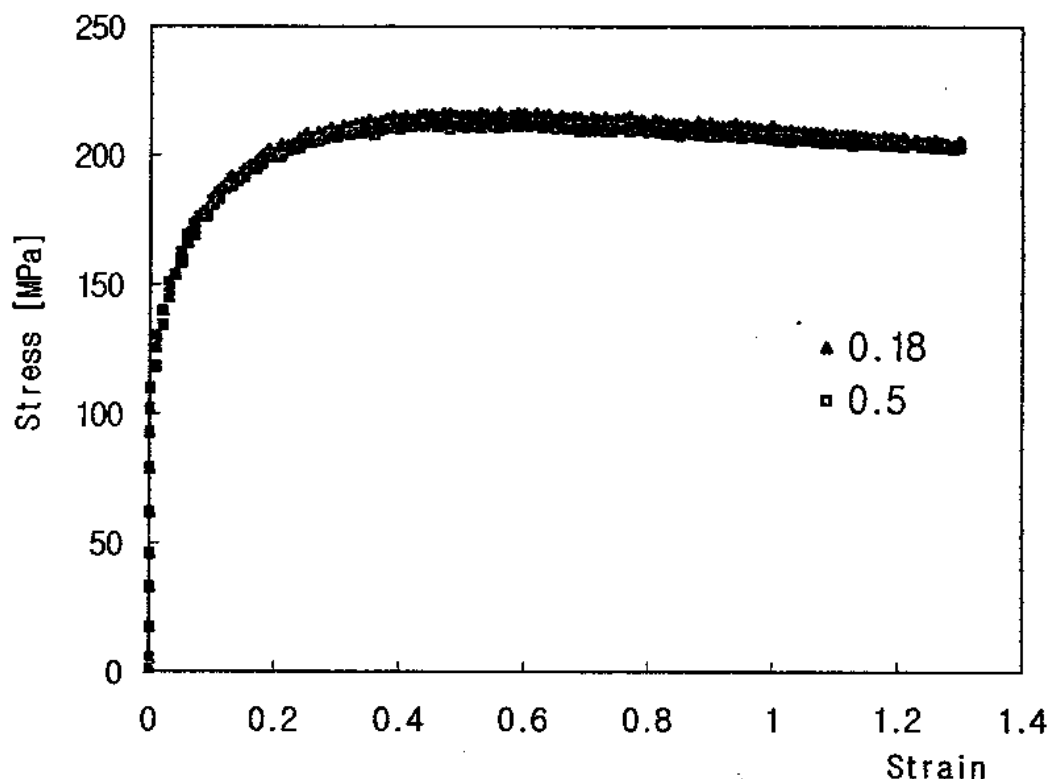


Figure D2 Equivalent stress/strain curve drawn using different spread coefficients (a) exponent $n = 0.5$; (b) exponent $n = 0.18$. Strain rate = 1 s^{-1} . Temperature = $1000 \text{ }^\circ\text{C}$ [Choi (1999)].

D.2 Finite Element Models

Determining the exponent in expression D1 for given values of b_0 , h_0 and μ experimentally is time consuming and requires testing specimens to various levels of strain, measuring average breadth and thickness at each strain and fitting equation D1 to the data. Finite element modelling provides a more accurate and less time consuming alternative approach for obtaining the spread coefficient, and this is illustrated in the worked example in Appendix J.

During a test it is necessary to estimate the spread to calculate equivalent strain (see Appendix G), which is in turn used to control the test machine to give a constant strain rate.

Appendix E Origin Correction

[Based on Silk & van der Winden, 1999].

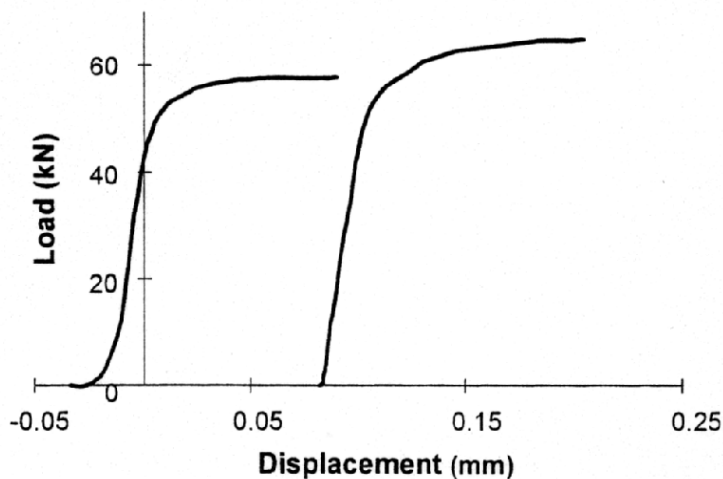
The application of lubricants complicates the determination of the start of specimen deformation. The PSC machine at the University of Sheffield was initially used mainly for deformation of steel specimens at high temperature ($> 800\text{ }^{\circ}\text{C}$). In this temperature region, graphite cannot be used and, normally, glass lubricants are applied, which can be up to 0.2 mm in thickness before deformation. To correct for the effect of excess glass being squeezed from the specimen/tool interface at the very beginning of the deformation, a method was originally proposed by Colas-Ortiz, (1983).

In recent tests conducted entirely on aluminium specimens with and without graphite lubricant, it was found that the graphite layers are so thin ($< 0.02\text{ mm}$) that ‘squeezing out’ does not significantly influence the load response. Indeed, it was found that there was some uncertainty in the origin even when testing unlubricated specimens. These experiments showed that any ambiguity in the origin arises from the tools being slightly misaligned from front to back (i.e. the tool faces not being perfectly parallel, and/or the specimen not being perfectly parallel across its width). The error introduced by these phenomena is $\sim 0.05\text{ mm}$ (for a specimen 50 mm in width). Therefore, it is believed that the method appropriate to correct for the squeezing out of the lubricant, which ‘artificially’ cleans up any effect of misalignment, is not justified for graphite lubrication. Obviously, the effect of this ‘misalignment’ disappears on subsequent deformations of the same specimen, where the specimen has deformed to the shape of the tools, as can be seen in Figure E1.

Therefore, the appropriate correction to apply to the raw data should be for possible errors in the zero position. This is done by measuring the mean thickness of the specimen after deformation. This value is then corrected for the thermal expansion of the specimen. (Thermal expansion must also be taken into account when calculating the initial thickness of the specimen from the ‘cold’ measurements.) From the initial and final ‘hot’ thicknesses, the maximum displacement of the tool $\delta_{\text{measured}}^{\text{max}}$ is derived. This is compared with the maximum displacement recorded by the displacement transducer on the PSC machine $\delta_{\text{nominal}}^{\text{max}}$. Any discrepancy between these two values is now corrected for by shifting the load-displacement curve in such a way that the maximum actuator displacement is equal to the maximum measured displacement. Thus,

$$\delta'_{\text{corr}} = \delta_{\text{nominal}} - (\delta_{\text{nominal}}^{\text{max}} - \delta_{\text{measured}}^{\text{max}}) \quad (\text{E1})$$

$$= \delta_{\text{nominal}} - \delta_{\sigma_c} \quad (\text{E2})$$



3 Example of load-elongation curve for double deformation test carried out at 450°C and 2.5 s⁻¹

Figure E1 Examples of load-elongation curve for double deformation test carried out at 450 °C and 2.5 s⁻¹ on an Al alloy.

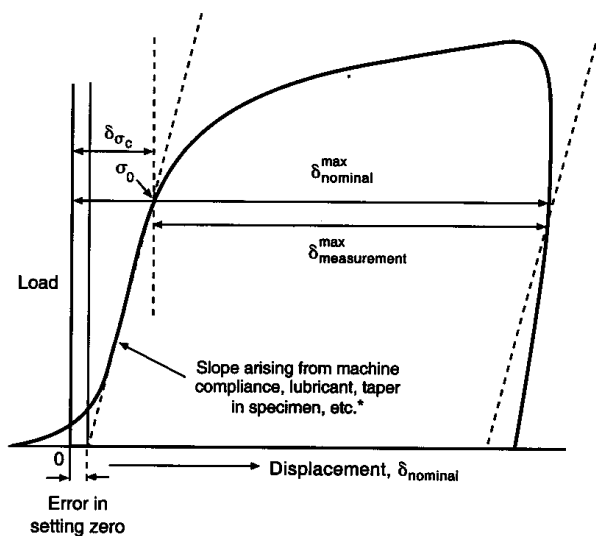


Figure E2 Schematic diagram showing origin correction symbols.

* Note - with graphite lubrication, electronic load compensation and ideal specimen geometry the slope of the initial part of the curve should be infinite and only an offset for error in setting zero may be required to obtain the corrected displacement, δ' .

If δ'_{corr} requires deformation to start at $\delta_{(\sigma_0)} \leq 0$ then an error in $\delta_{\text{nominal}}^{\text{max}}$ may have occurred because final readings, after the load decreases, are missing.

Appendix F Compliance Correction

Two approaches are given. The first is a general approach to compliance measurement while the second is based on Silk and van der Winden [1999].

F.1 General

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 from the load measurements in subsequent deformation tests. Thickness 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.

Conduct the compliance calibration with the top and bottom platens in direct contact. 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 loading with regular recording of displacements.

