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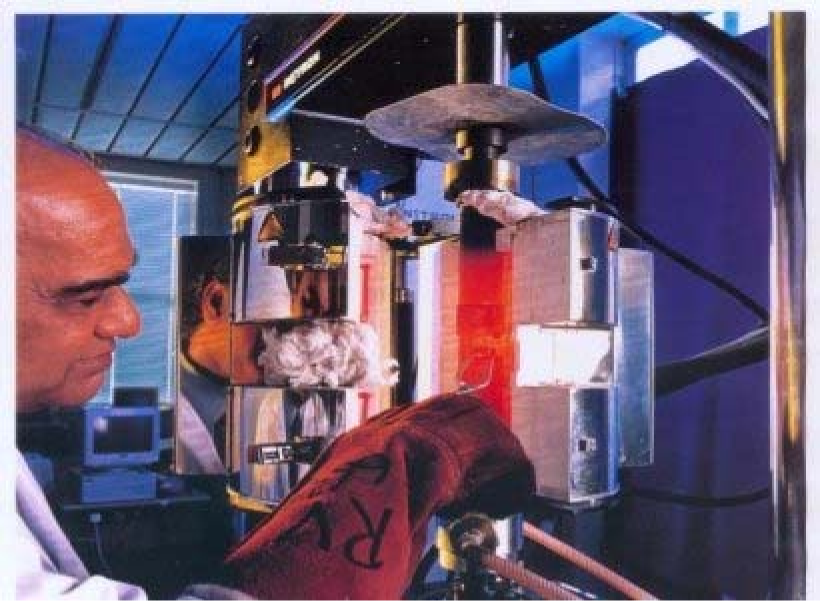
High Temperature Flow Stress Measurements: Quality & Traceability Issues

Abstract

Issues concerning calibration and traceability of the measurement apparatus used for the determination of flow stress data at high rates of strain for use in process control and modelling have been reviewed.

Three test methods for the measurement of flow stress are discussed, namely a) Hot Axi-symmetric Compression (HAC), b) Hot Uniaxial Tensile (HUT) and c) Plane Strain Compression (PSC). The traceability of the Load, Strain and Temperature measurement sensors are considered, together with matters relating to dynamic calibration.



Hot Axi-symmetric Compression Testing

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1 Introduction

This Measurement Note focuses on methods used for determining hot flow stress in metallic materials at medium to high rates of strain (10^{-3} to x 10^{2} s^{-1}), in Plane Strain Compression (PSC), Hot Axi-symmetric uniaxial Compression (HAC), Hot Uniaxial Tension (HUT) at deformation temperatures below the solidus, together with the Advanced Semi-Solid Elongation Test (ASSET). Flow stress data measured using these techniques is used for process control and process modelling by the forging and rolling industrial sectors.

The work in this present project has been carried out in the Materials Centre, National Physical Laboratory and at the Universities of Sheffield and Swansea.

The purpose of this note is to review the various techniques for calibrating the different items of equipment used in the measurement of flow stress and to show traceability to the National Measurement System (NMS).

A summary is given, Table 1, of the various tests undertaken at the different establishments together with details of the testing procedures and apparatus. For two of the test methods (HAC & PSC) new 'Good Practice Guides' have been developed in the absence of recognised Standards. For the 'ASSET' test in-house testing procedures have been written

(James 1997 & James et al 2000). Procedures based on EN 10002-5 have been used for the tensile tests, although of course the straining rates are higher than normally used for hot tensile testing.

The primary sensors that need calibration with traceability to the National Measurement System are

- Thermocouples or pyrometers for temperature measurement,
- Load cells for force measurement
- Extensometers for displacement or strain measurement.

In general the temperature measurement sensors are carried out under steady state iso-thermal conditions and it is assumed that the sensors and their readout systems have a sufficiently fast response rate to faithfully record transient and rapidly fluctuating temperatures. This is an issue that may be addressed at some time in the future, but in general it considered of less importance than in accuracies likely to be introduced to flow stress data due to the lack of consideration of the dynamic of force and strain sensors.

2 Calibration Routes

2.1 Load Calibration

2.1.1 Static calibration

In general testing machine force measurement systems are calibrated annually by a NAMAS Accredited agency in accordance with BS/EN/ISO 7500-1 (1999) which has now superseded

BS 1610 -1 for compression and EN10002-2 for tension. In addition, in some cases a spot check is carried out by applying a known mass to the loading train prior to testing.

2.1.2 Dynamic calibration

For high rate testing it could be argued that it would perhaps be more appropriate that force measurement system of the testing machines should be calibrated dynamically at rates comparable to those used during testing. This matter is certainly of concern because of the widely observed phenomena of 'load cell ringing'. An example of this effect is shown in Figure 2, recorded during a hot axisymmetric compression test using the NPL Cam-Plastometer (Roebuck et al, 2001).

