

Measurement Good Practice Guide No 58

High Temperature Solid Torsion Tests

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B Roebuck*, M S Loveday*
Y Chastel⁺ G Fiorucci⁺
and T Dal Negro^x

*Materials Centre, National Physical Laboratory, Teddington, UK

⁺CEMEF, Sophia Antipolis, Nice, France

^xUniversity of Padua, Italy

Abstract

This document outlines good measurement practice to be adopted for High Temperature Torsion tests on solid metallic materials. The Guide is applicable to hot (isothermal) tests at medium to high rates of strain (10^{-3} to 10^2 s⁻¹) at deformation temperatures relevant to metal working practice. Technical input to the document has been provided by the steering group of a European SMT funded project on High Temperature Testing, TESTIFY, that contains representatives of industrial users and producers of a wide range of engineering materials as well as academic modellers.

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 could be produced that, in principle, could form the equivalent of a CEN or ISO Standard.

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National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW
www.npl.co.uk

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These guidelines are also supported by collective experience gained at various organisations, particularly including the University of Sheffield and the University of Wales, Swansea in the UK.

Further Information

For further information on the EC SMT TESTIFY Project contact Dr Yvan Chastel or Yannick Tillier at Centre de Mise En Forme Des Materiaux, BP 207-F 06904 Sophia Antipolis Cedex, France:

Tel: +33 4 93 95 7464 or 7563

Fax: +33 4 92 38 97 52

E-mail: chastel@cemef.cma.fr

Website: <http://testify.cemef.org>

High Temperature Solid Torsion Tests

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Executive Summary

These guidelines were prepared as part of project ‘TESTIFY’ within the EC SMT Programme, an underpinning measurement research activity financed by DG XII, Brussels (Project TESTIFY, Mechanical Tests and Identification of Parameters for Metal Forming Processes, Project N° GRD1-1999-10714). It describes a method for measuring the torque versus rotation and for deriving from these measurements the torsion stress/strain curve in solid metallic materials at medium to high rates of strain (10^{-3} to $\times 10^2 \text{ s}^{-1}$), relevant to metal working practice. Figure 1 shows a schematic diagram of a traditional horizontal machine. More recent developments in torsion testing are using vertical machines.

These guidelines recommend good practice to minimise levels of uncertainty in the measurement process. The development of the procedure has been supported through tests on steels, brass, superalloys, titanium and aluminium alloys at strain rates ranging up to 10 s^{-1} .

Important work on the testing methodology for torsion tests has been undertaken by the groups at McGill University, Montreal, Canada, led by J J Jonas, [Jonas, 1985, 1993, Baczynski and Jonas, 1996, Bocher *et al* 1996], at Sheffield University, UK [Barracough *et al* 1973, and Barracough and Sellars, 1974] and at CEMEF, Sophia Antipolis, France [Barnett and Montheillet 2001 & 2002, Malcor *et al* 1983 a,b&c, and 1985, Montheillet *et al*, 1984 a&b, Perdrix *et al*, 1979 & 1981, Perrin *et al* 1987 and Regazzoni *et al* 1983]. Other recent informative publications concerning the methodology of torsion tests are by M Zhou and M P Clode [Zhou & Clode, 1996, 1997 a&b, 1998 a&b and Zhou *et al*, 1998] and by Gavrus *et al*, 1994 & 1995 a&b, Dal Negro *et al*, 2001 and Gaffard *et al*, 2001. Useful information on Torsion testing is also available on the GLEEBLE website (www.gleeble.com/AppNotes/application_note_20.htm). Finite Element Studies to support the development of the Guide were conducted by Y Chastel and co-workers at CEMEF under the TESTIFY Project including the development of the new software tool ‘IDENTIFY’ which incorporates corrections for true stress/strain data and deformational heating.

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

Members of TESTIFY Group:

CEMEF/Ecole des Mines de Paris, France
 National Physical Laboratory, UK
 Centro Ricerche Fiat, Italy
 Science & Computer Consultants, France
 Akademia Gorniczo-Hutniza, Poland
 Huta Czestochowa S.A., Poland
 BL Maskin Fabrik, Denmark

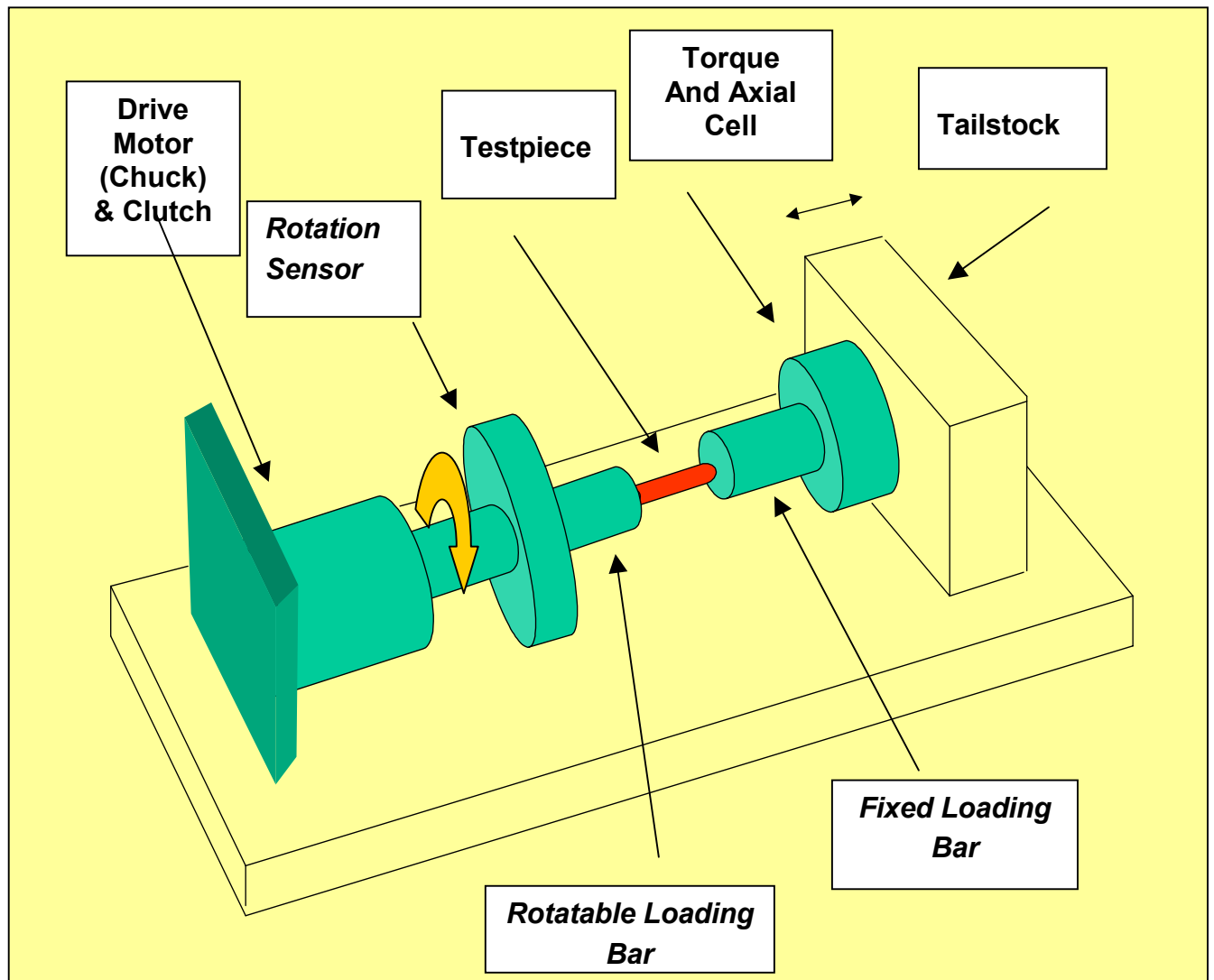
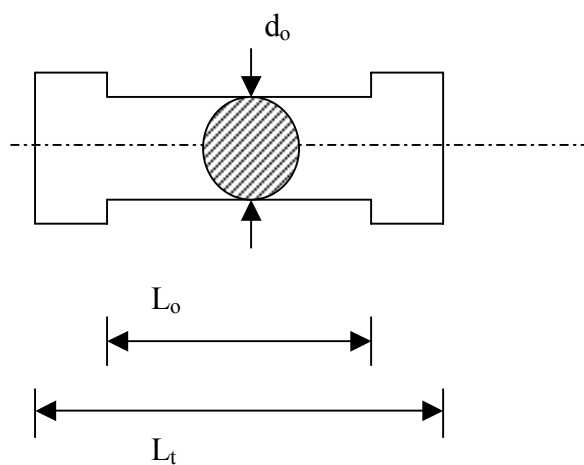


Figure 1a Schematic Diagram of Torsion Testing Machine
(Testpiece Heating System not shown)



$$R_{Ld} = L_o / d_o \quad \sim 2 \rightarrow 5$$

where R_{Ld} is the testpiece
length / diameter ratio

Figure 1b Schematic Diagram of Torsion Testpiece
(Details of grip ends not specified)

1 Introduction

1.1 Test Rationale

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

Internationally, for these applications, the four most commonly used types of hot deformation test are (i) uniaxial tensile (ii) hot axisymmetric compression, [HAC], (iii) plane strain compression [PSC] and (iv) torsion. Well established Standards exist for tensile testing (EN 10002 & ISO 9513) and Good Practice Guides (GPG) have been written for axisymmetric compression tests (Roebuck *et al*, 1997, revised 2002) and for plane strain compression tests (Lacey *et al* 2000, revised 2002). However no such recognised Guides or Standards exist for Torsion testing. This GPG has been produced to address this deficiency concerning the testing of solid torsion testpieces.

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 between 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 s^{-1} .

1.2 Background

Torsion testing of solid bars has been used by mechanical engineers for many years to determine material properties under simulated conditions encountered by components in service. The room temperature torsion testing machine used by Unwin are illustrated in 'The testing of materials of construction' [Unwin, 1910]. Details are given by Loveday (1982) of a high temperature torsion testing machine developed at the National Physical Laboratory by Tapsell and Bradley (1925), and details of high temperature torsion creep testing machines were reviewed by Henderson and Dyson, (1982). More recently the benefits of torsion testing for high strain rate testing at high temperature to derive data for modelling hot rolling and other metal working processes have been exploited at a number of research laboratories throughout the world, notably the group at McGill University led by J.J. Jonas (Montheillet *et al*, 1984, and Jonas, 1993, Yue *et al* 1994) and by Avramovic-Cingara *et al* (2003). A comparison of flow curves obtained under HAC, PSC and torsion has been reported by Kaspar *et al* 1993.

A number of workers have also investigated the phenomenon sometimes known as ‘the Swift effect’ which refers to the shortening or lengthening of rods freely deformed by rotation, (Swift 1947, Hardwick & McG Tegart, 1961, Stüwe & Turck, 1964, Morozumi, 1965, Billington 1977 and Shrivastava *et al*, 1991).

Other earlier work on torsion testing was undertaken by numerous people including Barraclough & Sellars (1973, 1974), Johnson, (1981), Sheppard & Wright (1979),

The torsion test basically comprises twisting a solid metal rod between a fixed grip and a rotating grip, whilst measuring the required torque to enforce the desired rotation, the rate of rotation, the number of turns and the temperature. It has the advantage that large strains may be achieved without the necking instability encountered in the conventional tensile test, or the bulging or lateral spreading encountered due to friction effects on the platens in the hot axisymmetric compression (HAC) or plane strain compression (PSC) tests. In addition, it is possible to easily maintain constant strain-rate conditions throughout a test. However, it should be noted that a radial stress gradient is inevitably developed across the testpiece, and thus corrections are necessary to derive true stress-strain curves from the measured torque - rotation curve. Such corrections are usually based on the models developed by Fields & Backofen (1957) and McQueen and Hockett (1970). It may also be necessary to correct the stress/strain curve to compensate the temperature rise in the testpiece due to deformational heating, similar to that necessary in HAC & PSC (see Roebuck *et al*, 1997 & Lacey *et al* 2000, Forestier *et al* 2002, Zhou & Clode 1996-98).

1.3 Test Criteria

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

- Geometry and surface finish of the testpiece
- Temperature measurement
- Temperature distributions
- Strain/rotation measurements
- Torque measurements
- Data analysis/models
- Calibration procedures (including machine stiffness effects)
- Grip materials and design
- Heating rates, soaking time and temperature
- Testpiece microstructure
- Oxidation

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

Examples of torsion testing machines are shown in Figures 2 - 4 and a close up view of a testpiece at room temperature and at high temperature are shown in Figures 5 and 6, respectively. An example of an axial-torque load cell is shown in Figure 7.



Figure 2 General view of high temperature torsion testing machine at CEMEF, Sophia Antipolis, France.



Figure 3 General view of torsion testing machine at Sheffield University, UK.

