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Temperature Control and Uniformity in High Temperature Metalworking Laboratory-Scale Tests

This Measurement Note provides a summary of the measurement methods available for monitoring the temperature during hot metalworking processes and during the simulation of such operations in laboratory-scale tests.

The note is in two parts. The first part deals with the relevant temperature measurement techniques, and discusses some of the applications and technical limitations of the different methods. The second part addresses some of the specific issues and requirements related to temperature measurement that have been highlighted in the development of Good Practice Guides for Hot Axisymmetric Compression and Plane Strain Compression tests.

Summary tables and references are provided where appropriate.

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Introduction

In the metal processing industry, accurate temperature measurement is vital for reliable process control. The efficiency of the process and controlled development of microstructure are two key factors which are strongly influenced by temperature. In this *Measurement Note* some of the more commonly available techniques for measuring temperature are discussed, together with recommendations and specific advice related to temperature measurement and control in laboratory-scale testing used for measuring flow stress.

Thermocouples

Thermocouples are by far the most widely used industrial temperature sensor by virtue of their simplicity, ruggedness, low cost, small physical size and wide temperature range (from about -270 to 3000°C). The practical thermocouple consists of at least 2 wires, made from dissimilar materials, joined at one end to form a junction. Contact between the two materials is best made by welding or soldering and the wires should be insulated and connected to a cold junction and appropriate instrumentation. When the thermocouple bead is placed in a temperature gradient a current is generated which manifests itself as an emf across the ends of the conductor - the *Seebeck effect*. It is important to note that the output emf is not generated solely at the point of measurement, but along all sections of the conductors which are subjected to temperature gradients (including extension leads and compensating cables) .

Thermocouple types

Many combinations of materials can be used to produce thermocouples [1,3] but the most common types are given in Table 1.

Comment on types. The most commonly used thermocouples are the ....

The emfs measured can be converted to corresponding temperature measurements by consideration of BS EN 60584-Pt 1 [4] which gives details of the polynomials and reference tables for the 8 types listed in Table 1.

Instrumentation

The magnitude of the emfs generated range from ~10μV/°C for Type S to a maximum of ~80μV/°C for Type E thermocouples. The simplest form of emf measuring device is the moving coil meter. Chart recorders can be used for the continuous recording of temperature, but most laboratory thermocouple measurements are now made using digital voltmeters (DVM), many of which are capable of 0.1μV resolution.

Direct readings of temperature can be achieved using digital thermometers. Some use Pt100, thermistor or diode sensors, but most use Type T or K thermocouple probes which can give readings to 0.1°C up to 200°C and ±1°C at higher temperatures.

All instrumentation should be calibrated annually to the appropriate NAMAS certification.

Reference Junctions

A reference junction should be used for accurate temperature measurement. The reference junction is usually maintained at 0°C (a 'cold junction'), but it can be fixed at some other temperature and, indeed, for multiple thermocouple installations it is often easier to maintain the reference junctions at some high temperature by placing them in a furnace or temperature cabinet. In modern digital temperature indicators a reference junction, based on a semiconductor thermo-electric cooling device, is often incorporated into the instrument itself.

Attachment

To ensure reliable heat transfer, the thermocouple junction must be in intimate physical contact with the object. A thermocouple can be attached to the surface of an object or specimen by wire or high temperature glass tape, but spot welding or soldering offers a more permanent solution. If the thermocouple is located inside a component or testpiece, precautions should be taken to ensure that the tolerances of the hole are such that good physical contact exists between the thermocouple bead and the bulk metal. Protective sheaths may be used to prevent mechanical and environmental damage to the wires and cables.

Calibration

As supplied, thermocouple wires are usually guaranteed to give an output within specified tolerances. For example, types R and S are usually quoted to ± 1°C at the gold melting point (1064.18°C) whereas type K might be supplied to ± 4°C or ± 7.5°C at 1000°C depending on the particular classification of wire. This only gives an indication of the accuracy of the measurement and it is still recommended that separate calibration tests are carried out for each complete thermocouple (including all wires, extension cables and instrumentation). Calibration is best carried out by comparison against a standard reference thermometer which is directly traceable to ITS-90 (the International Temperature Scale, 1990) and national primary standards. The typical reference device used is a Pt resistance thermometer or radiation pyrometer. In-house calibration can be acheived if a suitably calibrated transfer device exists, calibrated directly from the national standard or to appropriate NAMAS certification.

For thermocouples used to monitor temperature over a period of time, calibration should be checked annually.

In general materials testing and the tests described in the *Good Practice Guides* [6,7] for measuring flow stress the thermocouples are often damaged or destroyed during the test. If the thermocouple is repaired or a new thermocouple is used for each test it is important that it is calibrated before use. Prior to calibration, the thermocouple should be annealed to remove any inhomogeneities introduced through manufacture and mechanical strain.

Radiation Thermometry

A variety of types of radiation thermometers exist [8,9], but the three most popular include:

- Disappearing filament pyrometer
- Infrared thermometers
- Thermal imaging sytems

The disappearing filament pyrometer is still used for high temperature measurements where there is sufficient visible radiation. The eye is a very sensitive comparator and with this device the temperature and brightness of the filament is adjusted to match an image of the source. Temperatures in the range 700-3000°C can be measured to ± 5°C at 1000°C, but these types of device have largely been superceded by direct reading and automatic instruments.

The application of radiation thermometry has increased dramatically with the development of silicon photodiodes and pyroelectric detectors. Silicon photodiodes are suitable for measuring temperatures between 600 and 3000°C with a typical uncertainty of ±1°C. The devices have a very fast response and are suitable for controlling automatic processes where feedback on the variation of temperature is required.