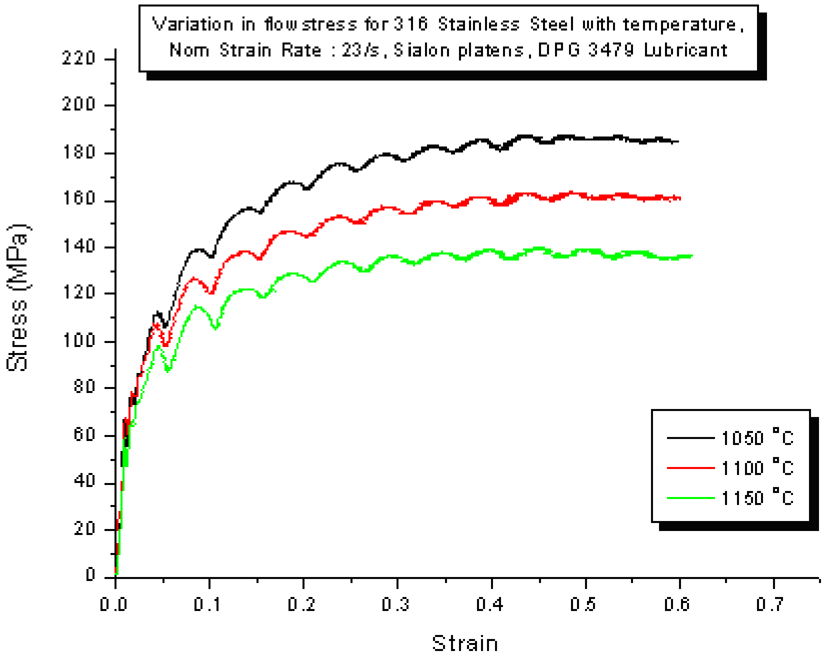

Figure 2. Cam-Plastometer Stress-Strain curves (Roebuck et al , 2001)

Most attention on the issue of dynamic calibration of load cells has focussed on cyclic loading (i.e. fatigue testing) with the notable exception of the work by Money & Sims (1989) concerning *in-situ* calibration of quartz load cells in a drop weight impact machine. In particular the issues of drift in the charge amplifiers used in conjunction with piezoelectric load cells was addressed and calibration procedures developed.; it was noted that errors up to several percent are encountered if the calibration masses are off-axis, as indicated by the scatter in the direct compression calibration measurements, see Figure 3.

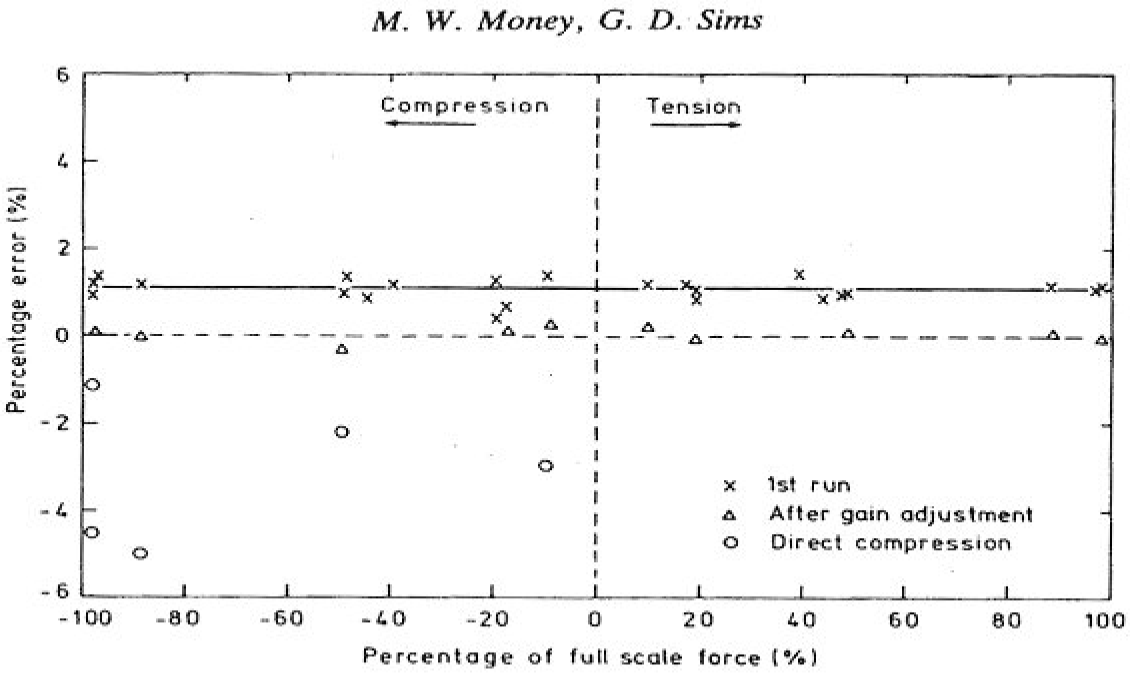

Figure 3. In-situ calibration of Quartz load cells in a Drop Weight Impact Machine: Variation in the percentage error in tension and compression, (Money & Sims, 1989)

The issue of dynamic force calibration was investigated at NPL over ten years ago by Mike Dixon under the supervision of Prof. R.D.Lohr of INSTRON and Ray Jenkins of Force Section, NPL and subsequently published by

Dixon (1995), see Figure 4. It can be seen that for Low Cycle Fatigue applications static calibration of the load cell is adequate, but for high cycle fatigue dynamic effects should be considered. In addition an inter-comparison of the method with that used at PTB, Germany, was undertaken and good agreement was obtained between the two primary standards laboratories, (Kumme & Dixon, 1992).