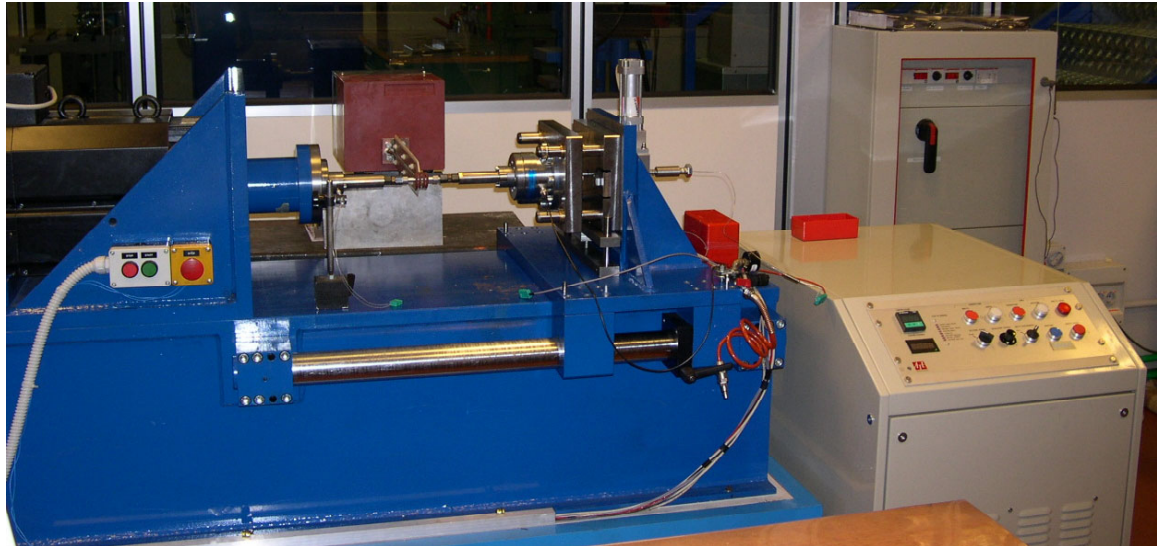


Figure 4 General view of Torsion Testing Machine incorporating RF Heating at Padua University, Italy. *(Photograph courtesy Tomasso Dal Negro)*

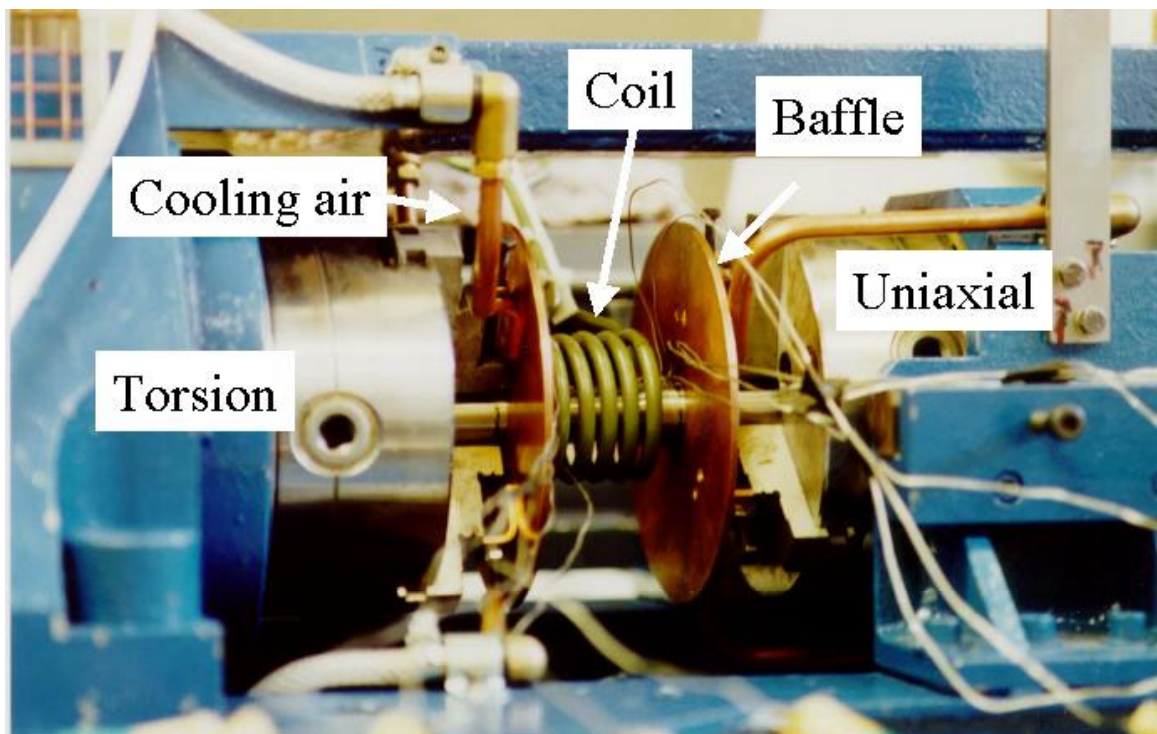


Figure 5 Close up view of testpiece gripped by two three jaw self-centring chucks and heated by RF heating, on Sheffield torsion machine.

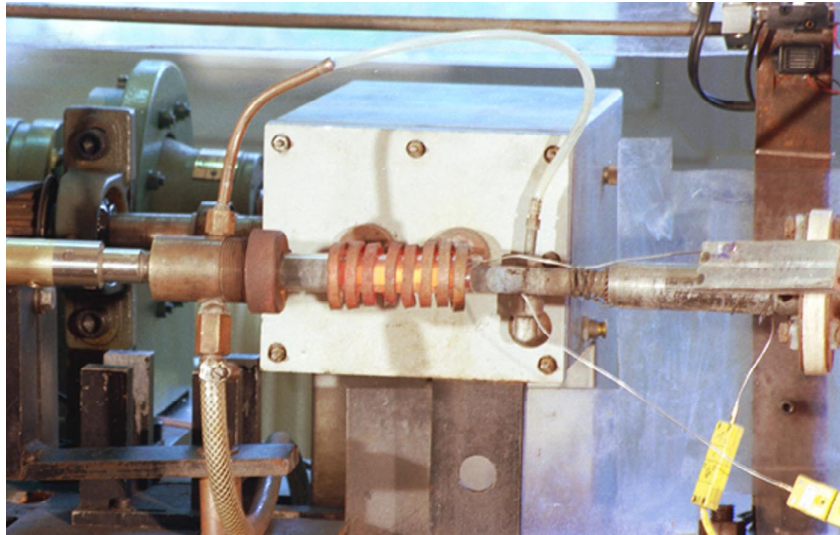


Figure 6 Close up view of torsion testpiece at high temperature heated using RF heating coils on CEMEF torsion machine.

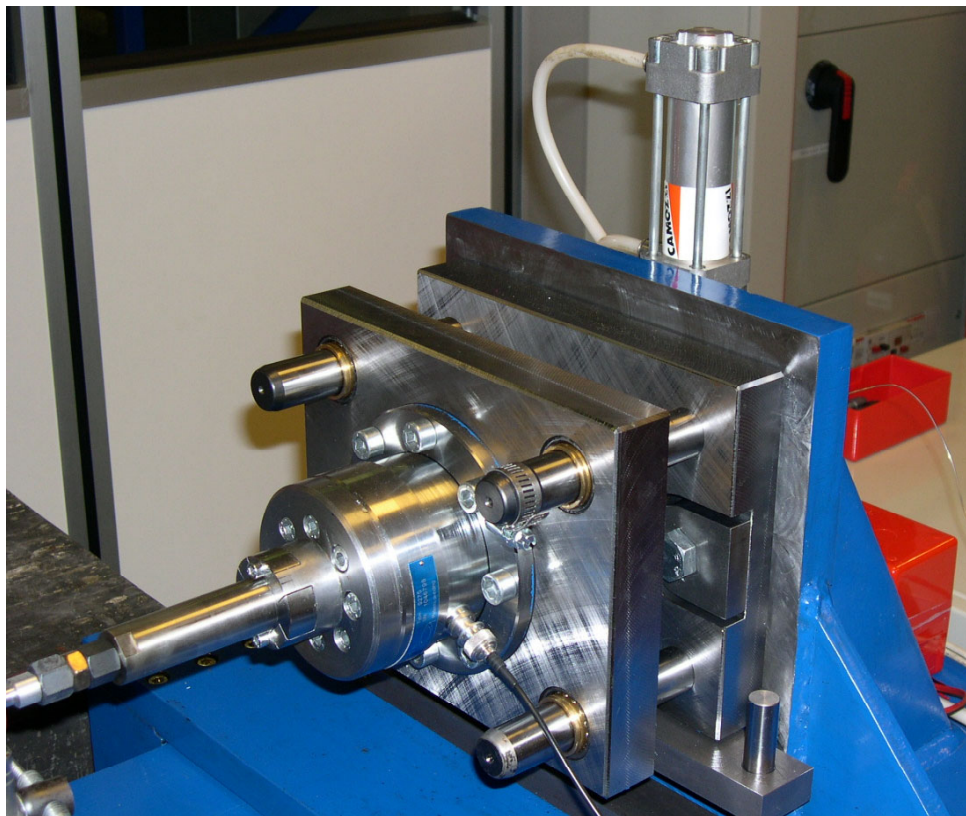


Figure 7 Combined torque and axial load cell on Torsion Testing Machine at Padua University. *(Photograph courtesy Tomasso Dal Negro)*

2 Scope

2.1 General

- 2.1.1 These guidelines are intended for use with metallic materials.
- 2.1.2 These guidelines apply to torsion tests shown schematically in Figure 1, on round testpieces of a specified geometry.
- 2.1.3 These guidelines apply to metal working deformation temperatures 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 hot shaping processes.

Note

The guidelines have been supported by tests over a nominal strain rate range from 10^{-3} to 10 s^{-1} on the equipment at CEMEF but are nevertheless still recommended for a wider range of strain rates and materials.

2.2 Outline of Procedure and Conditions of Testing

These guidelines for conducting hot torsion tests contain a number of basic steps (Figs 8-11):

1. Manufacture testpiece to chosen geometry.
Decide on testpiece numbers for each test parameter and check the dimensions of the machined samples.
2. Calibrate the test system for force (torque), displacement (rotation) and temperature.
3. Install testpiece in system.
Choose heating profile, i.e. temperature range and hold time.
4. Deform testpiece at specified temperature and strain rate.
Measure changes in force, rotation and temperature.
5. Quench or slow cool in an agreed predetermined manner, and remove testpiece from system.
6. Analyse and report data.