F.2 Load Elongation Compensation (LEC) - Silk and van der Winden

The PSC servohydraulic testing machine at The University of Sheffield has a machine stiffness of $\sim 410 \text{ kN mm}^{-1}$ (although this varies slightly as a function of temperature), which implies that, at maximum load, (450 kN), the machine frame and tooling will deform elastically by more than 1 mm. The control system incorporates an electronic circuit that automatically accounts for the stretch in the machine frame and adjusts the ram displacement as load is applied. The magnitude of the correction to the displacement readings is proportional to the instantaneous load and, in general, an analog correction for this effect is made online during the test by applying load-elongation compensation (LEC).

The load-elongation compensation circuit is calibrated by bringing the tools together without a testpiece between them. The machine is gradually loaded to its full capacity, unloaded and reloaded, and the change in displacement reading is noted as a function of load. The amount of compensation is varied through a helipot, and the required amount of compensation is that which does not lead to any variation in the displacement readings as the machine is loaded to full capacity. When properly compensated in this way, the machine effectively becomes infinitely stiff. The calibration is found to be

slightly sensitive to the test temperature and must be repeated each time a new temperature is used. Examples are given in Figures F1 and F2. Figure F1 shows uncorrected load-displacement data without the LEC circuit applied.

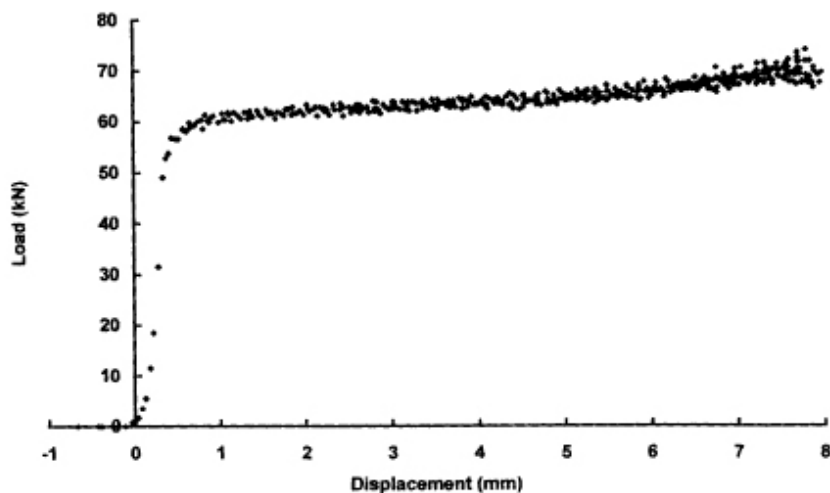


Figure F1 Raw Load-Displacement Data
(Aluminium AA5052, at 400 °C at strain rate of 0.1 per second)

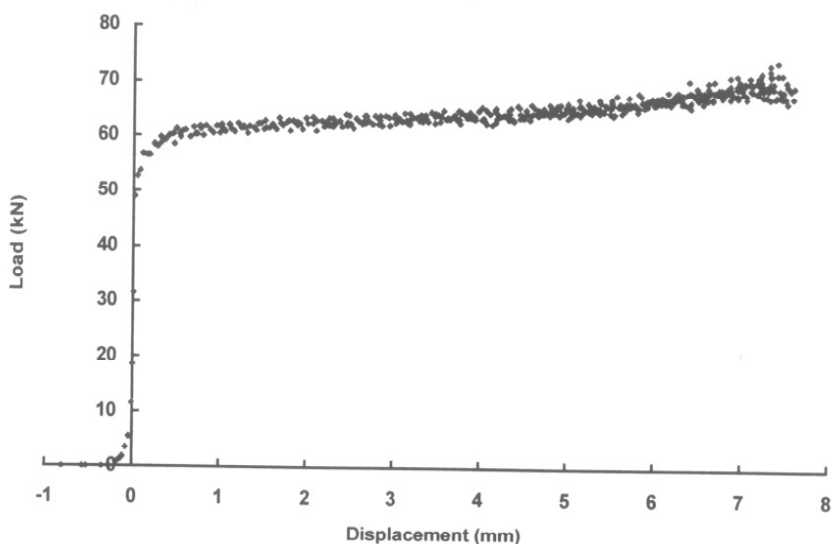


Figure F2 Load-Displacement Data Corrected for Machine Compliance
(Aluminium AA5052, at 400 °C at strain rate of 0.1 per second)

Appendix G Calculation of Equivalent Strain

G.1 Introduction

Equivalent strain, $\bar{\epsilon}$, is given by:

$$\bar{\epsilon} = \frac{\sqrt{2}}{3} [(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2]^{1/2} \quad (\text{G1})$$

If the equivalent tensile strain $\bar{\epsilon}$ in the testpiece deformation is calculated assuming **ideal** plane strain conditions, i.e. $\epsilon_1 = -\epsilon_3$ and $\epsilon_2 = 0$, then

$$\bar{\epsilon}^{\text{ideal}} = \frac{\sqrt{2}}{3} [\epsilon_3^2 + \epsilon_3^2 + 4\epsilon_3^2]^{1/2} = \frac{2}{\sqrt{3}} \epsilon_3 = \frac{2}{\sqrt{3}} \ln \frac{h}{h_0} \quad (\text{G2})$$

However, **accounting for lateral spread**, $\epsilon_3 = \ln (h/h_0)$, $\epsilon_2 = \ln (b/b_0)$, and $\epsilon_1 = -\epsilon_3 - \epsilon_2$. Then, by substitution, the equivalent strain, $\bar{\epsilon}$, is given by

$$\bar{\epsilon} = \frac{\sqrt{2}}{3} [(2\epsilon_2 + \epsilon_3)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_2 + 2\epsilon_3)^2]^{1/2} \quad (\text{G3})$$

$$\text{i.e. } \bar{\epsilon} = \frac{2}{\sqrt{3}} [(\epsilon_2^2 + \epsilon_2 \epsilon_3 + \epsilon_3^2)]^{1/2} \quad (\text{G4})$$

Because ϵ_2 ($\ln b/b_0$) is related to ϵ_3 ($\ln h/h_0$) by Equation D2, a factor, f , can be defined as:

$$\bar{\epsilon} = -f \epsilon_3 \quad (\text{G5})$$

In the limits of zero spread $f = 2 / \sqrt{3} = 1.155$, or, if the spread = extension, i.e. $\epsilon_{11} = \epsilon_{22}$ for axisymmetric conditions, then $f = 1$.

This equation is used after the test to convert the values of thickness at intermediate times into equivalent strain. However, during a test, it is necessary to calculate the equivalent strain at intermediate times online. This requires a very simple algorithm, as (even very modern) control systems cannot process the 'log function' quickly enough. Therefore, a nominal factor, f' , is calculated for use during the test from the initial breadth of the specimen and the tool width:

$$f' = \left((2 / \sqrt{3} (b_o - w) + w) / b_o \right) \quad (G6)$$

This first estimate, f' , is subsequently replaced by f during the post-processing of the data (off-line).

An example of the magnitude of the correction factor, f' , for a typical PSC testpiece geometry is given in section H2.

G.2 Experimental Evidence

Work carried out on lead at room temperature (i.e. hot working conditions, but no temperature gradient problems) is in the attached Figures G1 and G2, taken from the Report on Plane Strain Compression Testing at Elevated Temperatures, C M Sellars, J P Sah, J H Beynon and S R Foster, October 1976.

In the analysis of these data the value of f' was calculated from equation (G6).

$$\text{i.e. } f' = 1.155 - 0.155 b / w \quad (G7)$$

For the typical conditions of spread on a specimen $h_o = 10$ mm $b_o = 50$ mm, $f' \cong 1.02f$ and when $b_o = 15$ mm $f' \cong 1.01 f$. Thus the differences are negligible, and the corrections applied in the figure are still valid. The curves after correction are all within the reproducibility expected for repeat tests of the same geometry, with no systematic trend in Figure G1, when $(b_o/w)_{\min} = 2.6$, but possibly some in Figure G2, when $(b_o/w)_{\min} = 1.03$.