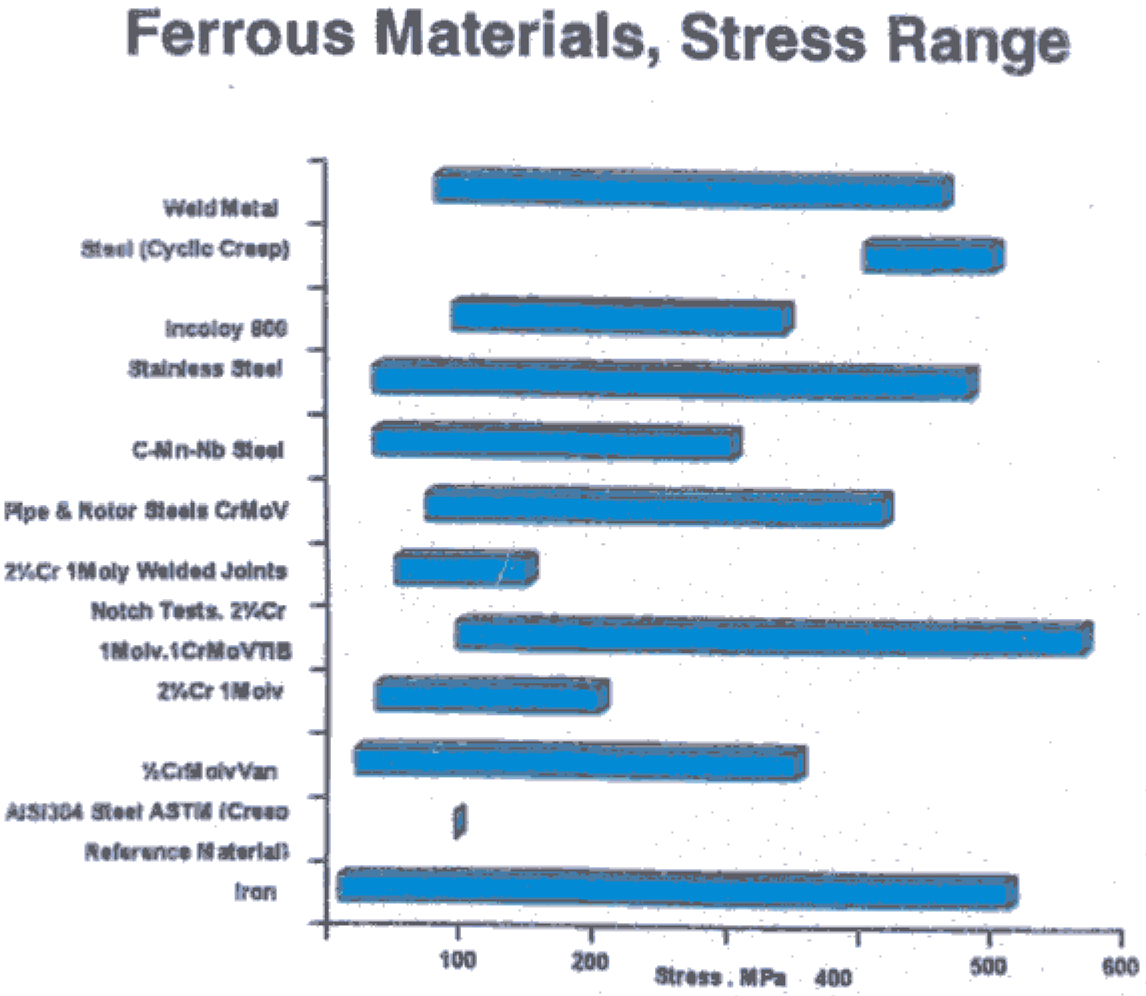

Figure 4. Dynamic calibration of load cells : Showing the effect of with & without compensation provided by an accelerometer, for different stiffness testpieces. (Dixon, 1995)

A new British Standard, BS 7935-1: 2000 '*Method for Constant Amplitude Dynamic Force Calibration-Part 1: Calibration of non-resonant uniaxial dynamic testing systems.'* is shortly due to be published. However a difficulty exists since this new Standard refers to BS7935-2 *Static and Dynamic Calibration of Force Proving Devices,* which unfortunately has not yet been drafted.

In addition as yet an infrastructure has not been established at NPL for providing a traceable route to the National Measurement System (NMS), although work is being done at PTB, Germany, to address this issue, using accelerometers (Kumme & Sawla, 2001).