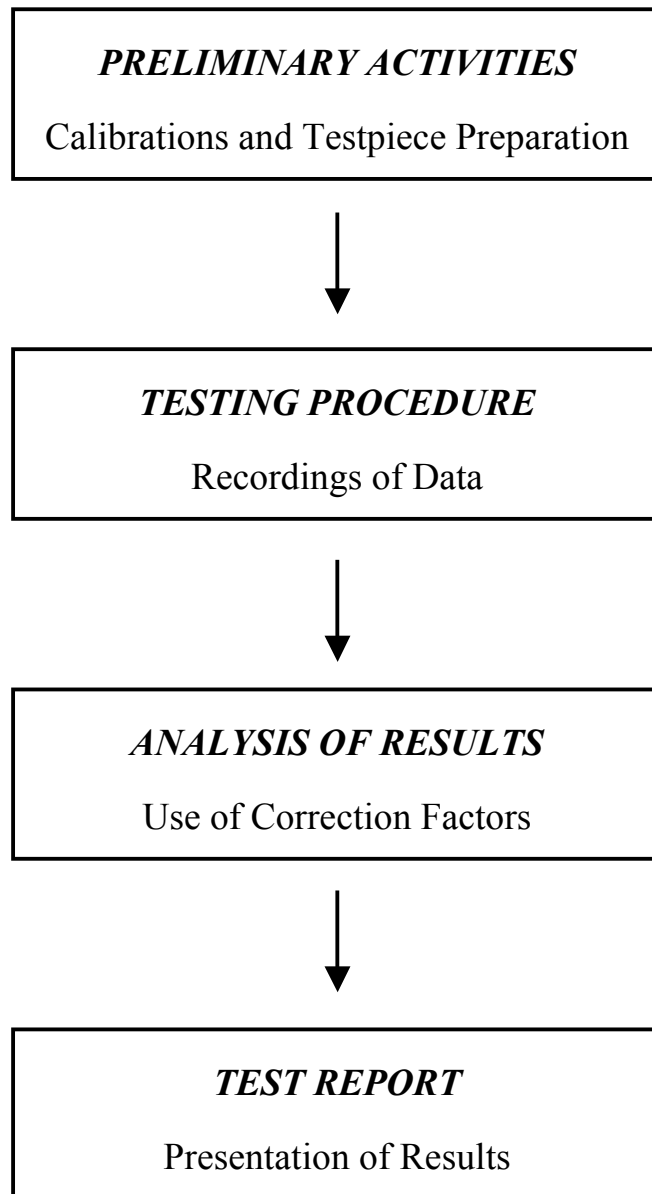


Figure 8 Schematic – Outline of Procedure

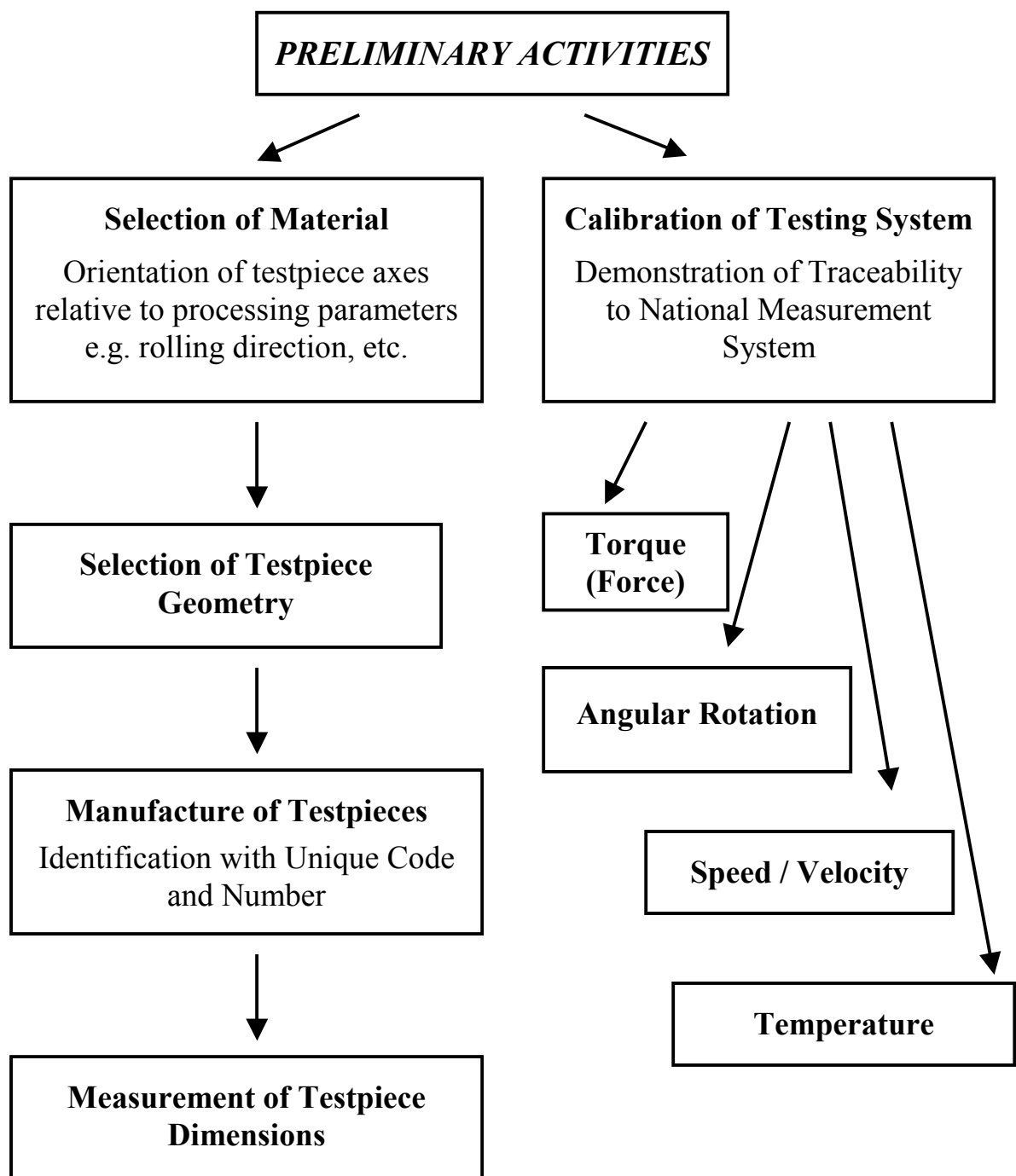


Figure 9 Preliminary activities

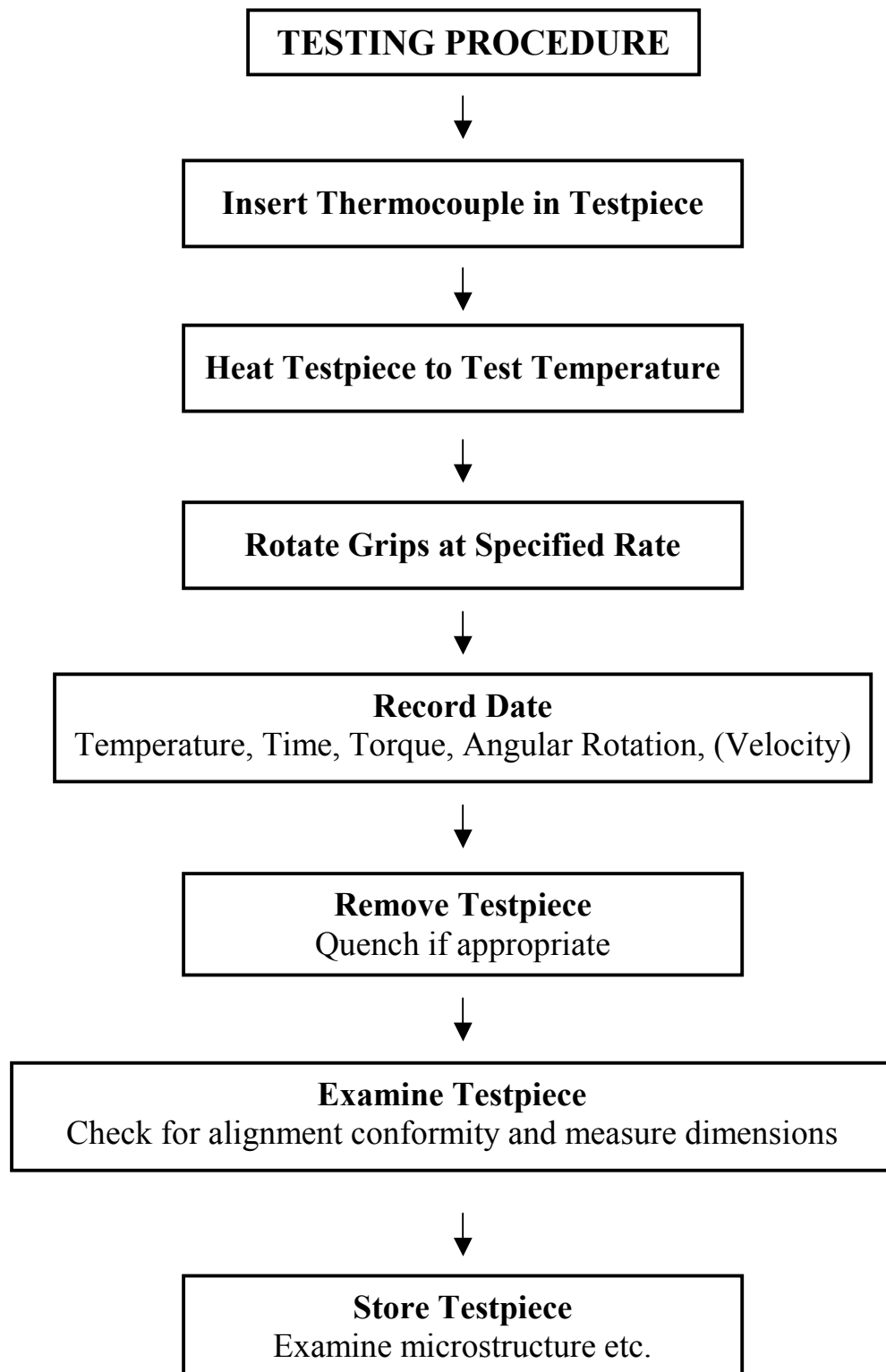


Figure 10 Test procedure flow diagram

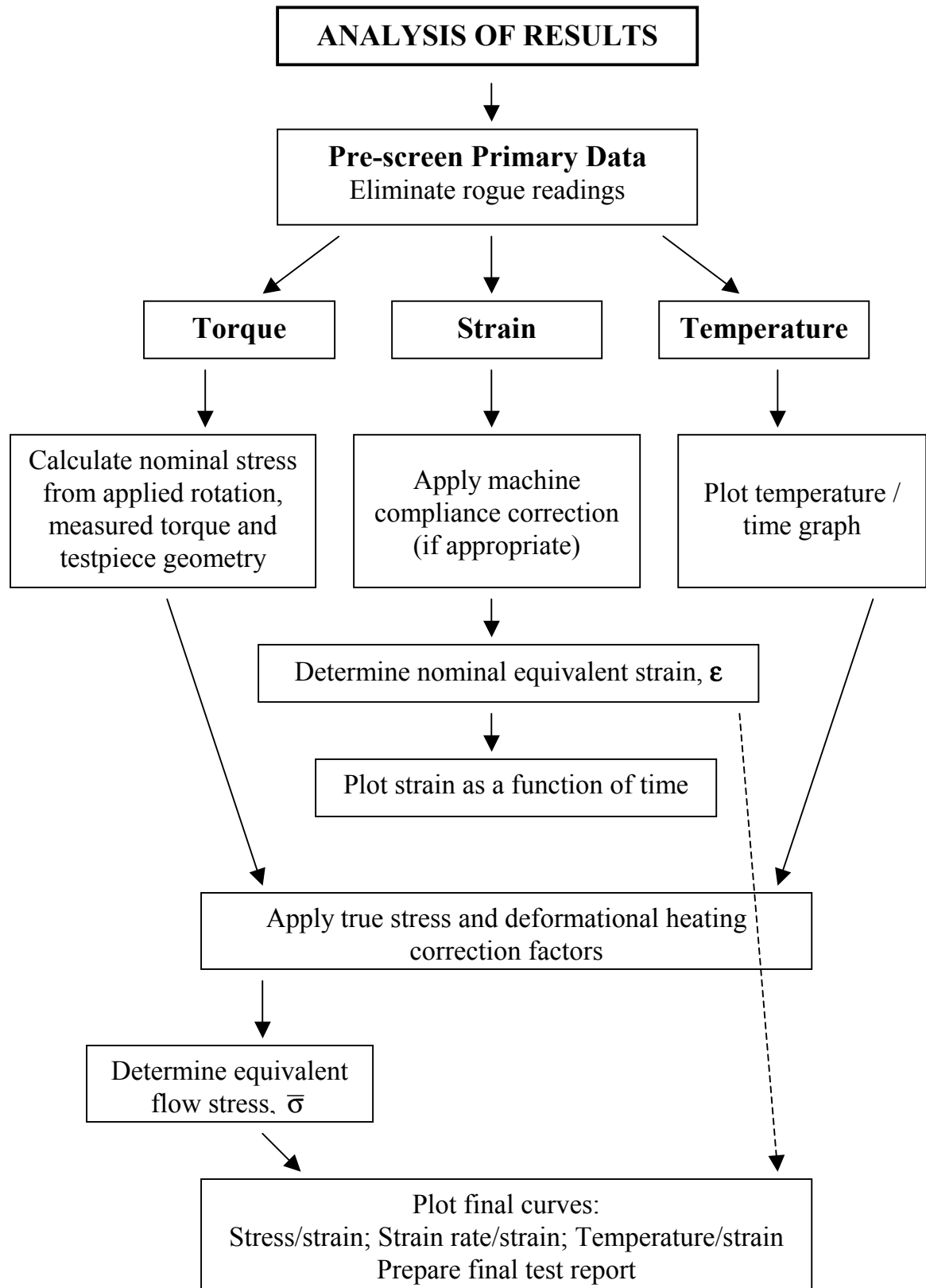


Figure 11 Analysis procedure flow diagram.

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*
θ	Grip end rotation	° or Turns
θ'	Corrected testpiece rotation	° or Turns
ϵ	Rotational strain	-
$\epsilon_1, \epsilon_2 \text{ \& } \epsilon_3$	Principal strains (see section 4.1.1)	-
$\bar{\epsilon}$	Nominal equivalent strain	-
ϵ_f	Total applied strain at end of test	-
$\dot{\epsilon}$ or $\bar{\dot{\epsilon}}$	Nominal strain rate (equivalent)	s ⁻¹
$\bar{\sigma}$	Nominal equivalent stress	N mm ⁻²
$\sigma_1, \sigma_2 \text{ and } \sigma_3$	Stress tensors (see section 4.1.1)	N mm ⁻²
γ	Shear flow stress	N mm ⁻²
A	Area of testpiece at intermediate time ($A = \pi^2/4$)	mm ²
A_f	Final area of deformed testpiece	mm ²
A_o	Area of undeformed testpiece gauge length ($A_o = \pi d_o^2 / 4$)	mm ²
d_o	Average diameter of testpiece before deformation	mm
d	Diameter of testpiece at intermediate time	mm
d_f	Final average diameter of testpiece	mm
L_o	Length of testpiece gauge length before deformation	mm
L	Length of testpiece gauge length at intermediate time	mm
L_f	Final length of testpiece gauge length	mm
L_T	Total length of testpiece	mm
$\tilde{m}$	$\tilde{m} = \left(\frac{\partial \ln T_q}{\partial \ln \dot{N}} \right)_N$ coefficients derived from Backofen & Fields analysis (1957), see Appendix E	
$\tilde{n}$	$\tilde{n} = \left(\frac{\partial \ln T_q}{\partial \ln N} \right)_N$ coefficients derived from Backofen & Fields analysis (1957), see Appendix E	
N	Number of revolutions	-
r	Radial coordinate	mm
R_o	Initial radius of testpiece	mm
R	Radius of testpiece at intermediate time	mm
R_t	Transition Radius (gauge length to grip end)	mm
R_{Ld}	Testpiece length/diameter ratio (L/d)	-
$S_{do}, S_{Lo}, S_{df}, S_{Lf}$	Standard deviations of average testpiece diameter or gauge length before and after testing, respectively	
T_q	Measured Torque	Nm
T_o	Nominal temperature of test	°C
T	Temperature of testpiece at intermediate time	°C
T_f	Temperature of testpiece at end of test	°C

* 1 N mm⁻² = 1 MPa

4 Definitions

4.1 Stress, Strain, Torque and Rotation

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 12. 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 torsion test for an isotropic material ϵ_1 typically noted as the radial strain, ϵ_2 is the strain in the orthoradial direction of the cylindrical sample (see Figure 12) and ϵ_3 is the length strain which is zero for an isotropic material.

Note: In the solid bar torsion testpiece a radial distribution of strains and stresses are developed across the testpiece, from zero along the centreline increasing to a maximum at the surface. Thus in this Good Practice Guide the terminology 'Nominal stress & strain' has been used to indicate that the parameters are not uniform across the testpiece.

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

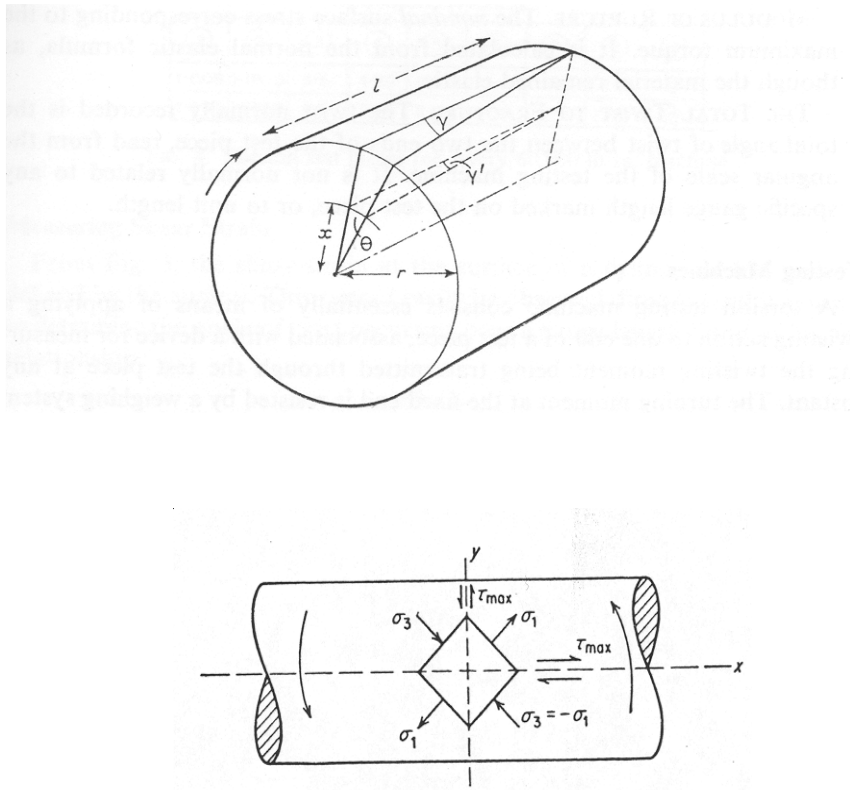


Figure 12 Schematic illustrations of stress and strain axes relative to torsion testpiece.