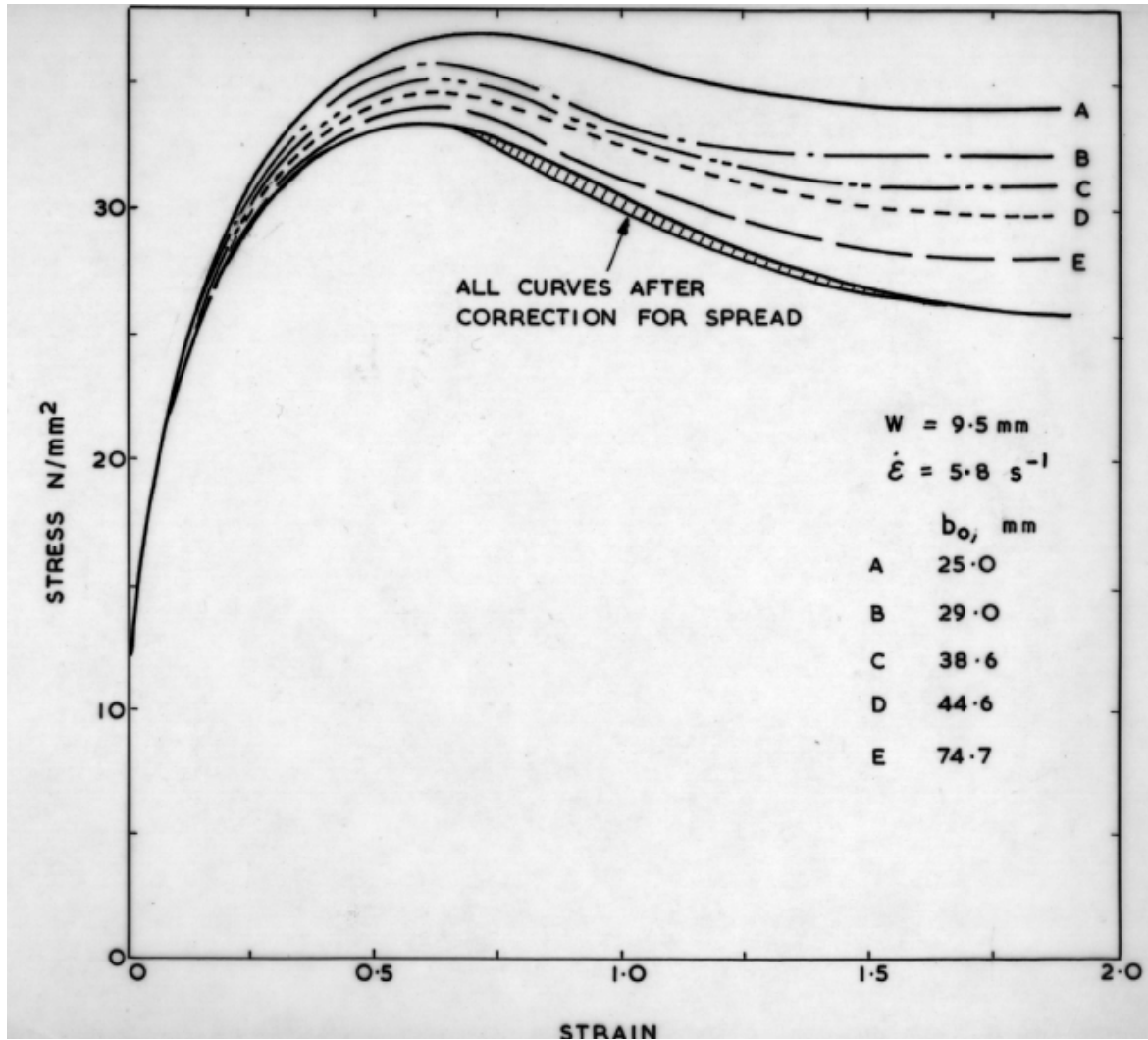


Figure G1 Plane Strain Compression test : Effect of the initial breadth on the stress - strain curves from lead. $w = 9.5\text{mm}$. Curves A-E without correction. Curves corrected for lateral spreading by equation (G7).

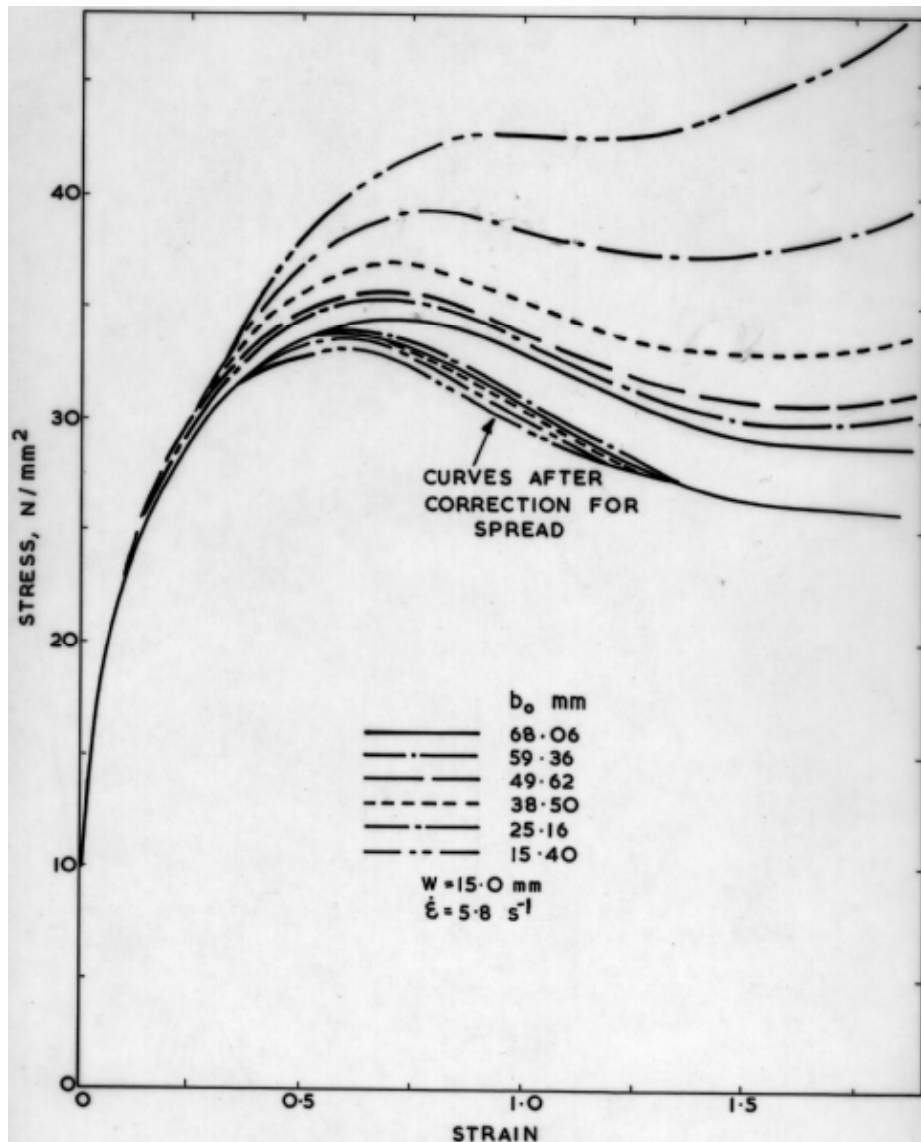


Figure G2 Plane Strain Compression test : Effect of the initial breadth at room temperature on the stress - strain curves from lead. $w = 15.0$ mm. $\dot{\epsilon} = 5.8$ s⁻¹. Curves corrected for lateral spreading by equation (G7). (Sellars et al, 1976)

Appendix H Friction Corrections

H.1 Analytical Approach

A ratio w/h of greater than 1.5 is required to avoid extremely localised (slip line field) deformation conditions but, as this ratio, increases, so the effect of friction increases. Increased friction between the tools and the specimen increases the pressure required to produce yielding.

Hill (1950) derived an approximation for the conditions during rolling that may also be applied to PSC testing. Assuming small values of μ (sliding friction) and $w > h$, Rowe (1965) derived an expression to describe the average pressure exerted by the tools in terms of the shear flow stress, k .

$$\frac{\bar{p}}{2k} = \frac{h}{\mu w} [\exp[\mu w / h] - 1] \quad (\text{H1})$$

where μ is the friction coefficient. For sticking friction conditions, relative movement of the specimen and tools is by shearing of the material at the interface rather than sliding between the specimen surface and the tool surface. However, a modified form of the analysis enables a similar expression for sticking friction conditions to be derived.

$$\frac{\bar{p}}{2k} = 1 + \frac{w}{4h} \quad (\text{H2})$$

It is to be noted that equations (H1) and (H2) are only valid when either sliding or sticking friction conditions apply over the entire tool face. However, there may be an intermediate situation when the sticking condition exists only in the central region and the outer edges have sliding friction conditions. The position where the friction changes from sliding to sticking friction conditions z_0 may be found by equating the dp/dx terms of the equations for sliding and sticking friction. This yields

$$z_0 = \left(\frac{h}{2\mu} \right) \ln \left(\frac{1}{2\mu} \right) \quad (\text{H3})$$

The friction conditions become ‘partially sticking’ if $w > 2z_0 > 0$. It should be noted that z_0 is dependent on the thickness of the testpiece.

In cases where b is less than six to eight times the testpiece thickness, additional analysis is required.

Further details of the appropriate equations to be used for calculation of the position, z_0 , at which the friction require changes from (a) sliding, (b) partially sticking and (c) sticking, are given below, based on the work published by Silk and van der Winden (1999).

In practice, there will always be some spread which relaxes the frictional effects at the edges of the specimen. Orowan and Pascoe accounted for this effect for the case of sticking friction. They suggested that, at large specimen breadths, the correction is relatively insignificant, but if the breadth is less than six to eight times the specimen thickness, such a correction becomes essential.

The method used by Orowan and Pascoe can be extended to derive expressions for all frictional conditions, and this leads to additional terms in each of the friction equations, which may be summarised as follows:

If $2z_0 > w$ (sliding friction)

$$\frac{\bar{p}}{2k} = \frac{1}{bw} \left[\frac{2h^2}{\mu^2} + \frac{(b-w)h}{\mu} \right] \left[\exp \left(\frac{\mu w}{h} \right) - 1 \right] - \frac{2h}{\mu b} \quad (\text{H4})$$

If $w > 2z_0 > 0$ (partial sticking friction)

$$\begin{aligned} \frac{\bar{p}}{2k} = & \frac{h}{\mu w} \left(\frac{1}{2\mu} - 1 \right) + \frac{(w/2) - z_0}{\mu w} + \frac{[(w/2) - z_0]^2}{hw} \\ & + \frac{1}{\mu b} \left(\frac{2z_0^2}{w} - z_0 - \frac{2hz_0}{\mu w} + \frac{h}{2\mu} - h + \frac{h^2}{w\mu^2} - \frac{2h^2}{\mu w} \right) \\ & + \frac{1}{hb} \left(z_0^2 - \frac{4z_0^3}{3w} - \frac{w^2}{12} \right) \end{aligned} \quad (\text{H5})$$

If $0 > 2z_0$ (sticking friction)

$$\frac{\bar{p}}{2k} = 1 + \frac{w}{4h} - \frac{w^2}{12hb} \quad (\text{H6})$$

These correction factors can be calculated quickly by modern PCs and z_0 is calibrated at each increment through the test using the current value of h . The value of z_0 is then used to determine which friction conditions prevail and the values of breadth and thickness b and h and substituted in equations H4 - H6 to determine k from the measured values of \bar{p} . The equivalent flow stress is then given by

$$\sigma = 2k/f \quad (\text{H7})$$

where f is a factor discussed in Appendix G.