Thermal imaging systems use a special form of radiation thermometer, where a full field image of an object is built up by an array of detectors. They are particularly useful for identifying hot spots and temperature differences but accurate values of emiossivity are required for the best results.

A further important parameter to consider when selecting a radiation thermometer for a particular application is that of target size. Large errors will result if the target does not fill completely the field of view of the instrument.

Emissivity

Emissivity is the ratio of the intensity of the radiation emitted by an object to that emitted by a perfect radiator or "blackbody" at the same temperature. Values of emissivity lie between 0 for a perfect reflector to 1 for a blackbody, and for a given surface the emissivity depends on the wavelength, temperature, surface preparation and surface coatings. One of the main problems in measuring temperature with a radiation thermometer arises from the uncertainty associated with the emissivity of the object being measured. As an example, the emissivity of steel using a detector operating at a wavelength of 2μm varies from 0.2 in the polished condition, to 0.25 - 0.3 as rolled and 0.75 - 0.85 if oxidized [10].

Typical errors in the temperature measurement arising from a 10% error in the emissivity at 1000 and 1500°C are 23 and 44°C respectively. Such large errors are potentially critical in some materials processing where the microstructure and flow stress are strongly temperature dependent. process. In metalworking, the build up of oxide scale on the surface of the workpiece can have a considerable effect on the value of emissivity.

Calibration

Calibration tests can be carried out on the material or specimen of interest by direct comparison with a suitably calibrated thermocouple. It should be possible to correct for emissivity by ..

The major advantages of radiation thermometry are the ease of use and non-contact measurement. The speed of response is largely determined by the detector and it is possible to measure rapidly changing temperatures or the temperature of a rapidly moving object. However, if the emissivity of the source is variable or unknown considerable errors can result, and the instrument reading may also be susceptible to refelcted radiation and absorption by the intervening medium.

Other Techniques

- Digital Thermometers
- Novel transducers - including semiconductors, magnetic and acoustic methods, fibre optics and quartz crystal thermometers
- Laser techniques

There are still only relatively few cases where laser-based techniques are used on a routine basis for monitoring production processes. Materials processing - which includes hot metalworking - is an important example. In the plant, contact thermometry is often impractical because of moving materials, contamination and access and whilst conventional non-contact radiation thermometry is attractive (and extensively used) there are problems with emissivity and background radiation . Laser techniques have the potential to eliminate the uncertainties associated with these factors.

Temperature Measurement In Laboratory Tests

Recommendations regarding temperature measurement in high temperature mechanical testing already exist [5]. Further guidelines related to the hot axisymmetric compression [6] and plane strain compression tests [7] have been developed as part of the current work.

Temperature Gradients

The *Good Practice Guides* on hot axisymmetric compression and plane strain compression testing [6,7] recommend that the uniformity of temperature along the testpiece should be checked before a series of tests, and at regular intervals not exceeding 100 tests. This can be carried out using a dummy specimen with a number of thermocouples positioned along the gauge length. The recommended maximum variation in indicated temperature along the testpiece and the deviation from the specified test temperature for hot axisymmetric compression testing [6], plane strain compression testing [7], high temperature tensile, low cycle fatigue and creep [5] are given in Table 2. These values are based on experience and the results of a survey and intercomparison exercise. Because flow stress is sensitive to temperature measurement it is important to reduce the uncertainty in temperature in the testpiece and additional work is ongoing to examine whether these figures can be refined.

Table 2: Recommended temperature tolerances for hot axisymmetric compression (AC), Plane strain compression (PSC), hot tensile, creep and low cycle fatigue testing [5-7].

	Test Temp (°C)	Spatial Variation (°C)	Precision (°C)
AC	< 800	± 10	± 10
	> 800	± 10	± 10
PSC	< 800	± 10	±
	> 800	± 10	±
Hot tensile	< 600		
	600-800		
	800-1000		
LCF + Creep	< 600		± 3
	600-800		± 4
	800-1000		± 6

Comment on spatial variation and precision ....

Thermocouples must be verified at intervals not exceeding one year over the complete working temperature range, and calibrated in accordance with BS 1041 Part 4: 1992.[3]

The accuracy of thermocouples can be affected by radio interference from induction coils. It is recommended therefore that they are not used as the only measurement system when induction heaters are used, and perhaps should be cross-referenced to pyrometry measurements or embedded thermocouples calibrated separately.

temp rise during processing

effect of temp on flow stress

Summary

Table 1: Characteristics of the main thermocouple types

Thermocouple Designation	Type	Temp range (°C)
Type S	Platinum - 10% Rhodium/Platinum	up to 1400
Type R	Platinum - 13% Rhodium/Platinum	up to 1400
Type B	Platinum - 30% Rhodium/Platinum - 6% Rhodium	600 to 1600

Type J	Iron/Copper - Nickel *(Iron/Constantan)*	-210 to 800
Type K	Nickel-Chromium/Nickel-Aluminium *(Chromel-Alumel)*	-250 to 1100
Type T	Copper/Copper-Nickel *(Copper/Constantan)*	-250 to 400
Type E	Nickel-Chromium/Copper-Nickel *(Nichrome/Constantan)*	-210 to 900
Type N	Nickel-Chromium-Silicon/nickel-Silicon *(Nicrosil/Nisil)*	up to 1250

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References

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More specific advice on aspects of temperature measurement can be obtained from the Temperature Group at NPL.

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