4.1.1 Shaft Rotation (θ, N)

The angular rotation moved by the rotating loading bar, measured in radians, (θ), or number of revolutions, N .

Note: Ideally the rotation should be measured as close to the testpiece as possible. If, however, the rotation is measured remotely from the testpiece, e.g. a) using a shaft encoder on the back of the drive motor, b) if a long drive shaft is employed, or c) or major components (e.g. a clutch or load cells) are between the testpiece and the rotation sensor, then under such circumstances it may be necessary to correct for the machine and loading shaft compliance.

4.1.2 Acceleration

Although modern drive systems and actuators are able to achieve the desired rotation speed very rapidly, nevertheless, it is inevitable that a finite time elapses before the testpiece reaches the required rotation rate, thus the initial region of the torque-rotation (stress-strain) curve will correspond to the material's response at a continuously changing strain-rate until the desired steady rotation rate is stabilised. Provided the rotation is recorded as a function of elapsed time, it will be possible to evaluate whether it is thought necessary to correct the stress-strain curve.

In some machines an overshoot of testing speed may occur, and it is likely that the recorded peak flow stress be higher than what is truly representative at the lower, desired steady rotation rate. It may therefore be necessary to use computational analysis based on physical material behavioural models to determine the correct values corresponding to the desired strain rate.

Note: In some machines the inertial effects introduced by a clutch in the loading train may be detrimental.

4.1.3 Nominal Strain Rate ($\dot{\epsilon}$ or $\bar{\dot{\epsilon}}$) and Rotational Strain (ϵ)

The strain rate tensor throughout the sample can be written :

$$\dot{\epsilon} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{\pi \dot{N} r}{L} \\ 0 & \frac{\pi \dot{N} r}{L} & 0 \end{pmatrix} \text{ in the reference frame (radial axis, orthoradial axis, longitudinal axis).}$$

The maximum rotational strain, ϵ , is then

$$\frac{\pi N R}{L} \quad (1)$$

Note: For testpiece geometries with a large transition radius (R_t) between the parallel gauge length and the grip ends, it may be necessary to give consideration to calculating an effective gauge length.

4.1.4 Nominal Equivalent True Strain ($\bar{\epsilon}$)

The nominal von Mises equivalent strain, $\bar{\epsilon}$, varies along the radius of the sample from zero to a maximum value of

$$\bar{\epsilon} = \frac{2\pi NR}{\sqrt{3} L} \quad (2)$$

4.1.5 Torque (T_q)

The torque, T_q , measured during the test is the integration of the shear stress across the radius of the sample.

$$T_q = \int_0^R 2\pi r^2 \sigma_{\theta z}(r) dr \quad (3)$$

4.1.6 Nominal Stress (σ)

For an isotropic material the stress state is only a shear component in the orthoradial-longitudinal plane:

$$\sigma = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma_{\theta z} \\ 0 & \sigma_{\theta z} & 0 \end{pmatrix}$$

The stress value can be derived from the measured torque using various techniques whether analytical (e.g. Fields and Backofen, 1957, see Appendix E) or numerical inverse methods.

For example

$$\bar{\sigma} = \sqrt{3} T_q (3 + \tilde{m} + \tilde{n}) / 2\pi R^3 \quad (4)$$

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 diameter (d)

Diameter of testpiece with the gauge length measured at the midpoint of the testpiece before the test as an average of three measurements (Appendix A). The initial diameter is d_o , the intermediate diameter is d and the final diameter is d_f .

4.2.2 Testpiece Length (L_T)

L_T is the total testpiece length, see Figure 1.

4.2.3 Testpiece Gauge Length (L)

The testpiece gauge length should be $5d > L > 2d$, see Figure 1.

The initial diameter is L_o , the intermediate breadth is L and the final length is L_f .

4.2.4 Testpiece Aspect Ratios

The critical aspect ratio which relate to the geometry of the testpiece used in the torsion test is the Gauge Length/Gauge Diameter Ratio. These ratios and recommended tolerances are given in Table 1.

Table 1 - Testpiece Aspect Ratios

Symbol	Title	Relationship	Preferred Values*	Permissible Values*
R_{Ld}	Ratio Length/Diameter	$R_{Ld} = L_o/d_o$	3	$2 \geq 5$

where d_o = initial testpiece diameter, L_o = initial testpiece gauge length.

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

5 Testpiece Preparation

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

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.

5.1 Measurement of Shape

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 d_o and L_o (Appendix A). Testpieces shall have a ground or milled finish to better than $R_a = 1.25 \mu\text{m}$ (see BS 308, BS EN ISO 1660 and BS EN ISO 1134).

The recommended testpiece length/diameter ratio (R_{Ld}) is 3. Testpieces with L_R other than 3 can be used but the ratio must be quoted in the test report. Typical examples are shown in Figs 13 -15.

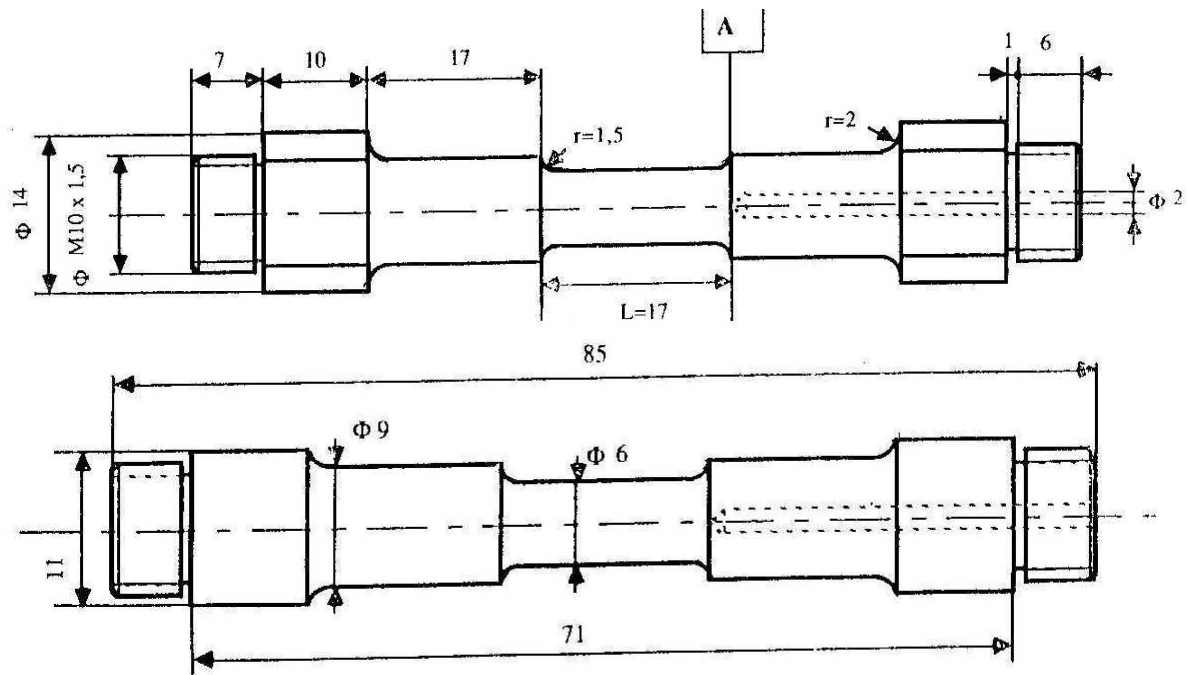


Figure 13 An example of typical testpiece dimensions and geometry as used at CEMEF, France. (Note: the type of grip end attachment e.g. threads, flats etc, will be dependent upon the type and manufacture of testing machine)

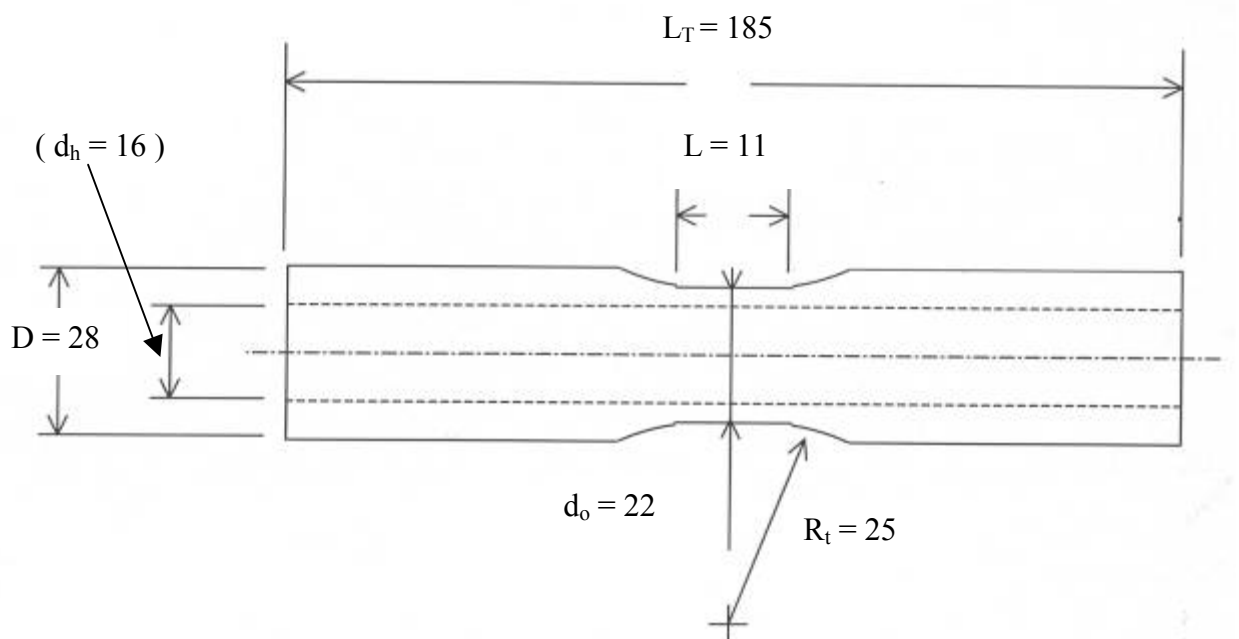


Figure 14 Typical testpiece geometry used at Sheffield University, UK.

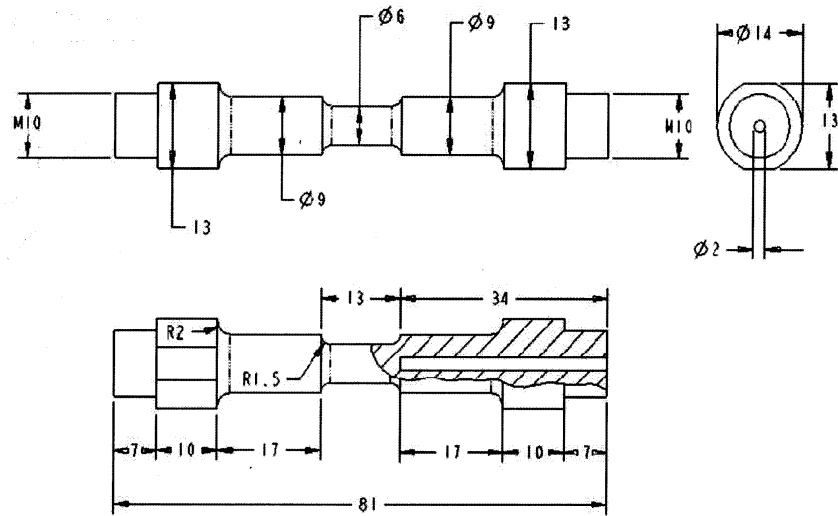


Figure 15 Typical testpiece geometry used at Padua University, Italy
(All dimensions are mm)

5.2 Surface Quality

For some materials it is more important to protect the surface of the testpiece from oxidation, since an interaction can occur with the environment than to specify a surface finish to a required standard. There are several options e.g. 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 EN ISO 1660 & BS 1134).

5.3 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 and therefore should be carefully controlled and recorded.

6 Apparatus

For historical reasons current practice encompasses a number of different types of machine although most are servoelectric and many machines are modified lathes. Machines are available that apply a rotation to the testpiece using mechanical methods. In addition the testpiece may be heated as follow :

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

For this reason these guidelines recommend only that the test machine be calibrated for torque, rotation 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. Frequently the testpiece is shrouded by a tube so that it can be surrounded by an inert atmosphere, or can be flooded with a quenching fluid without causing damage to the heating elements or RF coils. In the latter case the tube is often silica which allows direct visual observation of the testpiece; however if the tube becomes coated or gets dirty, care must be taken if the temperature of the testpiece is estimated using a pyrometer.

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 grips. Grips should be aligned such that angular rotation, lateral offset and parallelism should all be less than 0.05 mm over ~50 mm length.

Note. A simple method of checking the alignment is to use a divided testpiece which is cut transversely across the gauge length, as shown in Figure 16. The two halves of the testpiece are mounted rigidly in the two grips and the two moved together. Poor alignment is indicated by a mismatch of the two halves. A close fitting tube may be slid over the two halves; if the tube moves across freely then the loading train has good lateral and angular alignment.

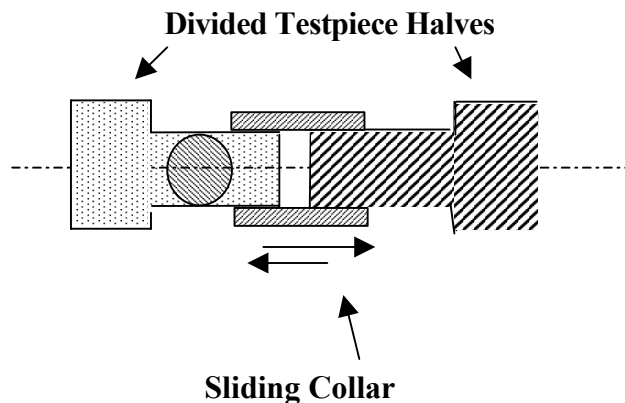


Figure 16 Loading bar alignment device based upon a divided testpiece.

[Note. Similar devices have been used for alignment of Low Cycle Fatigue machines and tensile testing load train by F. Kandil, NPL, 2001]

Departure from conformance, ie lack of parallelism between the grips, 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 grips, since the effect of misalignment is dependent upon the maximum strain to which the testpiece is subjected, i.e. if the testpiece is only rotated a small amount then a greater misalignment may be tolerated than if the testpiece is rotated by more than 360°.