H.2 Finite Element Modelling

Finite element modelling of deformation in plane strain compression tests (Mirza and Sellars, 2001 – Part 1) clearly shows the inhomogeneous distribution of strain, and the influence that the coefficient of friction has on it. Computed loads also show a marked effect of the coefficient of friction, Figure H1.

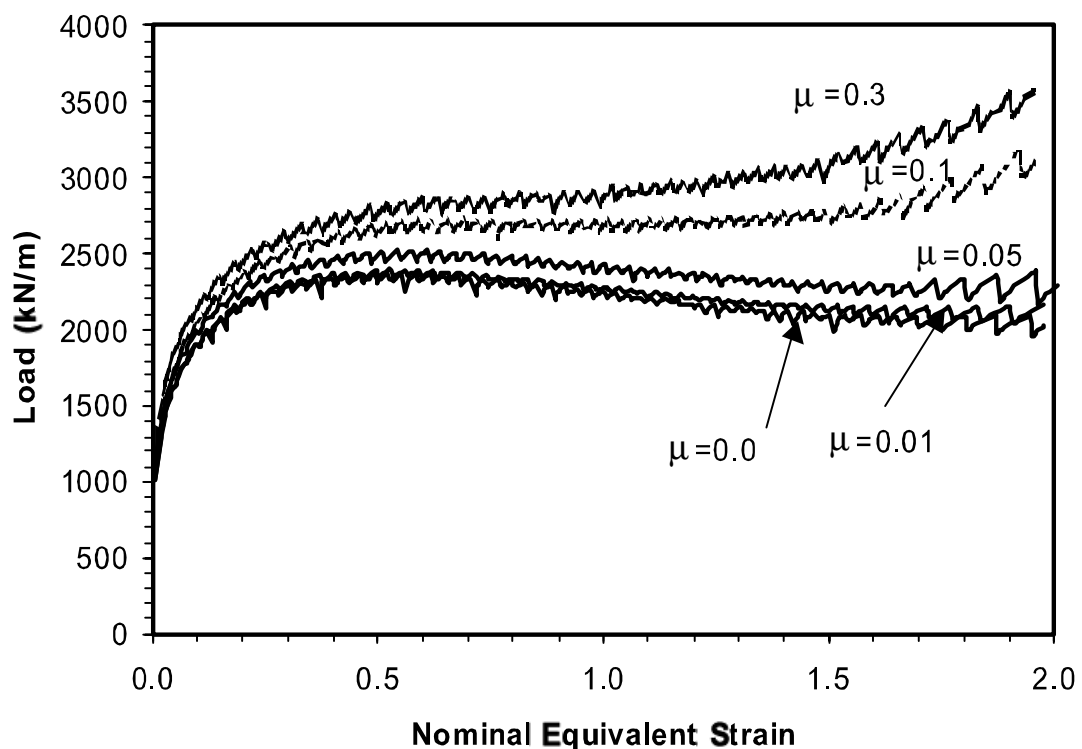


Figure H1 Effect of increasing friction coefficient on the load required to deform a SS316 specimen with $h_0=10\text{mm}$, $\dot{\epsilon}=10\text{s}^{-1}$, 1000°C

Calculation of the expected ratio of $\bar{p} = 2k$ from equations (H4) and (H5) (simplified in this case, because 2D modelling is equivalent to $b \gg w$) leads to the values of load/width (L/W) given in Table H1 assuming $\bar{p} = 2k$ when $\mu = 0$.

Table H1

Calculated loads/width from equations (H4) and (H5) at an equivalent strain of 1.0 for tool width $w = 15$ mm and $h_0 = 10$ mm.

μ		\bar{p}	L/w kN m ⁻¹
0.00		1.000	(2240)
0.01	Eq (H4)	1.018	2280
0.05	Eq (H4)	1.095	2453
0.10	Eq (H4)	1.201	2690
0.30	Eq (H5)	1.738	3893

Comparison of the measured load values with the computed ones in Figure H1 shows satisfactory agreement for slipping friction conditions, but a serious overestimate once partial sticking friction occurs, i.e. $w > 2 Z_0$, and equation (H5) is applied. The overestimation increases as Z_0 decreases towards zero, so the value of Z_0 should be calculated before applying the analytical approach for friction correction.

Using 3D finite element modelling to compute the spread in specimen breadth (b) as a function of specimen geometry and coefficient of friction (Mirza and Sellars, 2001 – Part 2) shows a significant effect of the coefficient of friction in reducing the amount of spread, Figure H2.

The computations also show close agreement between the computed spread and equation (D2) obtained from experimental data. Furthermore, equation (G6) for the correction factor to convert experimental data to equivalent tensile values is shown to be surprisingly accurate for a wide range of specimen geometries and coefficients of friction

An alternative approach to that provided by analytical procedures is to use FE modelling. A new data analysis package (see Appendix J) has been developed at the University of Sheffield for this purpose and a worked example is given in Appendix K.

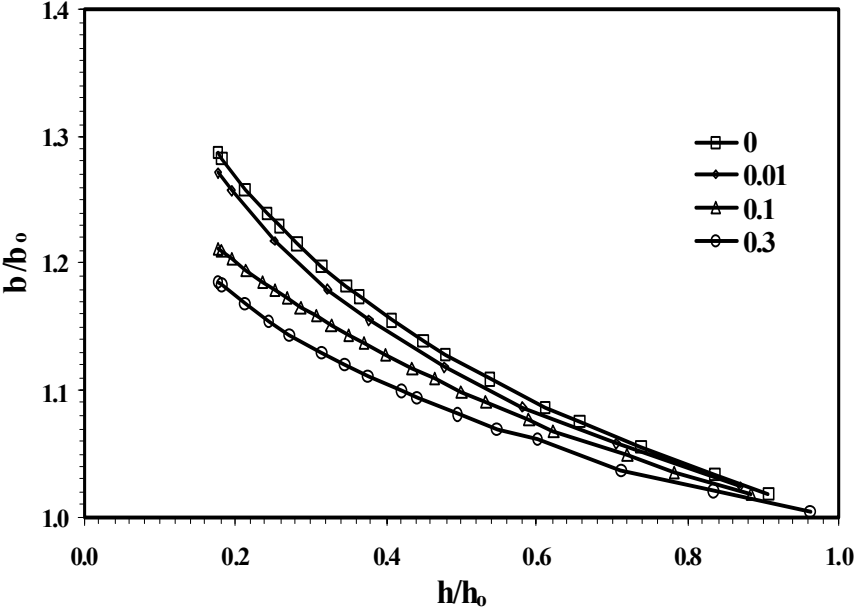


Figure H2 Effect of friction coefficient on the dependence of b/b_0 on h/h_0 for $b_0=50$ mm, $h_0=10$ mm

Appendix I Deformational Heating Correction

A significant rise in temperature takes place during testing at the strain rates of interest for hot working, as discussed in Section 6.8 and Appendix C. However, at strain rates less than $\sim 25 \text{ s}^{-1}$ the temperature rise due to deformational heating cannot be considered to be adiabatic for two reasons: (1) heat conduction from the deformation zone to the undeformed ends of PSC specimens, (2) heat transfer from the deformation zone through the lubricant film to the platens (Hand et al, 2000). In deriving constitutive equations from the measured stress-strain curves (Davenport et al, 2000) it is important to use the instantaneous value of temperature at each strain when correlating the flow stress values with strain rate. Ideally, the temperature (T_{inst} , K) is the mean value in the active slip line fields, but finite element modelling shows that this is close to the mean value in the deformation zone. The computed values of mean temperature in the deformation zone for nominally isothermal tests i.e. tests in which the platens, specimen and environment (furnace chamber) are all at the same initial temperature, are always slightly lower than the centre temperature, but for normal heat transfer coefficients to the platens, the differences are less than 4K (Hand et al, 2000). For practical purposes, a measured instantaneous centre temperature may therefore be used, except at small strains, when poor thermal contact between the thermocouple bead and the specimen may lead to an underestimate of the specimen temperature, as illustrated in Figure C1.

When a constitutive equation has been derived, this can be considered as an equation of state for most materials for the rates of change of temperature (and strain rate) encountered for nominally isothermal tests. The constitutive equation can then be applied together with the values of instantaneous temperature to derive true isothermal (or constant Zener Hollomon parameter) stress-strain curves, as shown in Appendix J.2. Such corrected isothermal curves are advantageous for comparison with the stress-strain curves from other test methods, in which heat transfer conditions differ from those in PSC.