The problem of load cell ringing has been widely recognised in single shot unidirectional loading as encountered in compression testing, drop weight and Charpy impact testing, however it should be noted that in all those situation the testpiece is not positively coupled to the loading train, unlike the situation encountered in fatigue testing. The lack of positive coupling almost certainly contributes significantly to the observed ringing effect, since in general such characteristics are observed in fatigue tests in which the testpiece experiences comparable load rise times in the first quarter cycle compared to those in impact or uni-directional loading. It should be noted that to a first approximation that for a steel sample with a yield stress of ~200MPa, then it can be shown that loading profile in the first quarter cycle of a fatigue test at 100Hz is equivalent to a high rate compression test at a strain rate of 1 s^{-1}.

For the dynamic calibration of load cells in fatigue testing machines, the work has concentrated on the determination of the errors introduced by the inertia effects of the grips and that part of the loading train (i.e. push rods and couplings etc.) between the testpiece and the load cell. To compensate for the effects accelerometers may be incorporated into the load cell and, when activated, can compensate for the inertia errors so as to bring the load applied to the testpiece to within the tolerance limits specified in the testing machine load calibration Standard (Lohr, 2001), see Figure 5.

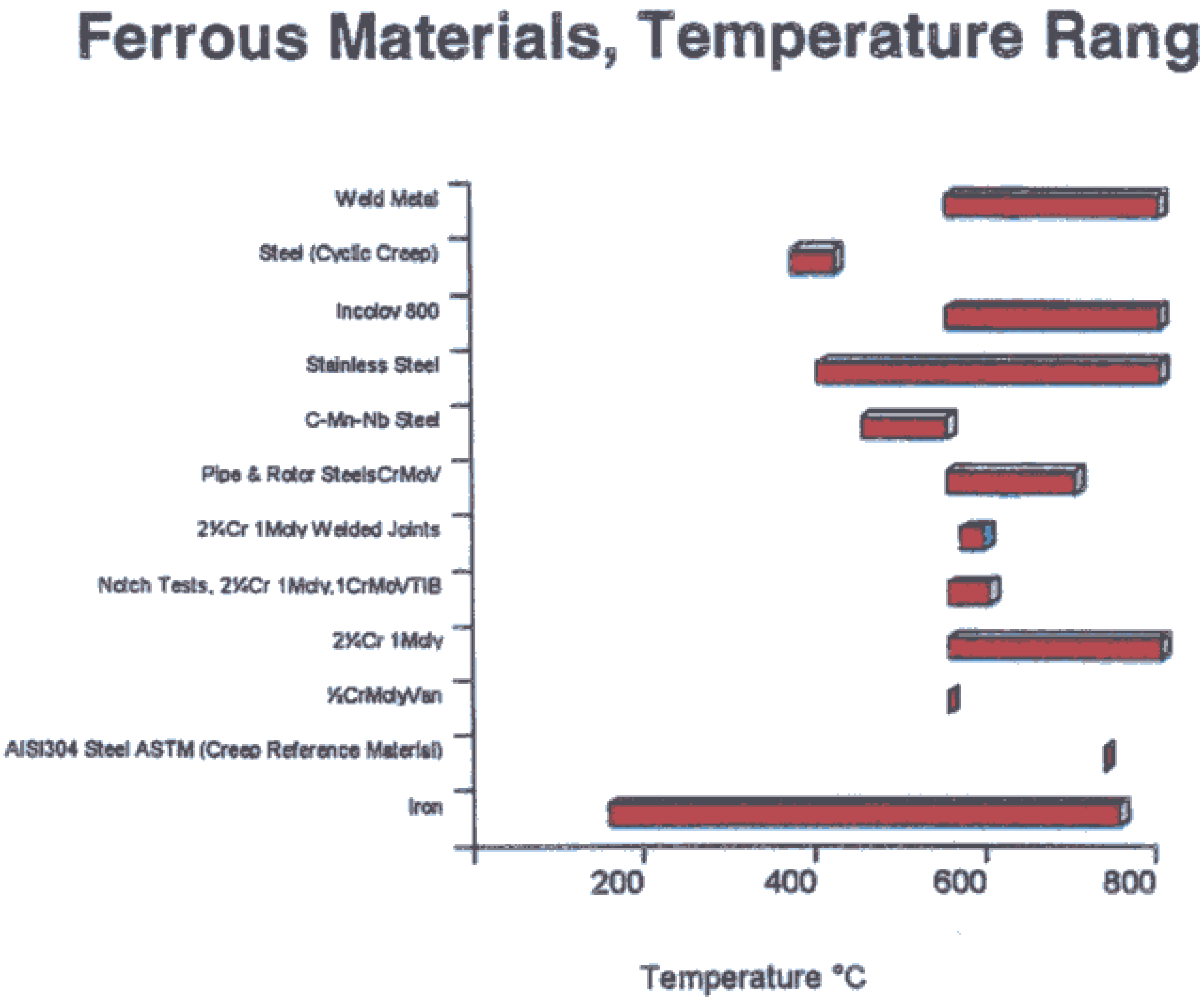

Figure 5. Dynamic Force Calibration : commercially available load cell with accelerometer compensation (Lohr, 2001).