6.2 Operating Mode

There are three main modes of operation of a torsion machine, and depending upon the design, all three modes of operation may be possible in one machine. However, more often, only the first two modes are possible:

- Mode 1 Freely sliding tailstock (see Figure 1a)
- Mode 2 Clamped tailstock
- Mode 3 Servo controlled tailstock

Ideally in all three cases it is recommended that the machine incorporates a load cell which measures the axial load sustained by the testpiece, in addition to the torque.

In older machines, particularly those that are based on converted lathes, in Mode 1 operation, it is frequently assumed that the axial load on the testpiece is negligible, however since the axial load will depend upon the friction between the lathe-bed and the tailstock, and the mass of the tailstock, it is unwise to assume that the axial load can be neglected and it should therefore be monitored with an axial load cell.

In Mode 2 operation with a clamped tailstock, clearly the axial load will increase significantly as the number of rotations increases, and thus it is essential that the axial load is recorded.

In advanced servo machines, in Mode 3 operation, it should be possible to control the magnitude of the applied axial load as rotation of the testpiece takes place, and record both axial load and the torque. As yet there are only a limited number of machines that can operate under Mode 3 control.

In most modern machines, both the torque and the axial load can be measured using a single multipurpose load cell, and frequently the axis of the machine is vertical, rather than horizontal, see Figure 17. In addition the actuators may be servo-hydraulic rather than servo electric and it should be noted that the addition of a clutch between the drive motor and the loading train may result in more problems than benefits.

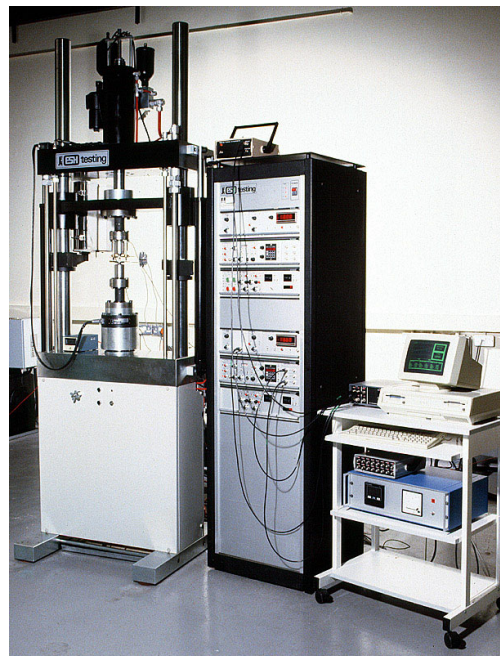


Figure 17 Vertical orientation combined Torsion – Compression (Tension) testing machine at Swansea University, Wales, UK.

6.3 Strain Rate Control

It is recommended that tests are performed in equivalent strain rate control. Constant grip rotation speeds may be used as an alternative. In the latter case the nominal strain rate of the test is defined from the rotation 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 rotation speeds introduces an additional uncertainty due to the variation of strain rate with applied strain. For example, in a test at a given nominal rotation speed the strain rate varies as the testpiece rotates through 360°. 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 of the testpiece. If a grip rotation transducer is used, machine compliance must be measured and a correction applied.

6.4 Torque Measurement and Calibration

The torque measurement system shall be verified at intervals not exceeding one year. Consideration should be given to following procedures outlined in BS 7882 : 1997 – ‘Calibration & Classification of Torque Measuring Devices.’

For high rate testing consideration may need to be given to the dynamic response of the load cell (and extensometer); this has been covered elsewhere, [Dixon, 1995 and Albright, 1995]. For conventional load cells it was shown that for frequencies less than ~20 Hz, 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].

6.5 Grips and Torque Load Train Shafts

An important aspect of the test system is the use of grips and load train shafts which are strong enough to sustain the loads required for hot deformation and which will not react with the testpiece at the test temperature. Grips should have a fine ground surface with deburred edges. Torsion testpieces are frequently screwed to the ends of the load train shafts until shoulders on the testpieces butt up against the shaft ends. Care must be taken to not strain the testpiece when tightening the grips.

In the case of RF heating the grip ends are usually cooler than the gauge length section and thus the excess oxidation does not normally cause difficulty in testpiece removal on completion of the test.

6.6 Rotation Measurement and Calibration

The rotation measurement system should be calibrated at intervals not exceeding one year. And in most practical hot torsion tests test machine the shaft rotation is measured rather than direct measurement on the testpiece gauge length. If it is intended to use information from the initial elastic region of the stress-strain curve then a correction should be applied to compensate for the compliance of the drive shaft between the testpiece and the rotation sensor.

Note. Information relating to similar compliance correction procedures for HAC & PSC is given elsewhere (Roebuck et al, 1997, revised 2002 and Lacey et al, 2000, revised 2002.)

6.6.1 Strain

For most purposes, shaft rotation is used to measure strain, generally via a Rotary Variable Differential Transformer (RVDT), or photo cell with a serrated disc attached to the rotating loading bar other transducer, eg an encoder connected to the drive shaft. The transducer must be calibrated and verified at intervals not exceeding one year.

6.7 Heating Systems

6.7.1 Radiant Furnaces

It is necessary to calibrate the test system so that the furnace and testpiece temperature profiles are known. It is usually necessary to employ a split furnace to facilitate the insertion of the testpiece in the loading train. Conventional muffle furnaces may be used although in general the heating and stabilisation period will be long. Faster heating rates may be achieved with radiant lamp furnaces. It is recommended that the temperature profile of the testpiece is checked at least once per year and after any changes to the testpiece and loading train geometry, or replacement of lamps or furnace elements. Similarly the temperature profile should be re-verified if any components in the temperature recording system or software are replaced.

6.7.2 Direct Heating

For direct heating methods (using electrical resistance, either AC or DC) it is necessary to have contact thermocouples in place for each test or to use pyrometry. Pyrometric measurements should be treated with care. An example of a miniature test system employing direct resistance (AC) heating is shown in Figure 18a&b; Accurate values for the emissivity of the testpiece and for platens must be known and readings can be affected by surface roughness or background radiation. Again, calibration experiments should be performed to establish the variation of temperature along the testpiece 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. Calibration experiments should be performed to check for temperature gradients and these should be quoted in the results report.

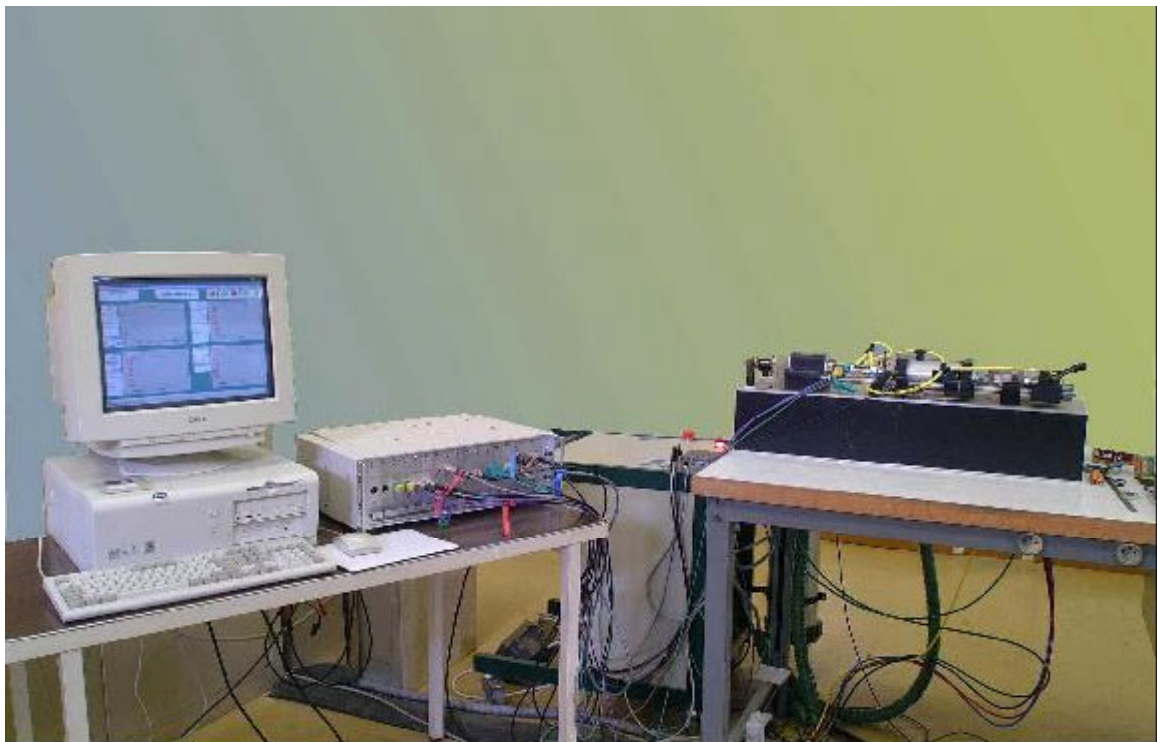


Figure 18a Photo of miniature torsion test rig using AC resistance heating of testpiece.
(*Courtesy of CEMEF*)

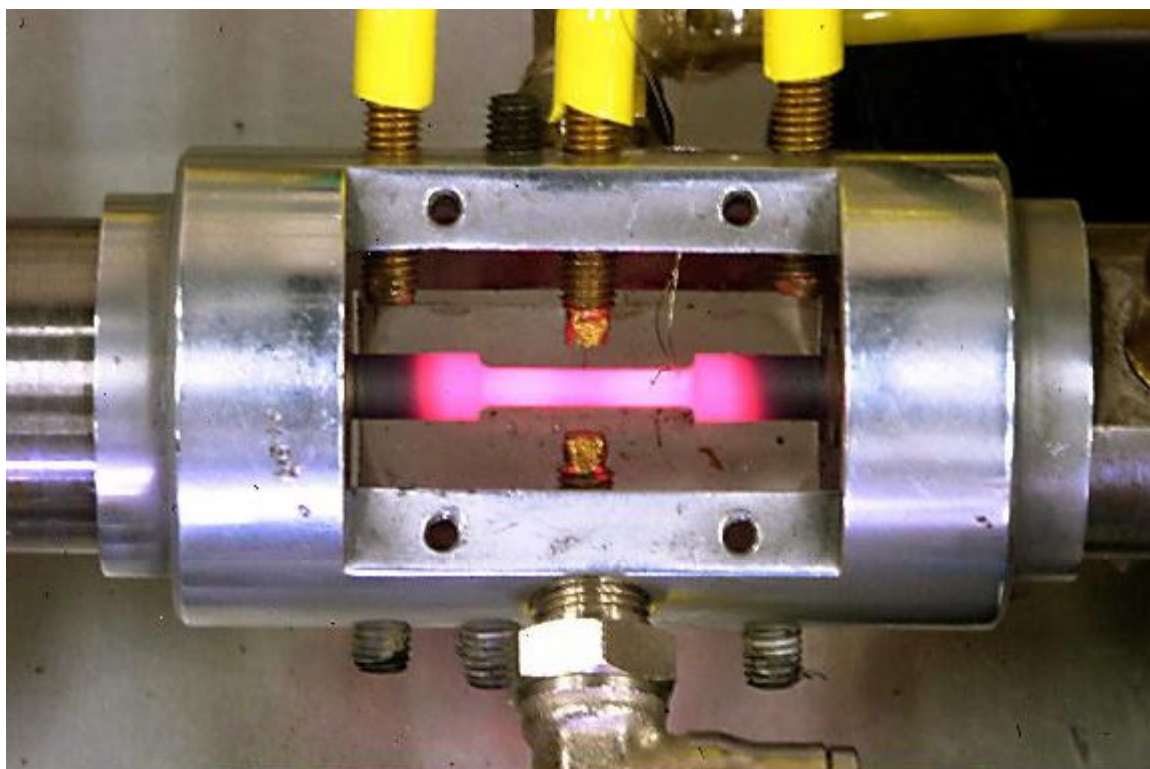


Figure 18b Close-up of testpiece at temperature in miniature torsion testing rig.

6.7.3 Inductive Heating

Some machines use Radio Frequency (RF) inductive heating of the testpiece, (see Figures 5 & 6). 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 pace makers, etc.

6.8 Temperature Measurement, Control and Calibration

6.8.1 General

Temperature profiles along the length of the testpiece are dependent on the geometry of the testpiece and the testpiece material, since thermal conductivity, which is material specific, can significantly alter the temperature profile, e.g. acceptable profiles along the length of Ti4-6Al alloys may be relatively easy to achieve, whereas significant temperature variations may be found along the length of steel testpieces of similar geometries.

The uniformity of temperature along the testpiece should be checked before every series of tests that introduces major changes to the test system geometries, 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. In the case of RF heating the temperature profile may be checked by passing a thermocouple along a hole drilled along the longitudinal axis of a special testpiece used for calibration purposes; and examples of such a testpiece is shown in Figure 19. A 1 mm diameter sheathed thermocouple is systematically moved along the interior of the testpiece to measure the temperature profile; an example of the temperature distribution is shown in Figure 20.

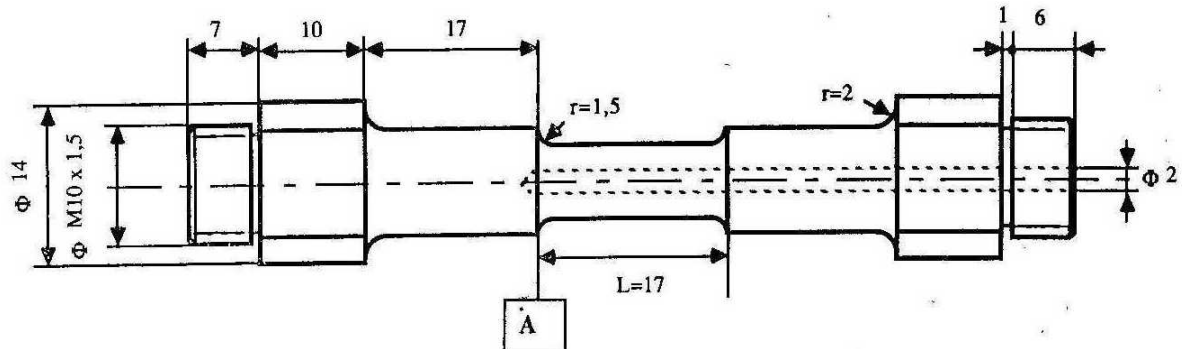


Figure 19 Testpiece used for verifying the temperature profile along the axis of a torsion machine which uses RF heating, as used at CEMEF.