Appendix J The Effect of Inhomogeneous Deformation on Flow Stress

Finite element modelling of the inhomogeneous nature of the plane strain compression test has facilitated the correction of flow stress curves for the effects of local strain and strain rate inhomogeneity allowing the true shape of the flow stress curve to be obtained. A data analysis package (Kowalski, 2002) has been developed at Sheffield, to carry out the corrections for elastic deformation, spread in the specimen breadth and friction effects. In addition a method of correction for the effects of inhomogeneous deformation has also been developed (Kowalski, Lacey & Sellars, 2002) and is incorporated into the data analysis software. An outline of the correction method is given below.

Figure J1 shows equivalent stress - equivalent nominal strain for three specimens of aluminium alloy AA5052. The specimens were lubricated with graphite and deformed at a temperature of 300 °C and strain rate of 3 s⁻¹. The specimens were of initial thickness 10 mm, 5 mm and 2.5 mm. A friction coefficient of 0.02 was used as an initial estimate.

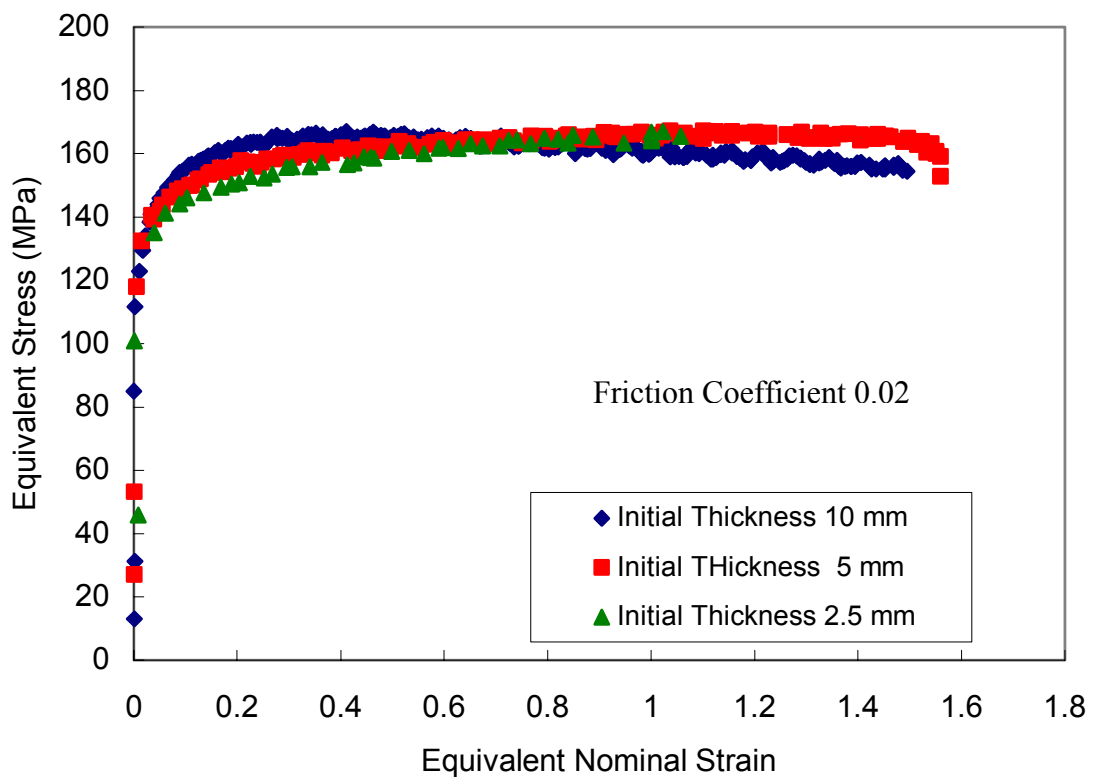


Figure J1 PSC data corrected for Spread in Specimen Breadth and Friction

Before a better estimate of the friction coefficient can be obtained the data have to be corrected for the effects of temperature rise during the deformation [Appendix I]. This is achieved using the equation

$$\sigma_{iso} = \sigma + \frac{Q}{\beta R} \left(\frac{1}{T_{iso}} - \frac{1}{T_{inst}} \right) \quad (J1)$$

where σ_{iso} is isothermal stress (i.e. corrected for temperature rise during deformation)

Q is Activation energy of deformation (156 kJ m⁻¹ K⁻¹ in the case of AA5052)

R is the Universal gas constant

T_{iso} is the desired isothermal temperature

T_{inst} is the instantaneous temperature recorded using a thermocouple embedded in the specimen or by a modelled temperature using a finite difference model (Hand, Foster, Sellars, 2000).

β is the material strength constant calculated from the following equation:

$$\ln Z = \beta \sigma + A \quad (J2)$$

where Z is the Zener – Hollomon parameter

A is a constant.

The value of β is obtained at several values of nominal strain and a curve fitted through the data in the form of a power law:

$$\beta = a \cdot \varepsilon_{nom}^b \quad (J3)$$

where ε_{nom} is nominal equivalent strain

a and b are constants. In this example $a = 0.0711$ and $b = -0.1837$

Figure J2 shows the effect on the flow stress curves after correction for temperature rise during deformation using equation (J1). The curves now show reasonable agreement towards higher strains, where the deformation is more homogeneous but the effect of inhomogeneous deformation is apparent in the flow stress in the strain

range 0 – 0.6, where specimens of different initial geometry show different levels of stress. The selection of the value of friction coefficient would seem to be reasonable in this case but there is evidence that the curves are beginning to diverge at higher strains indicating that the friction coefficient may have too high a value. However selecting a lower value will bring the curves back together at higher strains but then none of the curves reach a steady state value at a strain expected for this material.

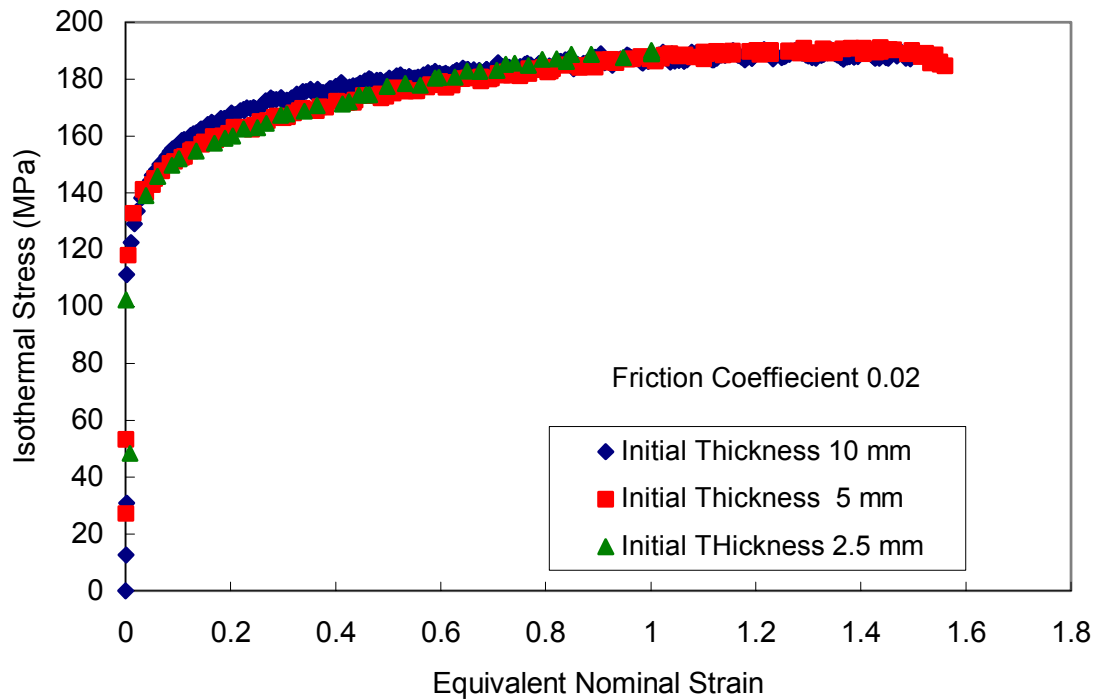


Figure J2 PSC data Corrected for Temperature Rise during Deformation

Analysis of the lubricant condition on the surface of the specimen after deformation shows evidence that the lubrication conditions are not the same for each specimen geometry. To deform each specimen to the same strain requires a greater specimen displacement in the specimen with initial thickness 10 mm than in the specimen with initial thickness 2.5 mm. The lubrication remaining after deformation of the specimen with initial thickness 10 mm has more evidence of breakdown than that on the thinner specimen. For this reason a simple linear relationship has been assumed between the friction coefficient and specimen displacement allowing the friction coefficient to vary according to the following equation:

$$\text{Friction coefficient} = c \cdot \delta_{spec} + \mu_0 \quad (\text{J4})$$

where δ_{spec} is specimen displacement

c and μ_0 are constants equal to 0.0041 and 0.03 respectively in this example.

The effect on the isothermal curves of allowing the friction coefficient to vary is shown in figure J3.