The issues of dynamic calibration are now receiving considerable attention as illustrated by the recent ASTM Meeting in Phoenix, Arizona in May, 2001, the Dynamic Calibration Workshop held at NPL in May, 1997 and the EUROLAB Workshop held at EMPA, Dubendorf, Switzerland, May 2001 (see proceedings edited by Satir & Sennhauser containing papers by a) Dahlberg, b) Kumme & Swala, c) Bruns & Kumme).

Table 2. Load Precision for each type of test

Type of Test	Nominal tolerance*	Class	Standard / Guidelines
HUT	+/- 1%	1	BS/EN/ISO 7500-1 (1999)
HAC	+/- 1%	1	GPG3/ BS/EN/ISO 7500-1
PSC	+/- 1%	1	GPG 27 BS/EN/ISO 7500-1
ASSET	+/- 1%	1	James et al, 2000, BS/EN/ISO 7500-1

* Note: ISO 7500 -1 will shortly be revised to include Uncertainty of measurement.

2.2 Strain / Displacement Calibration

2.2.1 Introduction

A number of different methods have been adopted to measure the deformation experienced by the testpiece during high temperature testing, depending upon the size and geometry of the testpiece and the practicalities of accessibility of the testpiece in a given loading train and heating system. The strain measurement systems may be categorised into three main classes :

- Direct measurement on the testpiece gauge length, either using extensometers attached to the testpiece, or by using non-contacting devices such as a Line scan camera;
- Displacement measurement sensors attached to the loading train immediately outside the heating device; or
- Remote sensing of the load train displacement from an actuator LVDT (linear variable differential transformer) or from the crosshead displacement sensor, usually a shaft encoder in the case of screw driven machines. A summary of the strain measuring sensor used in the present series of flow stress measurements undertaken at NPL and Sheffield & Swansea Universities is given in Table 3.

It should be noted that in general all these calibrations are carried out at room temperature and that it is tacitly assumed that remain valid for the tests that are carried out at high temperature; this assumption is probably reasonable provided the active elements of the displacement sensor are not actually in the hot zone.

Table 3. Precision of Strain for each type of Test

Type of Test	**Strain Sensor**	**Nominal Accuracy**	**Class**	**Standard / Guidelines**
HUT	Extensometer or Cross-head displacement sensor (shaft encoder or LVDT)	+/- 1%	1	BS/EN/ISO 9513*
HAC				
1) Servohydraulic	Actuator LVDT	~+/- 2%		GPG3
2) Plastometer	Fibre Optic Transducers	~+/-5%		
PSC	Actuator LVDT	~+/- 2%		GPG 27
ASSET	Line Scan Camera	-		James et al,2000

* Superseded EN10002-4 in 2000.

2.2.2 Calibration of Extensometers

Extensometers used with Hot Uni-axial Tensile testing are generally calibrated using a calibration rig which is verified at three yearly intervals by comparison with a laser interferometer at NPL. Such calibration rigs usually incorporate a divided testpiece of a similar geometry to the type of testpiece being tested. The calibration of extensometers is frequently undertaken by a UKAS accredited agency in accordance with BS/EN/ISO 9513*. Further details of calibration of extensometers and the calibration Standards is given elsewhere, (Walters,1995).

For the Fibre Optic Extensometers used on the NPL Camplastometer, traceability to the NMS has been provided by comparison with an ASL SLVC (Super linear Variable Capacitance) transducer and associated read-out system which has been calibrated using a laser interferometer by Length Section at NPL, [M.R.Brooks, NPL, private communication.]

2.2.3 Calibration of Transducers & Shaft Encoders

On servo hydraulic machines the position of the actuator ram is generally measured by a LVDT incorporated into the actuator on the opposite end of the actuator to the ram that is in direct contact with the push rods in the testpiece loading train. On servo-electric machines the load is applied to the loading train either via a central recirculating-ball lead screw or via a moving cross head connected to twin lead screws on either side of the loading frame; in either case the position of the loading train is usually determined by a rotary encoder attached to the lead screws. At present there are no standards that cover the calibration of the movement of loading trains, either for displacement or displacement rate, however simple checks may be made to measure independently the distance travelled by the loading train. Care needs to be taken when calculating the deformation in the testpiece from Encoders or Actuator transducers since a correction for the loading train compliance needs to be considered.