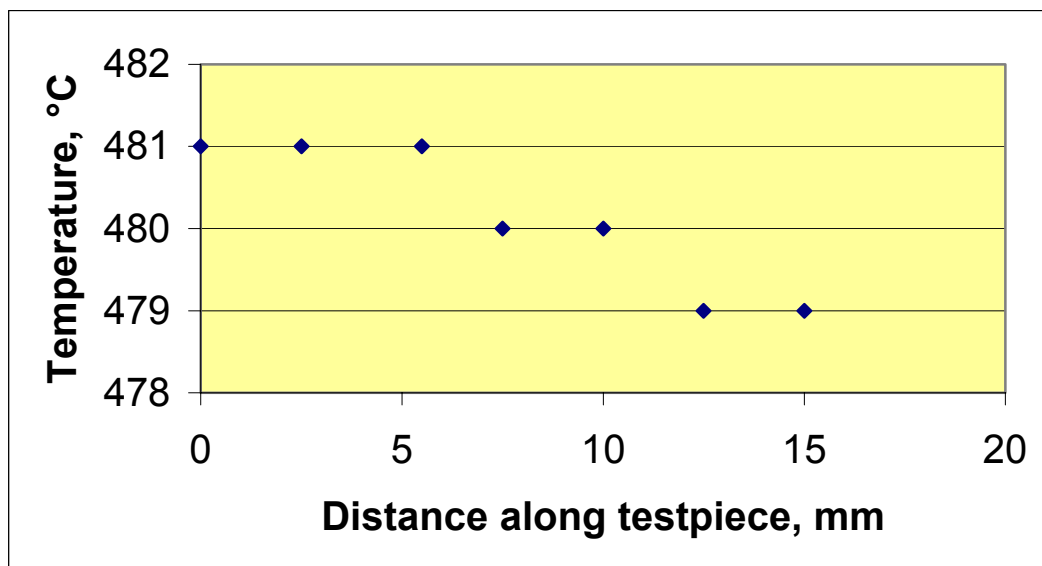


Figure 20 Temperature profile along the gauge length of a torsion testpiece heated using RF heating. Aluminium, nominal temperature 480 °C. (Courtesy of CEMEF).

An alternative approach has been to drill radial holes for the insertion of fixed thermocouples in a special calibration testpiece as shown in Figure 21. Results of the temperature profile measured in Ti6-4Al are shown in Figure 22.



Figure 21 Temperature profile calibration testpiece with holes drilled for calibration thermocouples, as used at Sheffield University.

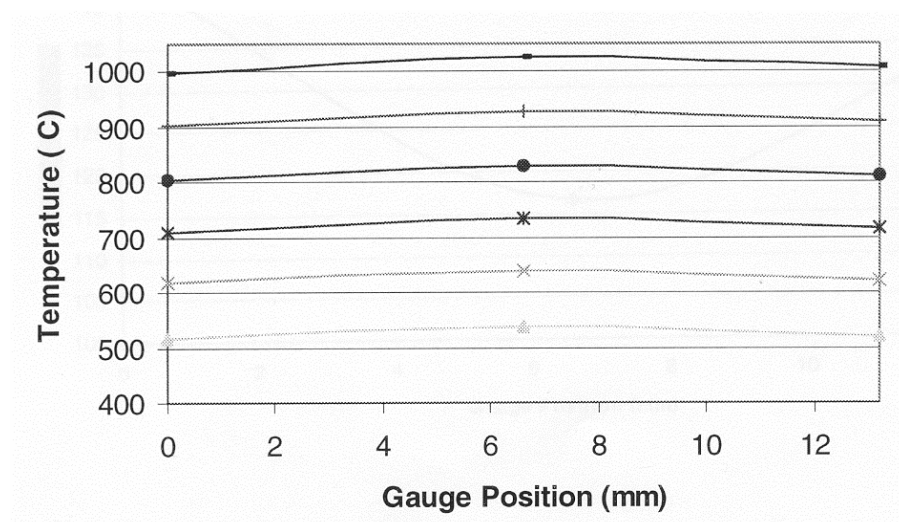


Figure 22 Temperature profile with RF Heating along Ti6-4 Al measured using embedded thermocouples. (Courtesy of Dr Brad Wynne, Sheffield University).

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 from point to point along the testpiece and the deviation from the specified test temperature should not exceed the values given in Table 2. These values are based on experience of torsion testing.

Table 2 – Initial Temperature Tolerances*, °C

Test temperature, T	Temperature variation ⁺ , °C	Precision ⁺⁺
T < 600	± 3	± 2
900 > T > 600	± 5	± 3
T > 900	± 7	± 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.

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

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 torque, rotation rate and rotation with time can be measured such that ~1000 data points can be recorded covering the total number of rotations. 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 1s^{-1} , this means a sampling rate of 100 Hz.

7 Testing Procedure

7.1 Testpiece Manufacture

Calculate the approximate maximum torque required to deform the chosen testpiece size at the relevant temperature, if necessary from a series of preliminary exploratory tests. Choose a testpiece geometry which will ensure that the torque capacity of the test machine is adequate to maintain sufficient torque 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. 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 torque, rotation, 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 grips are free and smooth in operation.

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

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.

7.4 Testpiece Heating

In general during heating up of the testpiece to the desired test temperature, one end of the loading train should be free to move in an axial direction to allow for expansion of the testpiece. Prior to starting the test the free grip end is usually clamped so that the testpiece gauge length is constrained. Occasionally special tests may be undertaken when the testpiece is free to move in the axial direction, e.g. investigation of the Swift effect, (Swift,1947).

7.5 Testpiece Removal

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

For parallel studies of microstructural evolution:

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

- strain variation
- deformational heating

Details, including worked example, are given in Appendices C-F. The use of FE or inverse analysis is essential to determine stress-strain curves from the measured load-displacement data.

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 Calculation of Equivalent Strain

From the rotation measurements recorded during the test, it is necessary to apply correction factors in order to determine equivalent strain, $\bar{\epsilon}$ (see Appendix E). In some machines, the control system will allow an approximate conversion of the rotations 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.

8.3 Flow Stress Corrections

Once all the corrections have been made the equivalent flow stress, $\bar{\sigma}$, of the material is then calculated.

8.4 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. For further information relating to deformational heating see the PSC GPG, Lacey *et al* 2000, revised 2002, Gavrus *et al* (1998) and Rietman (1999).

8.5 Repeatability Determination

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

Strictly, to ensure repeatability at least two testpieces for each condition of test should be tested. If the flow stresses from these first two tests, measured at applied true strains of 0.1 and 0.3, differ by more than $\pm 3\%$ 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 Holloman parameter or a fit to specified constitutive relations.*

8.6 Shape Validity Measurements

At this stage it is not sensible to specify or quantify post test bulging or alignment acceptance validity criteria for acceptable tests, since they are geometry and material dependent. Textured microstructure can give rise to helical ridges (Fig 23) which would invalidate a simple diameter test validation criteria. However it is recommended that post test testpiece geometry measurements are recorded so that over time a data base may be compiled to assist in the development of suitable acceptance criteria.



Fig 23 Helical ridges after testing.

8.7 Data Presentation

Record plots of $\bar{\sigma}$, $\bar{\epsilon}$ 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 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.

8.8 Assessment of Uncertainties

In 1994 an important new document was issued: 'Guide to the expression of uncertainty in measurement', published jointly by several authoritative standards bodies, namely BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML which is referred to here as the TAG4 Guide, after the ISO Technical Advisory Group 4 which drafted the document. It is a comprehensive document of over 90 pages based upon rigorous statistical methods for the summation of uncertainties from various sources. Its complexity has provided the driving force for a number of organisations to produce simplified versions of the TAG4 Guide, e.g. NPL (Bell, 1999), the National Institute of Science and Technology (NIST (Taylor & Kuyatt, 1993) in the USA, the National Measurement Accreditation Service (NAMAS 3000, 1997) in the UK and the British Measurement and Testing Association (Birch, 2001), 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). More recently, a series of Statements of Uncertainty of

Measurement relating to Mechanical Testing have been developed under an EU funded Project “UNCERT” (Kandil et al, 2000).

In addition, guidance on estimating measurement uncertainty has now been incorporated into the Standards for Tensile and Creep Testing (EN 10002, Part 1, and EN 1029).

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.

It should be noted that it is necessary to quote the measurement uncertainty and the confidence level, unless authorised deemed necessary, the 95% confidence level should be used, and thus if conventional statistics are used on repeat measurements. (Type A uncertainty), it is necessary to multiply the Standard Deviation by a factor of 2.

8.9 Final Analysis of Results

Worked examples of the analyses necessary for obtaining the equivalent flow stress data from the Torsion Test are given in the Appendices.

Appendix F outlines an analytical process based on the use of an inverse model using the Norton-Hoff constitute law.

9 Test Report

It is recommended that the proforma given in APPENDIX B is used for reporting the test results 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 R_{Ld} not equal to 3)
- Preheating temperature profile
- Temperature and strain rate history of test
- Temperature distribution along testpiece
- Grip 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	Tensile Testing of Metallic Materials – Part 1, Method of Test.
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 EN 10291	Uniaxial Creep Testing.
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.
BS 1134-1: 1988	Methods and instrumentation.
BS 1134-2: 1990	Guidance and general information.
BS 4641: 1996	Method for specifying electroplated coatings of chromium for engineering purposes.
BS 7882: 1997	Method for Calibration and Classification of Torque Measuring Devices.
EN 60584 - 1: 1993	Thermocouples - Part 1: Reference tables.
NF EN 10002	Load Calibration.

Appendix A: Torsion Tests

Testpiece Measurement Table

Testpiece identification	
Material	

Dimensions	Diameter*, mm		Length, mm	
Initial	d ₁		L ₁ (0°)	
	d ₂		L ₂ (120°)	
	d ₃		L ₃ (240°)	
Average	d ₀		L ₀	
Standard deviation	S _{d₀}		S _{L₀}	
Final	d ₄		L ₄ (0°)	
	d ₅		L ₅ (120°)	
	d ₆		L ₆ (240°)	
Average	d _f		L _f	
Standard deviation	S _{d_f}		S _{L_f}	

* Diameter measured at three positions along gauge length.

+ Gauge length measured at three radial positions.

Appendix B Test report Pro-forma

Hot Torsion 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 Length Ratio (L_R) Applicable standard(s)*	A*	
Testpiece information	Testpiece identification Testpiece diameter (initial), nominal Testpiece length(initial), nominal Cross-sectional area (initial), nominal Surface finish (comment on method of manufacture)		mm mm mm ²

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

2. Testing organisation

Organisation:- Name:- Date:-
--

3. Details of test procedure

Reference	Description	Value	Units/Notes
Test procedure	Type of test	Hot Torsion	
	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
	Grip material		
	Cooling Method		
	Cooling Rate		°C min ⁻¹
	Elapsed time (end of test - cooling start)		min
	Alignment - give details		
	Test control mode		
	Constant rotation speed		
	True strain rate control		
	Rate of strain application		s ⁻¹
	Nominal or true		
	Strain measurement method		
	Location of strain transducer		
	Rotation calibration method		
	Torque 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 58 and others if possible

4. Test Results

Reference	Description	Value	Units
Test results (individual values)	Maximum torque Hot flow stress, $\bar{\sigma}$ Maximum - at 0.1 true strain - at 0.3 true strain		N N mm ⁻² N mm ⁻² N mm ⁻²
Test validity	Rotational strain - final value in test Initial diameter, d_o Final diameter, d_f Initial length, L_o Final length, L_f		mm mm mm mm
Test results (full curves)	Record plots of: T_q versus θ $\bar{\sigma}$ versus $\bar{\epsilon}$ <i>at true strain intervals of at least 0.01</i> $\dot{\bar{\epsilon}}$ 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 Torsion, Plane Strain Compression and Axisymmetric Compression Tests, 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 Gavrus *et al* (1998), Rietman (1999) and Hand *et al* 2000, see Figure C1.

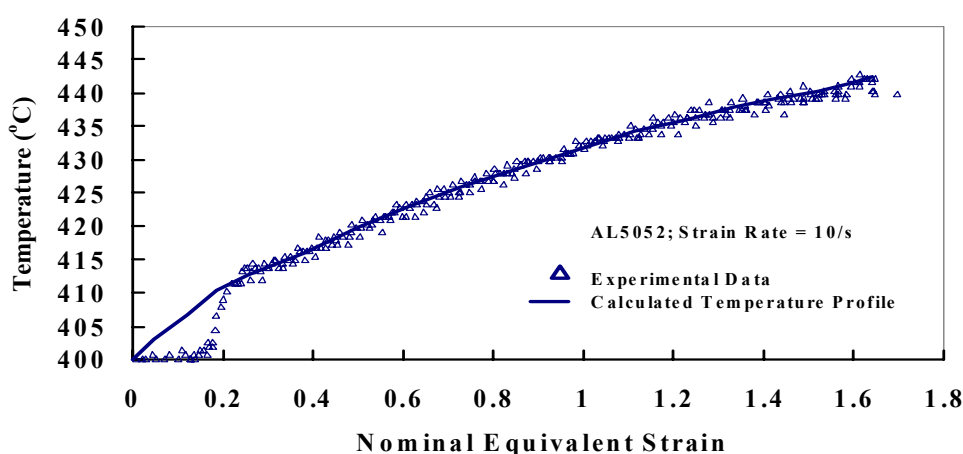


Figure C1 Deformational Temperature Change During Plane Strain Compression (Hand *et al*, 2000).

C.3 Traceability

In torsion tests the temperature of the testpiece may be measured using thermocouple(s) or 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 may be drilled into the testpiece and a 1 mm sheathed thermocouple inserted in the fixed grip end. 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, 1982; Desvaux, 1977; Osgerby & Loveday, 1992].

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 three types of heating systems used for torsion testing, (a) radiant furnaces, (b) direct heating system, e.g. Gleeble machines and (c) inductive heating as discussed in Section 6.7.