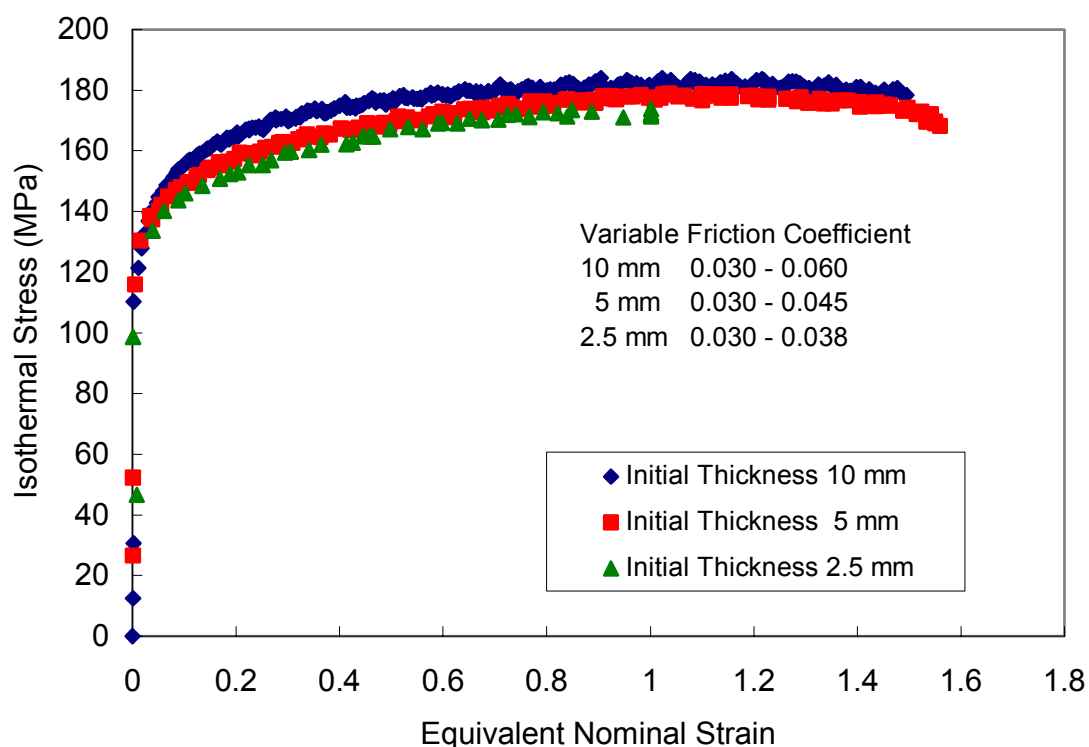


Figure J3 Isothermal Stress with Linear Variable Friction Coefficient

The curves no longer converge at higher strains but steady state is reached in each case at an approximate nominal strain of 1. The effect of specimen geometry on the flow stress level is now more apparent, with each specimen achieving a distinct level. This difference in flow stress is caused by the inhomogeneous distribution of strain rate and strain during the deformation. To correct for these effects an FE model has been used to predict the distribution of strain and strain rate (Kowalski, Lacey and Sellars, 2002) and is described by the following equations.

The strain rate distribution is given by:

$$\frac{\dot{\epsilon}_{SLF}}{\dot{\epsilon}_{nom}} = 1 + \left[A \exp\left(-\frac{(w/h) - 1}{B - 1} \right) \right] \quad (J5)$$

where $\dot{\epsilon}_{SLF}$ and $\dot{\epsilon}_{nom}$ are strain rate in the currently active slip line field and nominal strain rate respectively.

w is the tool width (15 mm) and h is the instantaneous specimen height .
 A, B are optimised constants with values 0.8 and 5.5 respectively.

The mean strain in the currently active slip line field is given by the following equation:

$$\epsilon_{SLF} = (s_o - 1) \cdot \left[m \cdot \sin\left(\frac{1}{\epsilon_{nom} + n}\right) \right] + \epsilon_{nom} \quad (J6)$$

where ϵ_{SLF} is the strain in the slip line field

m and n are optimised constants with values 0.25 and 0.32 respectively

s_o is a constant depending on the initial specimen thickness

$s_o = 1.50$ for specimen of initial thickness 10.0mm

$s_o = 1.25$ for specimen of initial thickness 5.0mm

$s_o = 1.10$ for specimen of initial thickness 2.5mm

The effect on the flow stress is shown in figure J4.

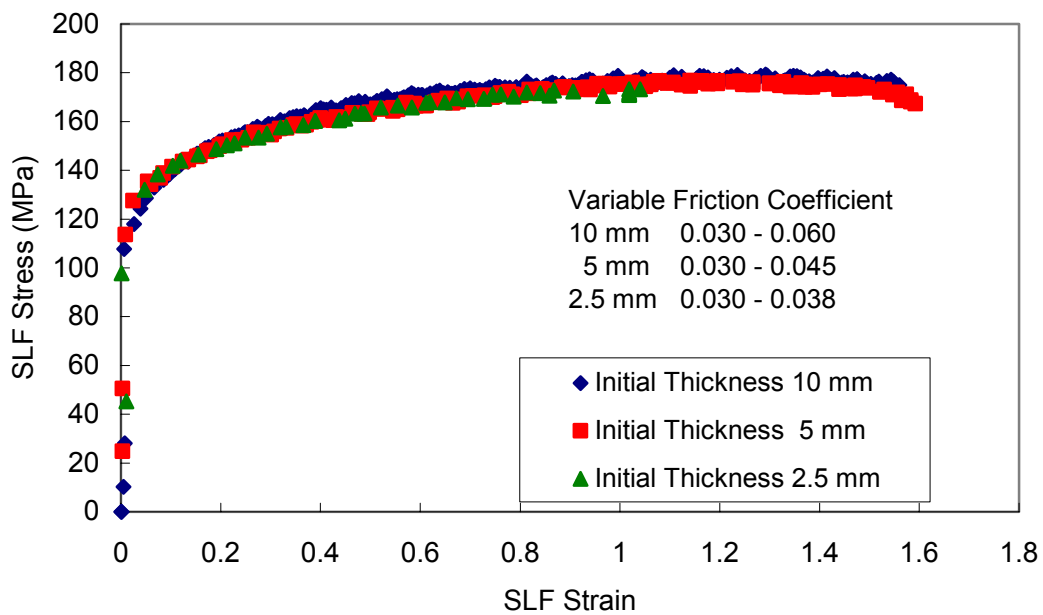


Figure J4 PSC data Corrected for Effects of Temperature Rise, Friction Conditions and local Strain and Strain Rate Inhomogeneity

It can be seen that the effect of specimen geometry has been eliminated and the three curves are superimposed within the limits of experimental error. The curves achieve steady state at a corrected strain of 1.1 when the friction coefficient is allowed to increase as the deformation proceeds, and the true shape of the flow stress curve is revealed. The above corrections for the effect of strain and strain rate inhomogeneity are not material specific and can be applied to other materials and deformation conditions without changing the constants in the equations (J5) and (J6).

Appendix K Worked Examples

K.1 Calculation of Equivalent Stress – Nominal Equivalent Strain

Two worked examples are given. The first is based on the use of an analytical approach (described in Appendices D to H) to obtain the stress vs nominal equivalent strain curve. The second example, in Appendix K.2, used the approach described in Appendix J to deal with effects of inhomogeneous strain and strain rate distribution in the testpiece.

A test was performed on a specimen of low carbon steel with dimensions shown in Table K1. The average dimensions were corrected for thermal expansion using an average thermal expansion coefficient of $1.7 \times 10^{-5} \text{ K}^{-1}$. The test was performed under conditions of constant nominal temperature 1000°C and nominal equivalent strain rate 5 s^{-1} .

Table K1. Testpiece dimensions, corrected for thermal expansion.

Specimen dimensions (mm)								
	h_1	h_2	h_3	h_4	h_5	b_1	b_3	b_2
Initial	10.188	10.120	10.133	10.137	10.110	50.190	50.320	50.210
Final	1.985	1.995	2.014	2.007	1.991	56.360	59.860	56.050
Average dimensions (mm)								
Cold			Hot			$T_o = 1000 \text{ }^\circ\text{C}$		
h_o	10.138		h_o	10.311				
h_f	1.998		h_f	2.030				
b_o	50.240		b_o	51.073				
b_f	58.033		b_f	58.990				
w	15.000		w	15.250				

Selected values of displacement, load and temperature from the raw data produced are shown in columns 2, 3 and 4 of Table K2. The complete load vs displacement data set is reproduced as Figure K1.

Table K2. Data recorded during a Plane Strain Compression test.

t s	δ mm	F kN	T °C	δ' mm	b mm	\bar{p} MPa	2k MPa	$\bar{\epsilon}$	f'	σ MPa
0.00	0.04	8.75	999	0.00	51.08	11.2	10.0	0.00	1.083	9.2
0.04	1.50	122.8	1003	1.20	51.93	155.0	135.9	0.13	1.086	125.2
0.07	2.78	143.5	1011	2.48	52.91	177.9	152.5	0.30	1.088	140.1
0.11	3.89	149.5	1016	3.59	53.82	182.2	152.0	0.47	1.091	139.4
0.15	4.82	149.5	1020	4.52	54.64	179.4	145.2	0.63	1.093	132.8
0.18	5.64	147.3	1023	5.34	55.43	174.2	135.9	0.80	1.096	124.1
0.22	6.35	146.8	1028	6.05	56.16	171.3	128.0	0.97	1.098	116.5
0.26	6.90	152.0	1031	6.60	56.78	175.6	125.2	1.12	1.100	113.8
0.29	7.43	160.8	1033	7.13	57.41	183.6	123.2	1.30	1.102	111.8
0.33	7.86	175.0	1038	7.56	57.96	198.0	124.2	1.46	1.104	112.5
0.37	8.26	196.8	1041	7.96	58.52	220.5	126.7	1.63	1.105	114.6

The data was analysed in the following sequence:

1. Correct for zero off-set (Origin correction, see Appendix E) and machine compliance (see Appendix F)
2. Calculate spread coefficient (see Appendix D)
3. Calculate equivalent strain (see Appendix G)
4. Determine friction correction factor (see Appendix H)
5. Calculate flow stress

Origin Correction

The raw displacement data were corrected for zero offset, machine compliance and squeezing out of excess glass lubricant (Colas – Ortiz, 1983). A straight line was fitted through the initial part of the curve as shown in Figure K1. The entire curve was then moved along the displacement axis so that the straight line passed through the origin to correct for any error in the zero position. The actual displacement was measured from the specimen and a vertical line drawn at a corresponding distance measured from the final recorded displacement data point. The position of the line, δ_0 , then gave the true specimen displacement by subtraction from the raw displacement data. The measured values of actual specimen displacement, gradient of the initial part of the curve and position of the vertical line, δ_0 , are shown in Figure K1. The curve of load vs origin corrected displacement is shown as Figure K2.

