

Strain Gauge Techniques for Measuring Thermal Expansion

A novel strain gauge technique has been used to measure the thermal expansion behaviour of a number of materials including copper, aluminium and both polymer and metal matrix composites. Copper and aluminium were used for calibration purposes and validation of the technique. The values obtained from the strain gauge method for the coefficient of thermal expansion, between 25-100°C, of copper and aluminium were 16.6 and 23.4 x 10⁻⁶/°C respectively and these are in good agreement with typical handbook values. Two case studies are presented in this document, but a number of other materials are covered in an NPL report [1] which describes the technique in more detail and discusses the merits and application of the strain gauge method. Practical tips are given where possible and conventional dilatometry data are presented for some materials for comparison.

It is difficult to quantify the absolute accuracy of the measurements because this depends to a large extent on the quality of the strain gauge installation, but uncertainties associated with the measurements are typically 5-10%.

J D Lord

August 1997

Introduction

For most applications using strain gauges, careful attention is taken to avoid generating thermal strains by using self temperature compensated gauges and constant temperatures. It is possible however, to exploit the thermal output of the strain gauge to measure the coefficient of thermal expansion (CTE) of a wide range of materials. The main advantages of the strain gauge technique over conventional dilatometry include the ability to carry out multiaxial measurements on relatively large testpieces or components, using relatively simple equipment readily available in most engineering test laboratories. The technique exploits the differential thermal expansion of identical strain gauges bonded to two different materials subject to the same temperature change. Some basic knowledge of strain gauges, strain gauge installation and instrumentation is required, but the test method itself is relatively straightforward. The main drawback of the method is the limited temperature capability of the strain gauge installation. Conventional foil strain gauges typically operate up to 200°C, and although high temperature strain gauges and adhesives can be used above this they are relatively expensive and specialised, and 200°C should be taken as the practical upper temperature limit.

Measurement Technique

Details of the measurements made are given in [Ref. 1](#), and background to the strain gauge technique is detailed in [Refs. 2 and 3](#). In its simple form the technique uses two identical strain gauges, one of which is bonded to a specimen of a well defined reference material, the second to the material of interest. Under stress-free conditions, and at a common temperature, the differential output of the two gauges represents the difference in thermal expansion of the two materials. If the thermal expansion behaviour of the reference material is well characterised, then the thermal expansion coefficient of the material under examination can be calculated using the following equation:

$$\alpha_{spec} = \frac{[\epsilon_{spec} - \epsilon_{ref}]}{\Delta T} + \alpha_{ref}$$

where α_{spec} and α_{ref} refer to the thermal expansion coefficients for the specimen and reference material over the temperature range, ΔT and ϵ_{spec} and ϵ_{ref} are the corresponding strain values.

Key Issues

The three key issues which must be followed for accurate measurements are:

- Identical strain gauge installations should be used on the reference material and the specimen of interest.
- The thermal expansion behaviour of the reference material is well characterised over the whole temperature range.
- Measurements on both materials are made at the same temperature.

In theory any reference material can be used provided that the thermal expansion behaviour is well characterised.

Validation of the Strain Gauge Technique

To validate the strain gauge technique, measurements were made from on a 6061 aluminium alloy and a copper specimen, and compared with handbook values for CTE.

Raw strain gauge data for the aluminium, copper and titanium silicate reference material are plotted against temperature in Fig 1. The variation of thermal expansion is shown also as a continuous plot in Fig 2, simply by subtracting the reference material strain data from the aluminium and copper data at the same temperature.