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 $\pm 5^\circ\text{C}$ ($600^\circ\text{C} < T < 900^\circ\text{C}$) as specified in Table 2, Section 6.8.1 at the start of the test. 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.

Appendix D Influence of uncertainty in sample dimension

Prepared by
Romain Forestier [CEMEF]

The effects of uncertainties in sample dimensions, d (diameter) and L (length), were examined using an inverse method of numerical analysis using the Norton-Hoff Law.

$$\bar{\sigma} = K(\bar{\epsilon})^n (\sqrt{3} \dot{\bar{\epsilon}})^m \exp(\beta/T) \quad (1)$$

The analysis was used to evaluate the fractional dependence of uncertainties in the Norton-Hoff Law parameters (K , m , n and β) on the fractional uncertainties in d and L ($\Delta d/d$ and $\Delta L/L$).

Example : Identification of the Norton-Hoff law coefficients for an NV6 steel.

The behaviour of the steel was analysed using 9 numerical experiments :

Temperatures (°C) Strain rates (s ⁻¹)	900	1000	1100
0.1	+	+	+
1	+	+	+
10	+	+	+

The best fit for final set of Norton parameters was found to be:

$$K = 440.2 \text{ Kpa.s}^{-1}, m = 0.115, n = 0.114, \beta = 5988.4 \text{ K}$$

If we denote λ^{opt} as the result of the following inverse problem :

$$\lambda^{\text{opt}} = \arg \min \phi(\lambda)$$

$$\phi(\lambda) = \frac{1}{2} \frac{\|T^{\text{exp}} - T^{\text{comp}}(\lambda)\|_2^2}{\|T^{\text{exp}}\|_2^2} \quad (2)$$

where λ^{opt} is the set of rheological parameters to be identified, T^{exp} the vector containing the torque measured during a torsion test and T^{comp} the computed torque.

It can be considered that T^{comp} and λ^{opt} are also functions of d , and a small perturbation on d is denoted δd . Finally δd is defined by :

$$\lambda^{\text{opt}}(d + \delta d) = \lambda^{\text{opt}}(d) + \delta \lambda \quad (3)$$

The following notations were used:

$$\begin{aligned} \lambda^{\text{opt}} &= \lambda^{\text{opt}}(d) \\ \lambda^{\text{opt}} + \delta \lambda &= \lambda^{\text{opt}}(d + \delta d) \\ T^{\text{comp}} &= T^{\text{comp}}(\lambda, d) \\ \phi &= \phi(\lambda, d) \end{aligned}$$

λ^{opt} and λ^{opt} were defined by the following relations :

$$\begin{aligned} \nabla_{\lambda} \phi(\lambda^{\text{opt}}, d) &= 0 \\ \nabla_{\lambda} \phi(\lambda^{\text{opt}} + \delta \lambda, d + \delta d) &= 0 \end{aligned} \quad (4)$$

and

$$\begin{aligned} \nabla_{\lambda} \phi(\lambda^{\text{opt}}, d) &= \nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d)^T (T^{\text{exp}} - T^{\text{comp}}(\lambda^{\text{opt}}, d)) = 0 \\ \nabla_{\lambda} \phi(\lambda^{\text{opt}} + \delta \lambda, d + \delta d) &= \nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}} + \delta \lambda, d + \delta d)^T (T^{\text{exp}} - T^{\text{comp}}(\lambda^{\text{opt}} + \delta \lambda, d + \delta d)) = 0 \end{aligned} \quad (5)$$

If it is assumed that

$$\begin{aligned} T^{\text{comp}}(\lambda^{\text{opt}} + \delta \lambda, d + \delta d) &\approx T^{\text{comp}}(\lambda^{\text{opt}}, d) + \nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d) \delta \lambda + \nabla_d T^{\text{comp}}(\lambda^{\text{opt}}, d) \delta d \\ \nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}} + \delta \lambda, d + \delta d) &\approx \nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d) \end{aligned} \quad (6)$$

then

$$\nabla_{\lambda} \phi(\lambda^{\text{opt}}(d + \delta d)) \approx \nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d)^T (\nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d) \delta \lambda + \nabla_d T^{\text{comp}}(\lambda^{\text{opt}}, d) \delta d) = 0 \quad (7)$$

So, finally,

$$\delta \lambda = - \left(\nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d)^T \nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d) \right)^{-1} \nabla_d T^{\text{comp}}(\lambda^{\text{opt}}, d) \delta d \quad (8)$$

Thus, if H is defined $H = \left(\nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d)^T \nabla_{\lambda} T^{\text{comp}}(\lambda^{\text{opt}}, d) \right)^{-1}$, then

$$\delta \lambda_i = -H_{ij} \nabla_d T^{\text{comp}}(\lambda^{\text{opt}}, d)_j \delta d \quad (9)$$

Then, if the relative error on the diameter is less than $\frac{\Delta d}{d}$, then the relative error $\frac{\Delta \lambda_i}{\lambda_i}$ is majored by the following expression :

$$\left| \frac{\Delta \lambda_i}{\lambda_i} \right| \leq \left| \frac{H_{ij} \nabla_d T^{\text{comp}}(\lambda^{\text{opt}}(d + \delta d))_j d}{\lambda_i} \right| \left| \frac{\Delta d}{d} \right| \quad (10)$$

Finally, using a sensitivity analysis module at the end of the optimisation procedure, it was possible to estimate the influence of an uncertainty on the size of the sample on the result of the identification. It was just required to compute $\nabla_d T^{\text{comp}}(\lambda^{\text{opt}}, d)$, which is the derivative of the Torque with respect to the sample size.

The results of the analysis are given below:

$$\begin{aligned} \left| \frac{\Delta K}{K} \right| &\leq 1.553 \left| \frac{\Delta d}{d} \right| & \left| \frac{\Delta K}{K} \right| &\leq 1.103 \cdot 10^{-1} \left| \frac{\Delta L}{L} \right| \\ \left| \frac{\Delta m}{m} \right| &\leq 1.049 \cdot 10^{-2} \left| \frac{\Delta d}{d} \right| & \left| \frac{\Delta m}{m} \right| &\leq 7.448 \cdot 10^{-4} \left| \frac{\Delta L}{L} \right| \\ \left| \frac{\Delta n}{n} \right| &\leq 1.348 \cdot 10^{-2} \left| \frac{\Delta d}{d} \right| & \left| \frac{\Delta n}{n} \right| &\leq 9.575 \cdot 10^{-4} \left| \frac{\Delta L}{L} \right| \\ \left| \frac{\Delta \beta}{\beta} \right| &\leq 3.116 \cdot 10^{-1} \left| \frac{\Delta d}{d} \right| & \left| \frac{\Delta \beta}{\beta} \right| &\leq 2.213 \cdot 10^{-1} \left| \frac{\Delta L}{L} \right| \end{aligned}$$

It can be seen that the exponent parameters of the Norton-Hoff law, m and n , are not sensitive to variations of the size of the sample. The effect on parameters K and β is a little higher, but even here the dependencies are not large. It must be remembered, however that the analysis was asymptotic and that it may not provide a good prediction of the uncertainty due to much higher variations in the dimensions, d and L . This is due to the fact that non linearities of the direct model are neglected for the analysis.

Appendix E Calculation of Nominal Equivalent Strain

From the measured experimental data the rotation - torque diagram is usually available. As an example the data is given for a test at a constant rotational speed of 1000 rpm and a nominal temperature of 800°C, see Fig E1..

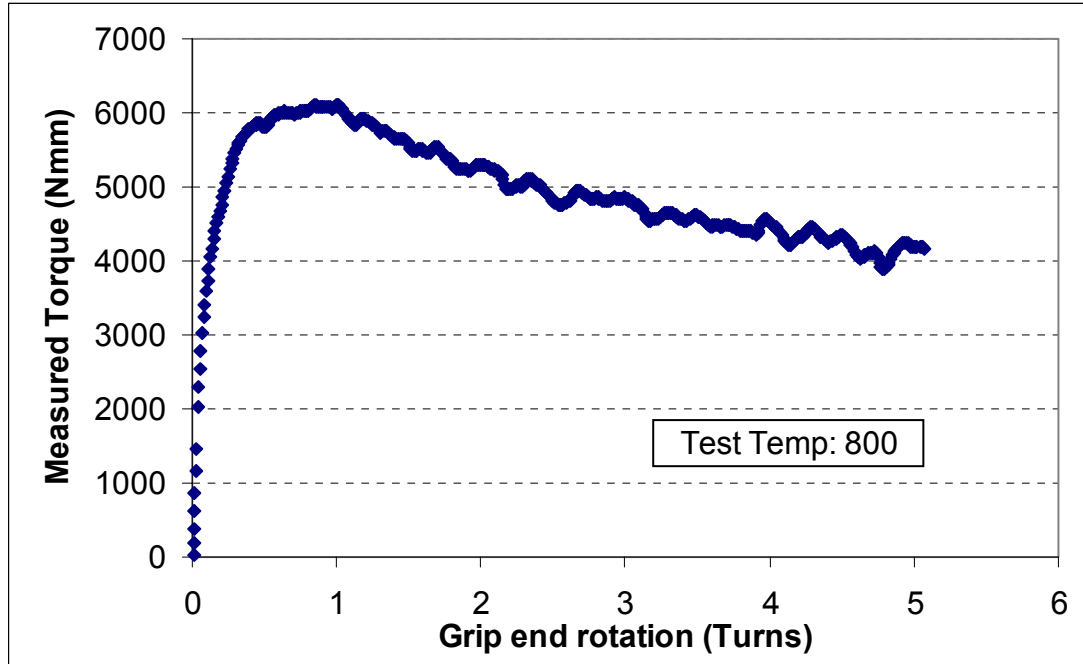


Figure E1 Experimental data

According to the simplified Fields and Backofen (1957) theory the material equivalent flow stress can be written as follows:

$$\bar{\sigma} = \frac{\sqrt{3}T_q}{2\pi R^3} (3 + \tilde{n} + \tilde{m}) \quad (\text{E1})$$

where:

$$\tilde{n} = \left(\frac{\partial \ln T_q}{\partial \ln \dot{N}} \right)_{\dot{N}} \quad (\text{E2})$$

and

$$\tilde{m} = \left(\frac{\partial \ln T_q}{\partial \ln \dot{N}} \right)_N \quad (\text{E3})$$

Usually the contribution of $\tilde{m}$ is neglected because several different experimental

conditions are necessary to compute its value which is usually quite small. Thus it is usually necessary only to consider the contribution of $\tilde{n}$.

From the plot of the natural log of the measured torque versus the natural log of the rotations it can be possible to compute a polynomial regression line that will be differentiated according to equation E3 and shown in Figure E2.

In the example the equation of the second order polynomial regression line is:

$$\ln T_q = -0.145(\ln N)^2 - 0.0525(\ln N) + 8.7146 \quad (\text{E4})$$

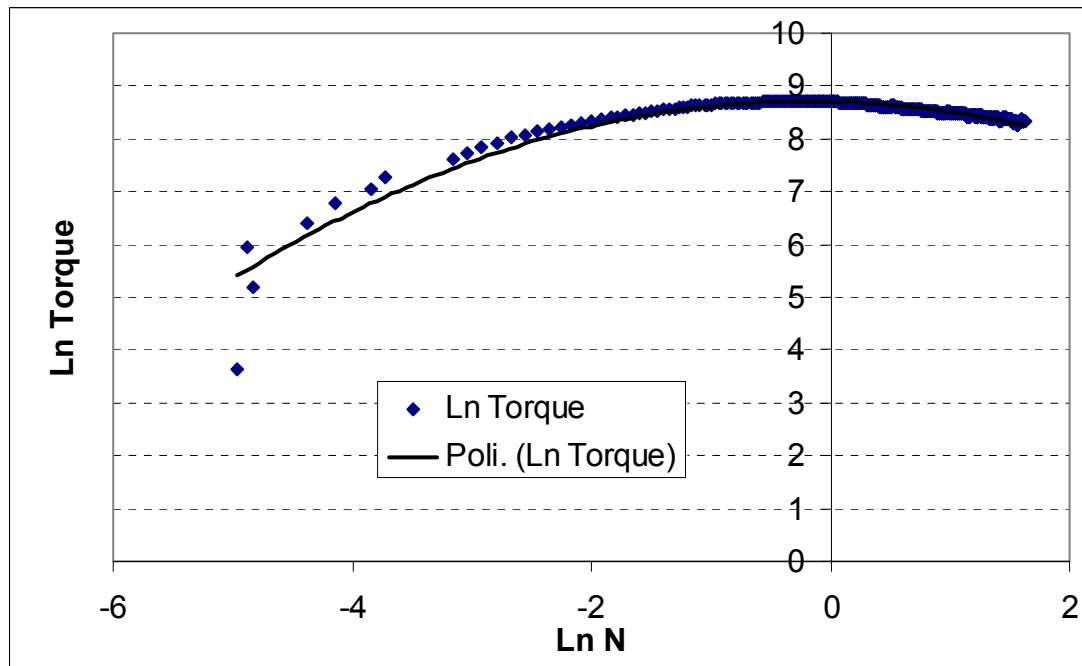


Figure E2 The natural log of the measured torque vs. the natural log of the rotations and the polynomial regression line.

From equation E4, $\tilde{n}$ can be computed:

$$\tilde{n} = -0.29 \ln N - 0.0525 \quad (\text{E5})$$

According to the definition of equivalent strain and strain rate described in section 4.1.2, where the equivalent strain is given by

$$\bar{\epsilon} = \frac{2 \pi N R}{\sqrt{3} L} \quad (\text{E6})$$

taking into account that the specimen gauge length (L) is 12 mm and the radius (R) is 3 mm the true stress - true strain curve can be obtained.