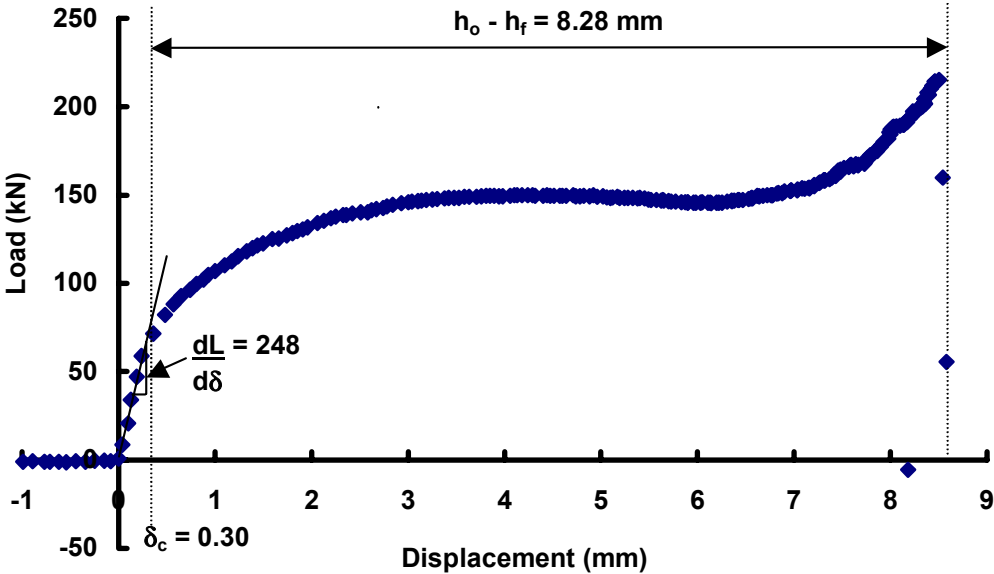


Figure K1 Plot of recorded raw data

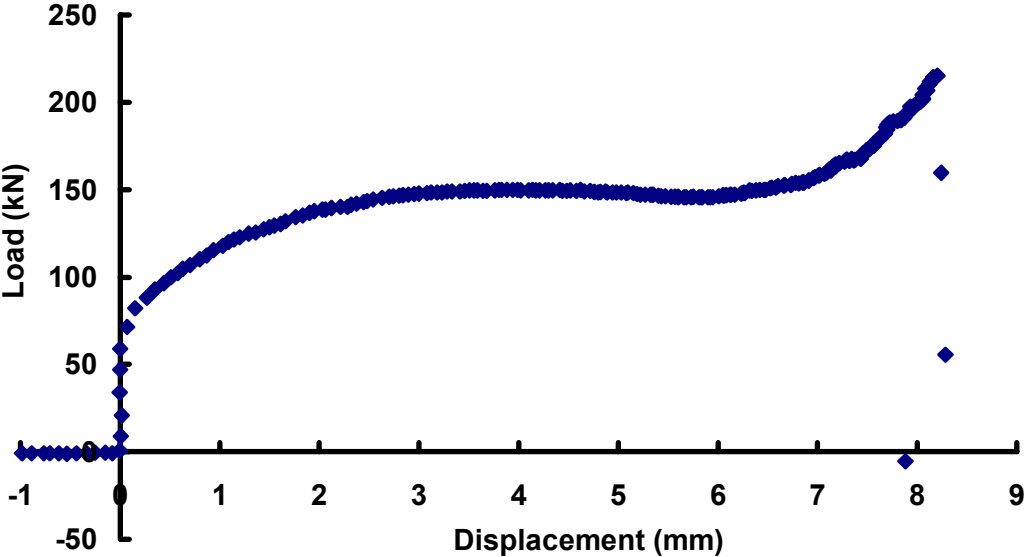


Figure K2 Plane strain compression test. Origin corrected data.

Instantaneous Pressure

The value of spread coefficient

C_b , was found to be 0.279 using Equation D1

$$C_b = \frac{(b_f / b_o) - 1}{1 - (h_f / h_o)^{0.5}} \quad (\text{K1})$$

where b_o, b_f and h_o, h_f are the initial and final (hot) specimen breadth and thickness respectively.

Values of instantaneous breadth were calculated using Equation D2 with an exponent of 0.5

$$b = b_o [1 + C - C(h / h_o)^{0.5}] \quad (\text{K2})$$

Instantaneous pressure was found from equation

$$\bar{p} = L / wb \quad (\text{K3})$$

where w is the hot tool width.

Selected values of b and \bar{p} are shown in Table K2.

The pressure curve is shown as Fig. K3

Flow Stress

The friction conditions occurring during the test were determined from the value for z_o , the position in the tool width where friction changes from sliding to sticking conditions.

$$z_o = \left(\frac{h}{2\mu} \right) \ln \left(\frac{1}{2\mu} \right) \quad (\text{K4})$$

The coefficient of friction, $\mu = 0.17$, thus $z_o < w/2$ when $h < 2.403$ mm and sticking friction begins to occur at the centre line of the tool width.

The predominant friction conditions for the present test are therefore sliding friction and shear flow stress, k , in terms of average pressure was found from Equation H4

$$\frac{\bar{p}}{2k} = \frac{1}{bw} \left[\frac{2h^2}{\mu^2} + \frac{(b-w)h}{\mu} \right] \left[\exp\left(\frac{\mu w}{h}\right) - 1 \right] - \frac{2h}{\mu b} \quad (K5)$$

For a reduction leading to $h < 2.403$ mm the friction conditions became partial sticking and the more complex equation (H5) was used, for example, for the last entry in Table K2. In this case the difference in $2k$ from equation (H4) is negligible, but for greater reduction (or higher friction coefficient) it would become significant.

The equivalent flow stress was then calculated from

$$\bar{\sigma} = \frac{2k}{f'} \quad (K6)$$

where f' is defined below.

The complete flow stress curve is shown in Figure K3, and selected values of $\bar{\sigma}$ are shown in Table K2.

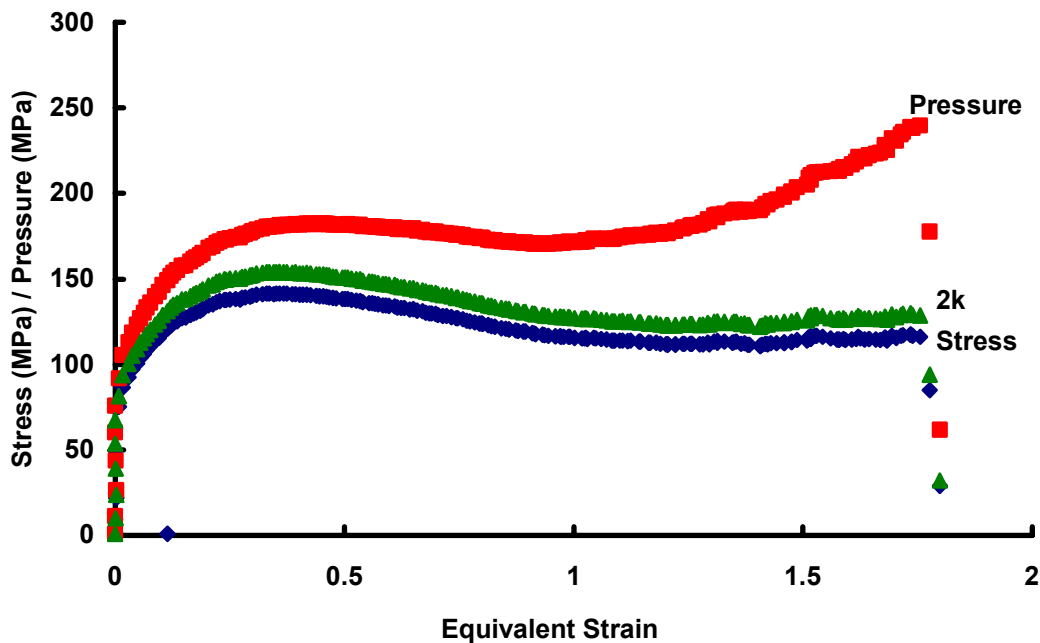


Figure K3 Plane Strain Compression Test

Upper curve: Instantaneous Pressure versus Equivalent Strain

Middle curve: Plane Strain Flow Stress versus Equivalent Strain

Lower curve: Corrected Equivalent Stress versus Strain Curve

Equivalent Strain

Equivalent strain is defined by Equation G4.