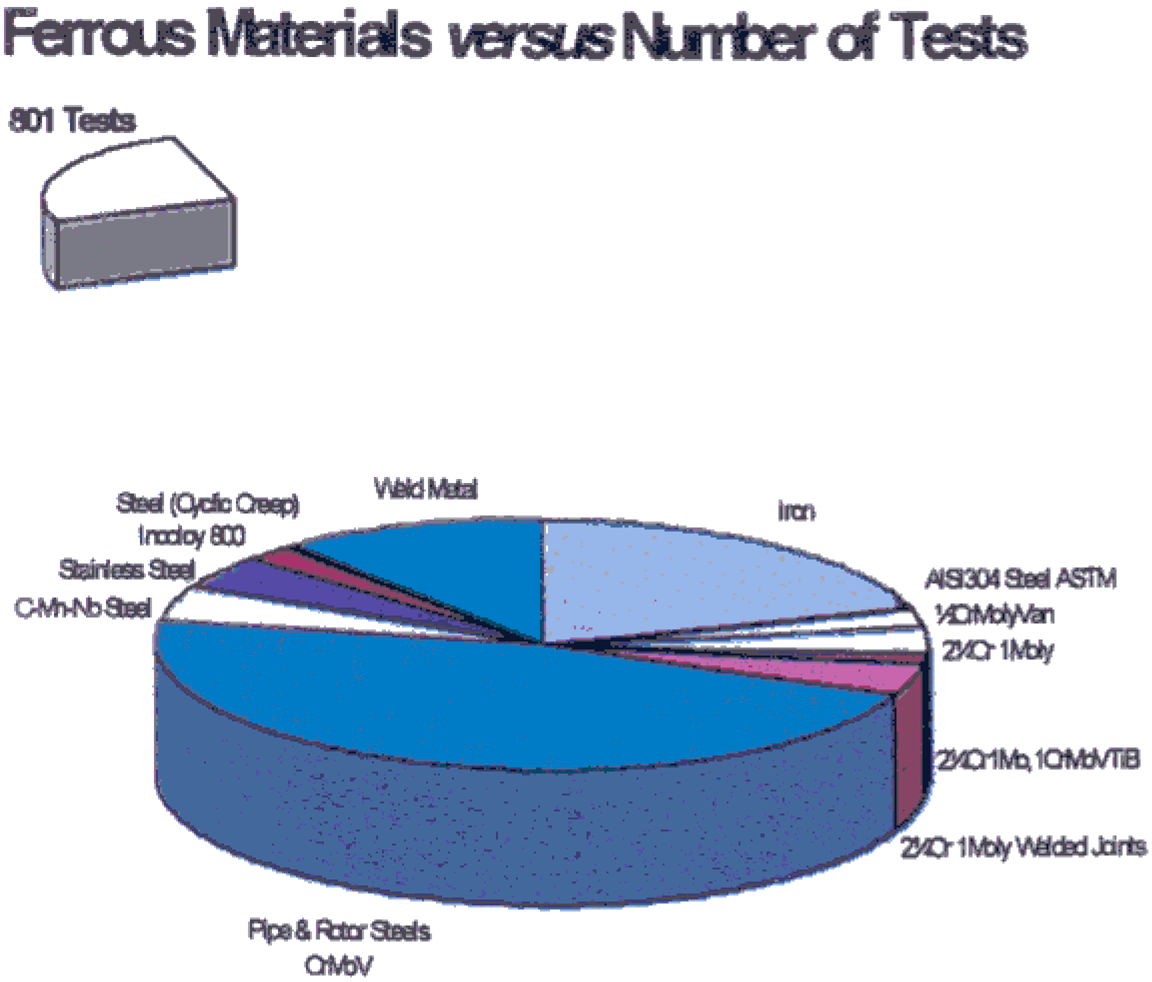

Figure 6 Dynamic calibration of extensometers, indicating errors due to resonances, (Albright, 1995)

Table 1. Summary of Flow Stress Testing Systems and Sensor Calibration-Traceability Routes.

Type of Test	**Establishment**	**Testing procedure**	**Apparatus**	**Calibration Methods**		
				Load	**Strain**	**Temperature**
Hot Axisymmetric Compression (HAC)	Sheffield University	GPG 3	SERVOTEST Servo-hydraulic	NAMAS BS/EN/ISO 7500-1	Actuator LVDT	In House procedure using NPL Ref T/C
Hot Axisymmetric Compression (HAC)	NPL	GPG3	INSTRON Servo hydraulic	NAMAS BS/EN/ISO 7500-1	Actuator LVDT	In House procedure using NPL Ref T/C
Hot Axisymmetric Compression	NPL	GPG 3	NPL Camplastometer	NPL Force Section BS/EN/ISO	Fibre Optic Extensometer	In House procedure

(HAC)				7500-1		
Hot Axisymmetric Compression (HAC)	Swansea University	GPG 3	ESH Servo-hydraulic	NAMAS BS/EN/ISO 7500-1	Actuator LVDT	In House procedure using certified T/C supplied by TC Ltd.
Plane Strain Compression (PSC)	Swansea University	GPG 27	GLEEBLE Servo hydraulic	BS/EN/ISO 7500-1	Actuator LVDT	In House procedure using NPL Ref T/C
Plane Strain Compression (PSC)	Sheffield University	GPG 27	SERVOTEST Servo hydraulic	BS/EN/ISO 7500-1	Actuator LVDT	In House procedure using NPL Ref T/C

Table 1 (cont'd) . Summary of Flow Stress Testing Systems and Sensor Calibration-Traceability Routes.