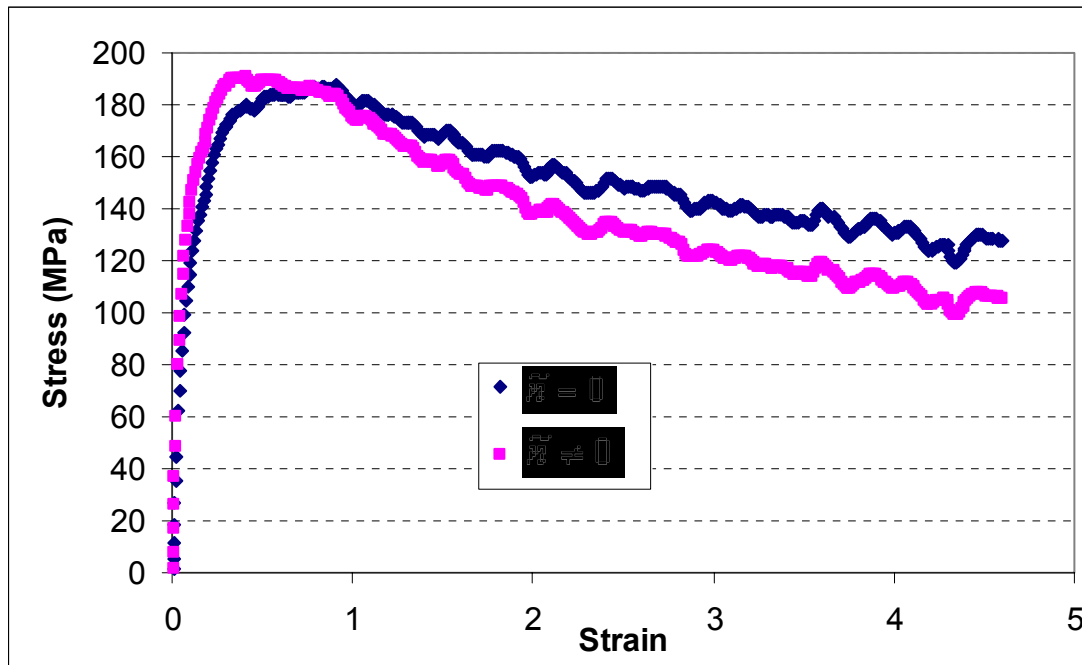


Figure E3 True stress – true strain curve with and without the $\tilde{n}$ correction factor.

Appendix F Analysis of Results – Worked Example using Inverse Modelling

As a worked example using inverse modelling,, a testing campaign on a C-Mn steel is described and the results are analysed.

Preliminary Activities :

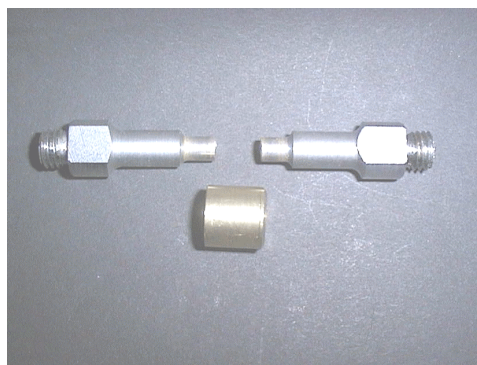
The material grade was described by the material provider (exact grade, cast number). Samples were extracted from a thick cylinder, with the longitudinal axis of the samples aligned with the vertical axis of the cylinder. The location of the samples was noted by the material provider.

The geometry of the samples was selected (Figure 13 in Section 5.2). Each sample was machined and identified.

The testing campaign was set to span a range of temperatures and strain rates. No coating was applied, but a high pressure Argon flow was maintained during all the heating and testing.

The tests were performed on a torsion bench using induction heating (see Figures 2 and 6, section 1.3). The testing system was calibrated (torque, rotation, rotation speed) and checked in December 2002 (the Standard NF EN 10002-2 for tensile tests was used as a basis and adapted to determine the class of the torsion equipment : class 0.5). The induction equipment was controlled for this material to obtain less than 10 °C throughout the sample.

The alignment of a sample in the grips was tested as suggested in section 6.1 with a fitting tube and a divided testpiece :



Testing campaign :

The testing procedure indicated in Figures 8-11 were respected and the times for heating up and temperature uniformity were recorded.

Typical experimental data for torque v time is shown in Fig. F1-3. Some tests results are also repeated to verify the reproducibility of the experiments. For instance, the difference in peak torque for the tests at 900°C and at 0.1 s⁻¹ strain rate was about 2%.

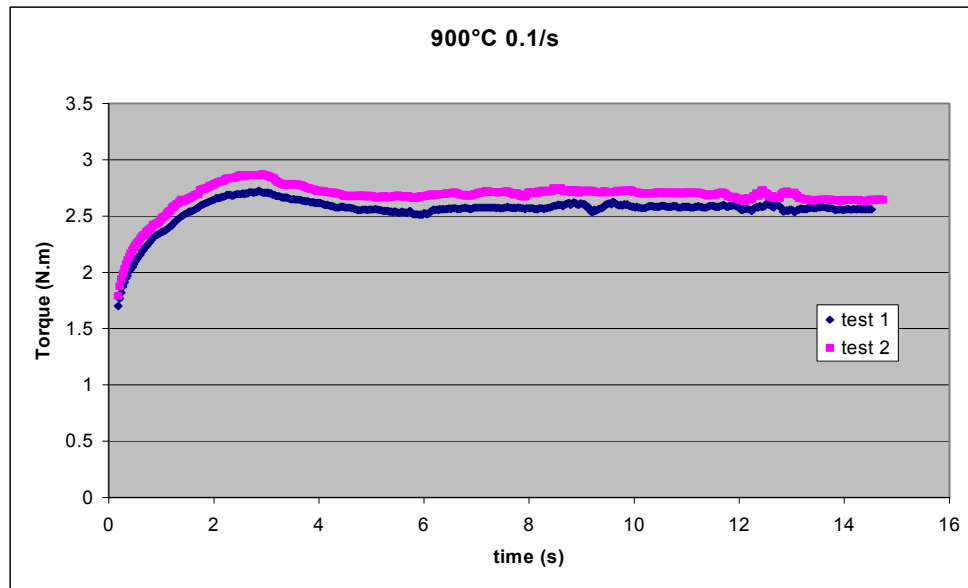


Figure F1 Torque versus time at 900°C and at 0.1 s⁻¹.

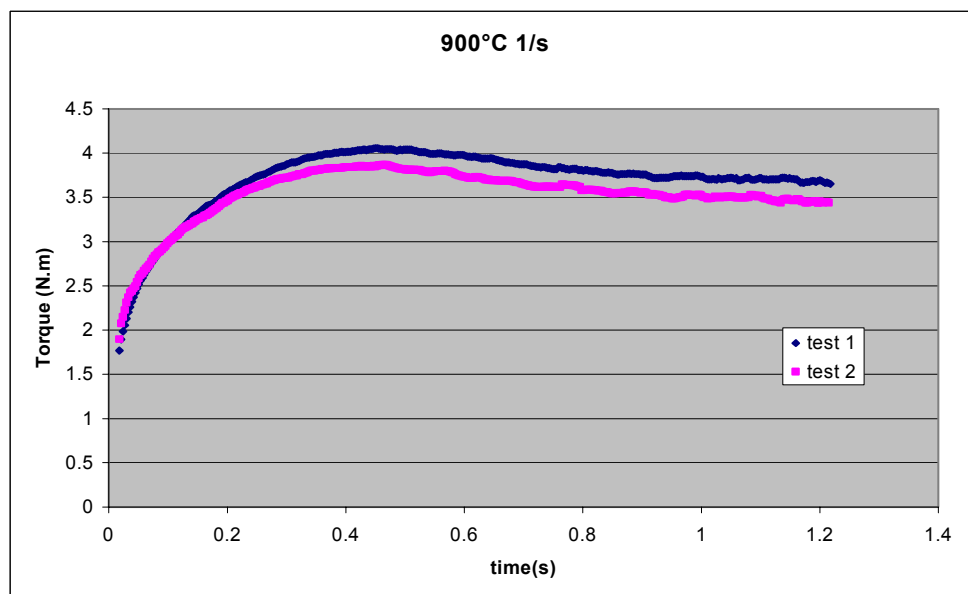


Figure F2 Torque versus time at 900°C and at 1 s⁻¹.

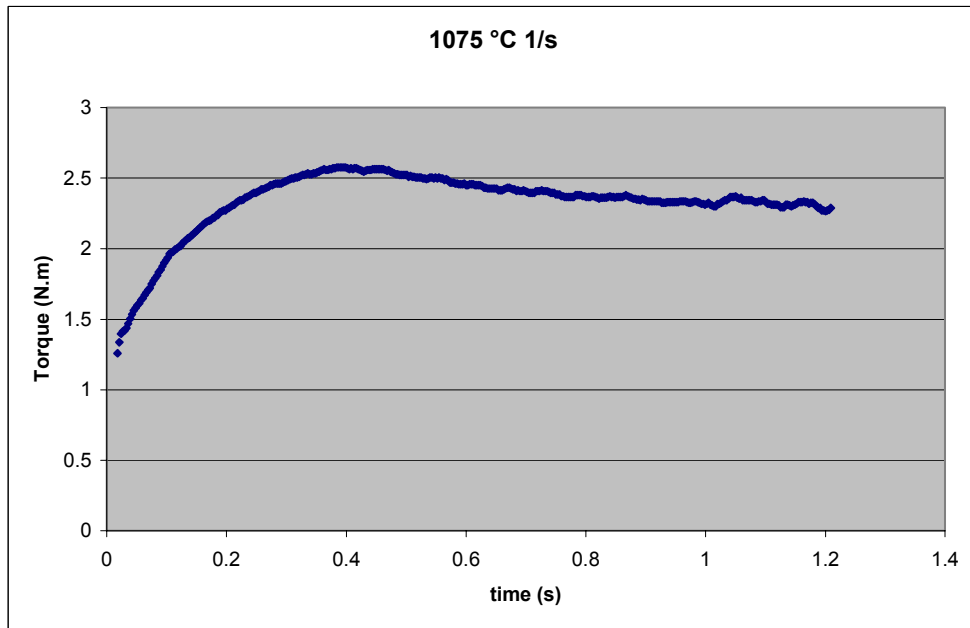
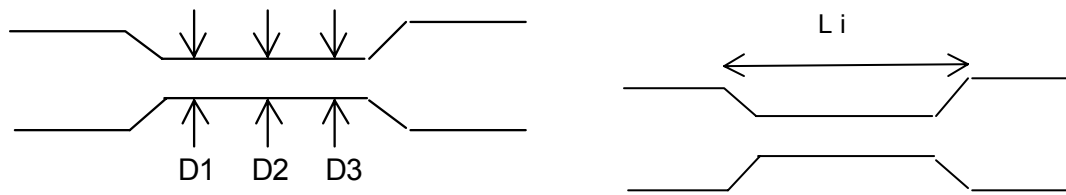


Figure F3 Torque versus time at 1075°C and at 1 s⁻¹.

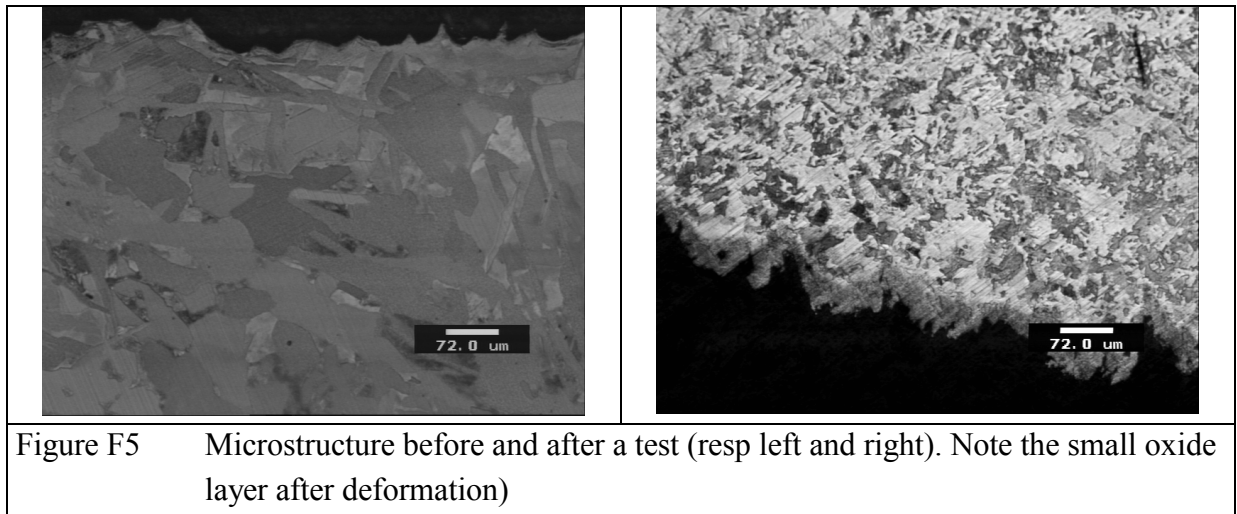
The testpiece dimensions were measured before and after all tests :



For example :

Test		Diameter	mm	Length	mm
900-01-a	Before	d1	5.99	L1 (0°)	17.71
		d2	5.99	L2 (120°)	17.71
		d3	5.99	L3 (240°)	17.71
	After	d1	5.98	Mean	17.71
		d2	6.01		
		d3	5.98		

The microstructure was analysed and reported for all test conditions using the format of Figure F4.



Mechanical analysis of the tests :

The torsion tests were analysed using the inverse analysis tool “Identify” developed in project TESTIFY. The inverse analysis [Forestier *et al*, 2002] was performed using the three experimental results shown in Figs F1-3. The constitutive law used was a classical Norton-Hoff law [Gavrus *et al*, 1996]:

$$\sigma_0 = K \exp\left(\frac{\beta}{T}\right) \bar{\epsilon}^n (\sqrt{3}\dot{\bar{\epsilon}})^m \quad (\text{F1})$$

The results of the analysis process are shown in Table F1. The cost function is a mean square difference between measurement data and each corresponding result of the simulation of the test using the constitutive law with the parameters values.

Table F1 Result of the identification of the Norton-Hoff law parameters

K	1.8 MPa.s ⁻¹
m	0.17
n	0.090
β	4206.6 K
Cost function final value	8%

- [F1] Estimation of constitutive parameters using an inverse method coupled to a 3D finite element software, R. Forestier, E. Massoni, Y. Chastel, (2002). *Journal of Materials Processing Technology*, 125-126, 594-601.

- [F2] A. Gavrus, E. Massoni, J.L. Chenot, 1996. An inverse analysis using a finite element model for identification of rheological parameters, *Journal of Materials Processing Technology*, 60, 447-454.