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} (\varepsilon_2^2 + \varepsilon_2 \varepsilon_3 + \varepsilon_3^2)^{0.5} \quad (\text{K7})$$

where $\varepsilon_3 = \ln h / h_o$ and $\varepsilon_2 = \ln b / b_o$

Because ε_2 is related to ε_3 by Equation D2, f' can be defined as

$$f' = -\bar{\varepsilon} / \varepsilon_3 \quad (\text{K8})$$

As shown in Appendix G, for true plane strain, when $\varepsilon_2 = 0$ then:

$$f' = 2 / \sqrt{3} = 1.155$$

For axisymmetric conditions, when $\varepsilon_2 = -\varepsilon_3 / 2$

$$f' = 1$$

Selected values of $\bar{\varepsilon}$ and f' are shown in Table K2.

K.3 Correction for Effects of Inhomogeneous Deformation

Flow stress is determined by the deformation conditions in the currently active slip line fields. For the development of constitutive equations for material flow stresses, they should be related to the instantaneous values of strain rate and temperature.

For the present example from equation (J5) Appendix J.

$$\dot{\varepsilon}_{\text{SLF}} = 1 + \left[0.8 \exp\left(-\frac{(15/h) - 1}{4.5}\right) \right] \dot{\varepsilon}_{\text{nom}}$$

where $\dot{\varepsilon}_{\text{nom}}$ is found from the values of t and δ in columns (1) and (2) of Table K2 by differentiation (Figure K4).

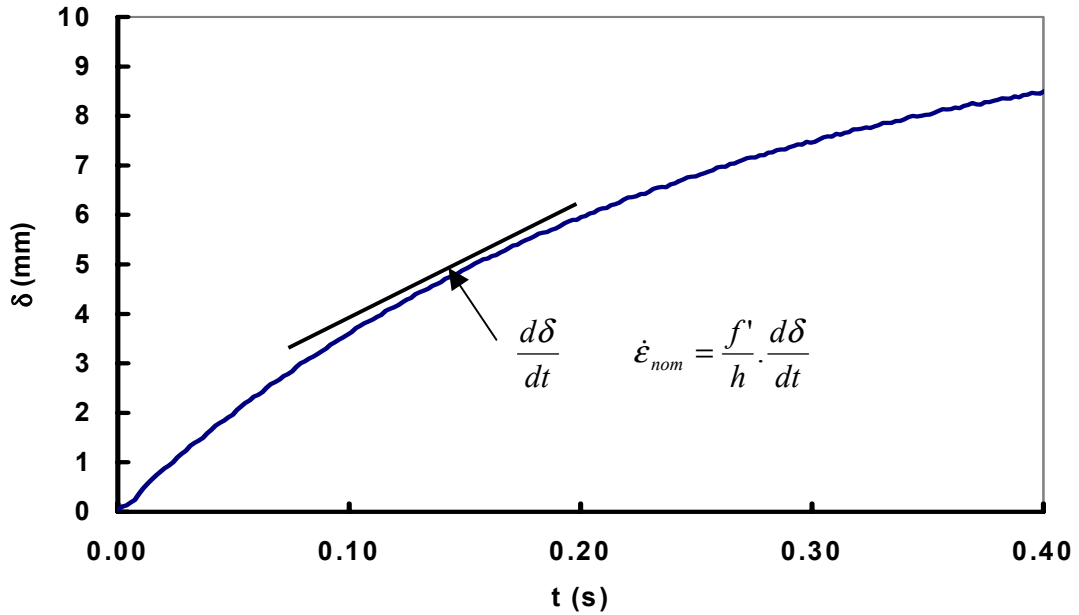


Figure K4 Calculation of nominal strain rate

The values of $\dot{\epsilon}_{nom}$ are given in column (2) of Table K3. The corrected instantaneous values of h are given by

$$\begin{aligned}
 h &= h_0 - (\delta - \delta_c) \\
 &= 10.138 - (\delta - 0.3)
 \end{aligned}$$

The results are shown in column (3) of Table K3. Hence the values of $\dot{\epsilon}_{SLF}$ in column (4) of Table K3 are found.

Table K3 Corrections for Inhomogeneous Deformation

t	$\dot{\epsilon}_{nom}$	h	$\dot{\epsilon}_{SLF}$	ϵ_{SLF}	$Z_{nom} (\times 10^{13})$	$Z_{SLF} (\times 10^{13})$
0.00	4.43	10.43	7.65	0.00	2.90	5.00
0.04	4.38	9.24	7.44	0.24	2.62	4.45
0.07	4.43	7.96	7.33	0.42	2.19	3.63
0.11	4.44	6.85	7.17	0.59	1.96	3.16
0.15	4.41	5.92	6.91	0.74	1.78	2.79
0.18	4.36	5.10	6.63	0.90	1.64	2.49
0.22	4.30	4.39	6.31	1.06	1.44	2.12
0.26	4.17	3.84	5.92	1.20	1.30	1.85
0.29	4.12	3.31	5.62	1.37	1.23	1.68
0.37	4.13	2.52	5.22	1.68	1.04	1.32

From equation (J6) in Appendix J

$$\epsilon_{SLF} = (0.5) \left[0.25 \sin \left(\frac{1}{\epsilon_{nom} + 0.32} \right) \right] + \epsilon_{nom}$$

substitution of $\bar{\epsilon} = \epsilon_{nom}$ from Table K2 gives the values of ϵ_{SLF} in column (5) of Table K3.

Also using the values of T, in Table K2, and $\dot{\epsilon}_{SLF}$ the instantaneous values of Z_{SLF} are obtained from

$$Z_{SLF} = \dot{\epsilon}_{SLF} \exp \left(\frac{Q}{RT} \right) \quad (K9)$$

Where $Q = 312 \text{ kJ mol}^{-1}$. For mild steel. (Fig. K5).

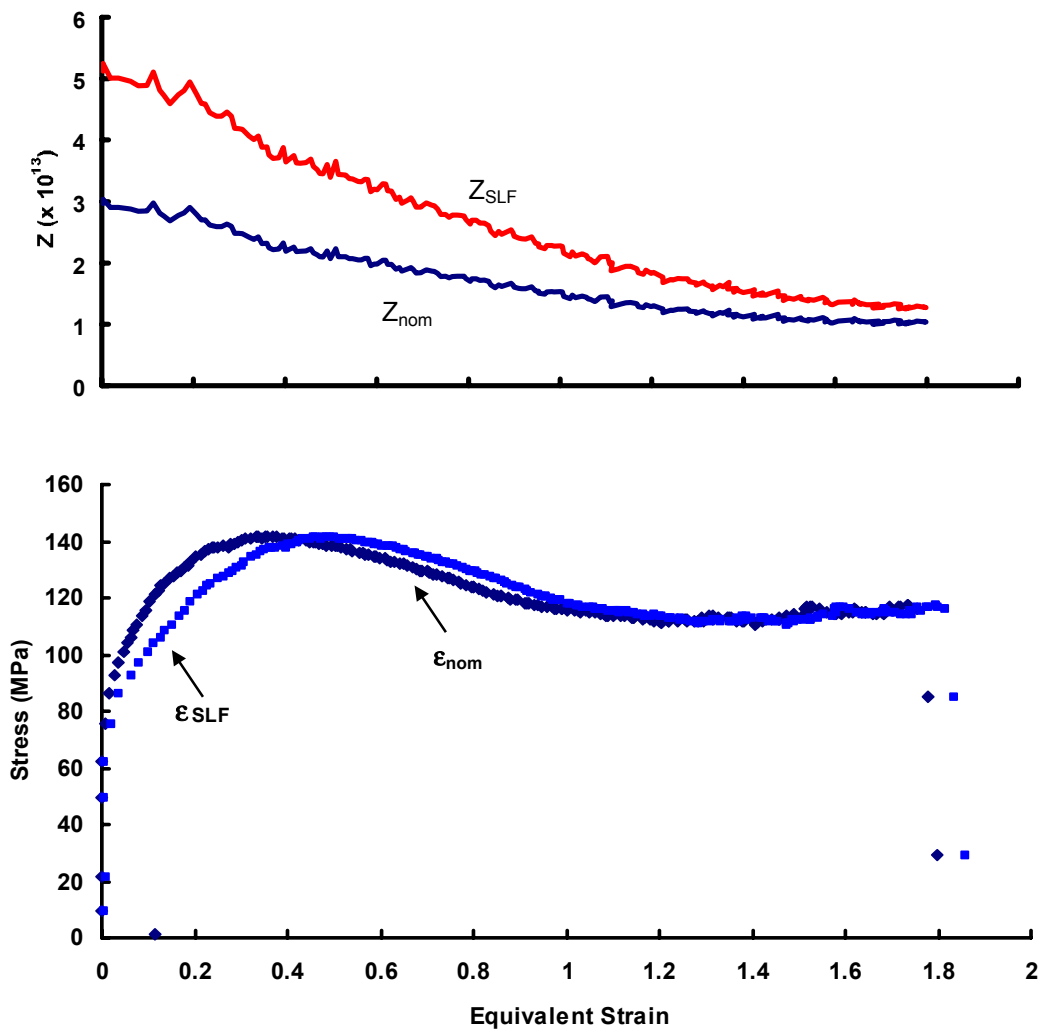


Figure K5 Effect of slip line field (SLF) strain rate correction on the value of Z and the effect of the SLF strain correction on the shape of the stress-strain curve obtained from PSC of a low carbon steel testpiece.