Type of Test	**Establishment**	**Testing procedure**	**Apparatus**	**Calibration Methods**		
				Load	**Strain**	**Temperature**
Hot Uniaxial Tensile (HUT)	Sheffield University	Based on BS EN 10002-5	DELTA NENE Servo-electric	BS/EN/ISO 7500-1	Extensometers BS/EN/ISO 9513 Class 1,	In House procedure using NPL Ref T/C
Hot Uniaxial Tensile (HUT)	NPL	Based on BS EN 10002-5	INSTRON Servo Electric	NAMAS BS/EN/ISO 7500-1	Extensometers BS/EN/ISO 9513 Class 1, or Displacement from M/C encoder	In House procedure using NPL Ref T/C [Osgerby & Loveday, 1992]
Advanced Semi-Solid Elongation Test (ASSET)	Swansea University	In house procedure. [James et al , 2000]	Customised Hounsfield: Servo-Electric with Gleeble-AC Heating	BS/EN/ISO 7500-1	Line Scan Camera,	In House procedure using NPL Ref T/C [James ,1997]

2.2.4 Dynamic Calibration

All the methods for displacement validation mentioned above are essentially static techniques and it is questionable whether for testing at high rates of strain dynamic methods of calibration should be employed. However, like the situation concerning load verification, at present there is no infrastructure yet in place to provide traceability to the NMS for dynamic strain measurement. Nevertheless it would be prudent to ensure that the electronic data capture systems have sufficient bandwidth and data capture rates to ensure that the transient forces and strains may be faithfully recorded. Further information concerning dynamic verification of extensometers has been given elsewhere by Albright,1995.

2.2.5 Re-verification period.

Since all the displacement or strain measurement devices invariably incorporate an electronic readout systems it is good practice to re-verify the devices at time periods not exceeding 12 months. In addition the systems should be re-calibrated if an active part of the measurement system is repaired or replaced.

2.3 Temperature Calibration

Consideration of the measurement of testpiece temperature during Hot Compression testing has been given in the Good Practice Guides (Roebuck *et al* 2000 & Loveday *et al*, 2000), see Appendix 1. The acceptable temperature tolerances and gradients at the start of tests for the various flow stress measurements are given in the Table 4.

In general for the various tests the majority of the Laboratories have compared the emf output of 'working' thermocouples against that from a Certified Reference Thermocouple provided with a certificate demonstrating traceability to the National Measurement System. Care has also been taken to demonstrate that the electronic readout systems used for the emf measurements, or the software used for conversion into °C do not introduce significant errors. In some cases it was necessary to apply correction factors determined during calibration to ensure true readings of the testpiece temperature were obtained. The magnitude of such corrections is dependent on the test set-up and is affected by factors such as a) the size of the testpiece relative to the push / pull rod assembly, b) the type and size of the heating assembly, c) the precision of the temperature sensors and d) the accuracy of the temperature read-out system. The issues concerning control of temperature are discussed elsewhere, Loveday and Lord, 2000, however it should be noted that there may be significant discrepancies (up to ~250°C) between the temperature indicated by the heating system controller and the true temperature of the testpiece at the start of the test.

Table 4. Acceptable temperature parameters for each type of test

Type of Test	**Indicated Test Temperature °C**	**Initial tolerance* °C (permitted deviations between the Indicated temperature and the Specified temperature)**	**Resolution/ Precision of Measurement System °C**	**Standard / Guidelines**
HUT	T < 600 600 < T < 800 800 < T < 1000 'by agreement' T > 1000	±3 ±4 ±5 see Note 1	Resolution[$] :1 Accuracy: ± 2	EN10002-5 * ISO 783
HAC & PSC	T<600 600 < T< 900 900 < T	To be revised. (see Note 2.)	Precision[†] ±2 ±3 ±4	GPG3 (A'mend2001) GPG 27 (A'mend2000)
ASSET	±2 (variation along GL=2D)	±4	±2 (corrections up to 5°C may need to be applied)	James, 1997, & James et al, 2000

[*] The term 'initial tolerance' has been used since at very high strain states inherent 'deformational' heating generated within the testpiece may cause the temperature to deviate outside the specified tolerances during the test. Details concerning corrections to be applied to the flow stress data to allow for this effect are given in the PSC Good Practice Guide.

[$] Resolution[#] is the smallest discrete value of temperature recorded or displayed by the indicator of the temperature measurement system. Most measurement systems used in mechanical testing will have a Resolution of better than 1°C.

[†] 'Precision'[#] here 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. It includes an allowance for the resolution of the indicator.

[#] A useful glossary of terms and definitions is given in Appendix 1 to 'Materials Metrology and Standards: an introduction.' Chapt 1, pp1-18, in Materials Metrology and Standards for Structural Performance, Ed B.F.Dyson, M.S.Loveday & M.G.Gee. pub: Chapman & Hall, 1995.

Note 1 : For tensile testing with recommended gauge length to diameter ratios of 5:1, the European Standards are being revised to include the additional constraint that the maximum variation along the gauge length on any individual testpiece shall be no greater than, 3,4,5°C for the various test temperature ranges. This additional tolerance is also referred to as the 'temperature gradient' along the gauge length. See ISO 783 & EN10291(Creep Testing) This concept was introduced to minimise localised yielding at a hot spot and thereby ensure uniform deformation along the entire gauge length.