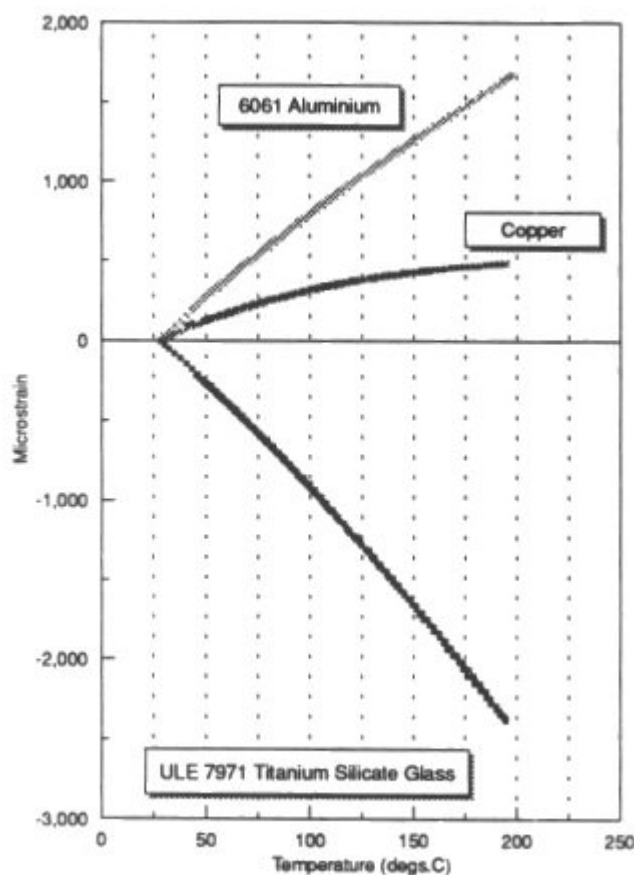


Fig 1: Raw strain data for the Al, Cu and reference material

The experimental CTE values vary slightly depending on the temperature range over which they are calculated, but from room temperature to 100°C the values for the 6061 aluminium alloy and copper are 23.4 and $16.6 \times 10^{-6}/^{\circ}\text{C}$ respectively. The corresponding handbook values for aluminium and copper are 23 and $17 \times 10^{-6}/^{\circ}\text{C}$

respectively which are in good agreement with the values obtained from the strain gauge method and this confirms the validity of the technique.