Note 2 : Further work is in hand to within a current DTI Funded Research project led by NPL which will review the tolerance values taking into account theoretical modelling of flow stress properties. This is likely to lead to the revision of the HAC & PSC Good Practice Guides.

It should be appreciated that at present the flow stress data acquired using HAC & PSC is primarily used for Finite Element Modelling or design of components whereas the Tensile Test Standard is widely used for product release testing. So in the Tensile test a tolerance of ±3°C for T < 600°C means that at test carried out at an indicated temperature of say 503°C is a valid test for reporting specified properties at 500°C, as opposed to stating that the data actually refers to a test carried out at 503°C.

3 Measurement Uncertainties

A full estimation of the measurement uncertainties for each type of test is beyond the scope of this note, but guidance is provided for Tensile Testing in EN 10002-1, and in an NPL Measurement Note (Loveday 1999).

However the testing tolerances given in this Note may be used as input parameters in the Uncertainty Estimate calculations in line with the ISO Guide to the Expression of Uncertainty of Measurement. General guidance can be found elsewhere (Bell, 1999 & Kandil et al 2000)

4 Conclusions

Information has been presented highlighting issues that need to be considered for the calibration of testing equipment used for the determination of flow stress characteristics of materials at high strain rates. Details are given of allowable tolerances, for the primary temperature, load and strain (displacement) sensors. Provided the specified testing tolerances for the various type of test are achieved, then the precision of the flow stress measurements are comparable.

5 Acknowledgements

Numerous colleagues from NPL, Sheffield University and Swansea University are acknowledged for informative discussions during the preparation of this note. It has been prepared as part of project MMP4.1 within the *Materials Measurements which affect Processability* (MMP) Programme, an underpinning materials measurement research activity financed by the UK Department of Trade and Industry.

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Standards

- BS 1610-1 *Load Calibration Compression for Uniaxial Testing Machines*
- BS 7935-1: 2000 *'Method for Constant Amplitude Dynamic Force Calibration-Part 1: Calibration of non-resonant uniaxial dynamic testing systems.'*
- BS 7935-2: 2001 *'Method for Constant Amplitude Dynamic Force Calibration-Part 2: Calibration of Force Proving Devices.*
- BS/EN/ISO 7500-1 *Load Calibration*
- BS/EN/ISO 9513 *Verification of extensometers*
- EN 10002-1 *Tensile Testing at Ambient Temperature*
- EN10002-2 *Load Calibration of Uniaxial testing Machines*
- EN10002-3 *Verification of Force Proving Devices*
- EN10002-4 *Verification of Extensometers*
- EN 10002-5 *High Temperature Tensile Testing En 10291 Metallic Materials : Uniaxial creep testing in tension- Method of Test.*
- ISO 783 *Metallic Materials: Tensile Testing at Elevated Temperatures*

Appendix 1 Temperature Measurement: Precision and Traceability

Based upon guidance included in the Good Practice Guides for Axisymmetric Compression and Plane Strain Compression Testing (BPG 3 & 27)

A.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.

A.2 Deformational Temperature Changes

In the case of high strain rate testing, as encountered in Hot Compression Tests, the temperature of the testpiece may rise during testing due to deformational heating. In practice it is rarely possible to provide adequate feedback control to compensate for this effect and maintain the testpiece at a uniform temperature. Thus, it is 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.

A.3 Traceability

In hot compression tests the temperature of the testpiece can be measured using thermocouple(s) rather than non contact temperature sensors. Depending upon the test temperature either base metal (Type K & N) or noble metal (Type R & S) may be used. Provided the testpiece is of sufficient size, ie greater than ~ 8mm diameter for HAC or ~5 mm thick for PSC, a small hole, ~1.2 mm diameter may be 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 (1982), Desvaux (1982), Osgerby & Loveday (1992) & Robson (1977).

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.

A.4 Heating Systems

In general there are three types of heating systems that may be used for hot compression testing, (a) heated muffle furnaces, and (b) resistance heating of the testpiece [either AC e.g. Gleeble machines, or DC current] and c) induction (RF) heating systems.

In the first type, the testpiece is heated in a furnace that surrounds the loading train. In this case the testpiece monitoring thermocouple must have sufficiently long trailing leads to accommodate the opening of the furnace. It helps to verify that the furnace has the capability of heating the testpiece uniformly to the desired temperature by using a special calibration testpiece which is instrumented with an array of thermocouples. As specified in Table 4, the testpiece temperature should be within ± 10°C (T < 800°C) at the start of the test for HAC & PSC.

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

In the case of resistance heating of the testpiece, as undertaken in Gleeble machines, independent temperature control of the grips is not practical. However, it is still essential to demonstrate that the testpiece is heated uniformly within tolerances of ± 10°C (T < 800°C) as specified in Table 4 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.

A.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. 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.

A6 References for Annex 1

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- Robson, H (1977) *'Temperature measuring techniques in a large creep laboratory'* J. Phys. E, Scientific Instruments **10.** 384-389.

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