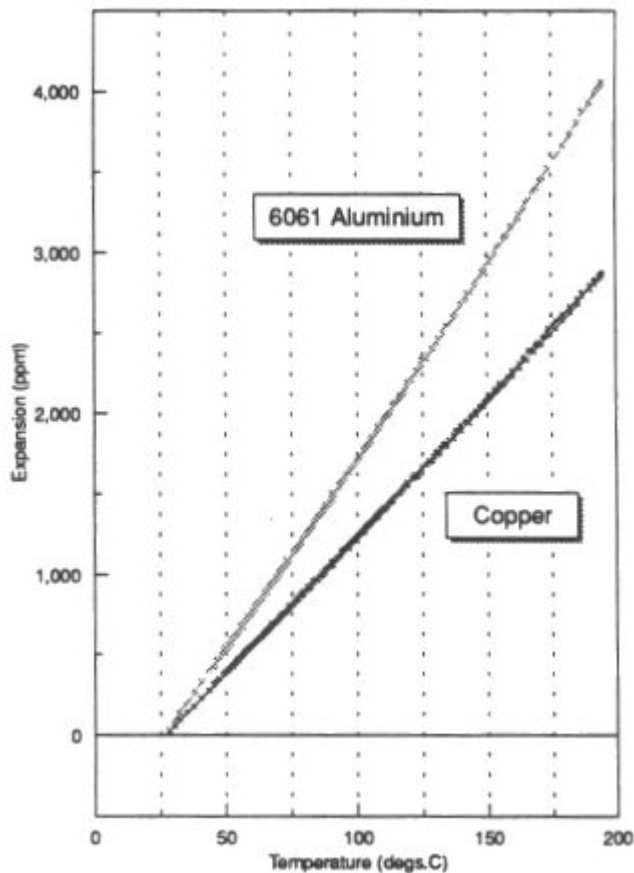


Fig 2: Thermal expansion behaviour of Al and Cu specimens

Case Studies

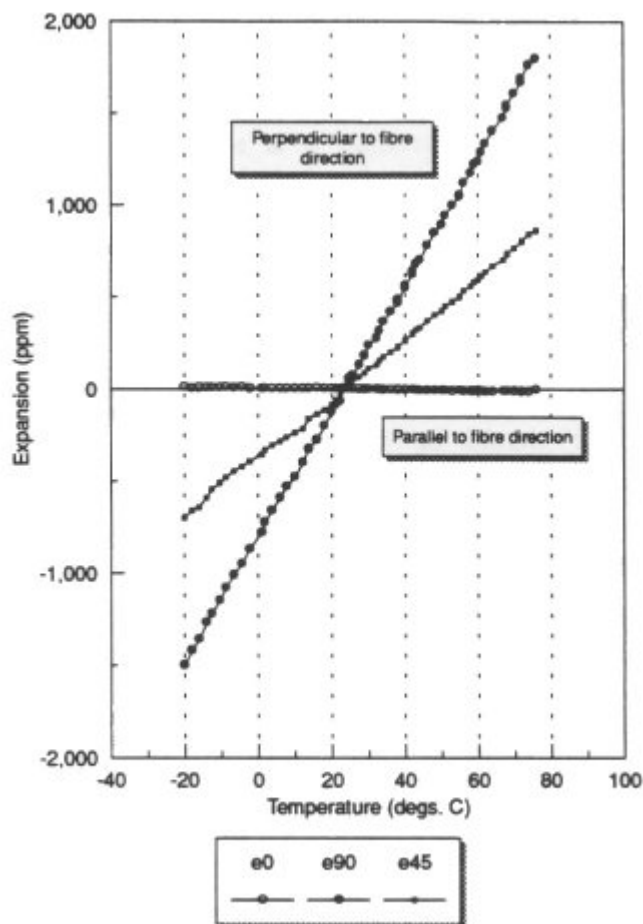
a) Particulate reinforced MMC

Strain gauge tests were carried out on two particulate reinforced metal matrix composites - a 6061 aluminium alloy with 20% Al_2O_3 reinforcement and a 2124 alloy reinforced with 20% SiC - following the procedures outlined above. A modified Linseis dilatometer was used also to measure CTE for comparison with the strain gauge data. [Fig 3](#) shows the thermal expansion behaviour for the SiC reinforced MMC up to 200°C, and a comparison of strain gauge and dilatometry.

Generally there is good agreement between the dilatometer and the strain gauge technique. Mean values for CTE for the 2124 alloy + 25% SiC, calculated from [Eqn. 1](#) between room temperature and 200°C were $16.1 \times 10^{-6}/^\circ\text{C}$ for the strain gauge technique compared to $16.5 \times 10^{-6}/^\circ\text{C}$ for the dilatometer; and for the 6061 + 20% Al_2O_3 MMC over the same temperature range the mean CTE values calculated using the two techniques were identical at $18.3 \times 10^{-6}/^\circ\text{C}$.

b) Unidirectional carbon fibre/epoxy composite

Tests were carried out using a 3-gauge rosette to measure thermal expansion both in and perpendicular to the fibre direction of a unidirectional carbon fibre/epoxy composite. The same test conditions were used as described above except the thermal cycle was from -20 to 70°C with a heating rate of 3°C/min. 3 runs were carried out prior to taking the measurements to eliminate hysteresis in the material and gauge installation. The thermal expansion behaviour is plotted in [Fig 4](#). Codes e0 and e90 refer respectively to strains in the composite along and perpendicular to the fibre direction, e45 is data from the gauge at 45° to these.

Fig 3: Comparison of strain gauge technique and dilatometry**Fig 4: Thermal expansion behaviour of a UD carbon fibre/epoxy composite**

Carbon fibres are highly anisotropic and the CTE values along and perpendicular to the fibre direction are very different. The predicted values for CTE, calculated using the *NPL Composites Design and Analysis (CoDA)* software are 0.14 and $31.2 \times 10^{-6}/^{\circ}\text{C}$ respectively for the fibre direction and perpendicular to this. Corresponding experimental values from the strain gauge technique, calculated over the whole temperature range -20 to 70°C are -0.3 and $34.4 \times 10^{-6}/^{\circ}\text{C}$, which are in reasonable agreement with the model predictions.

Summary

The strain gauge technique has been used successfully to monitor dimensional change and CTE of a variety of materials, and the versatility of the technique has been proven by a number of case studies. The main advantages of the strain gauge technique over dilatometry are the ability to carry out multiaxial measurements on large testpieces and components with relatively simple equipment and a basic knowledge of strain gauges and gauge installation. It is difficult to comment on the absolute accuracy of the measurements because this depends to a large extent on the quality of the strain gauge installation. From the validation exercise in this work, calculated values for CTE for aluminium and copper were in good agreement with handbook values, but the uncertainties involved with the measurements are typically 5-10%.

Some of the practical points which must be emphasised are the requirement for identical strain gauge installations on the material of interest and the reference material, which should be well characterised. In theory any material can be used as the reference, with the requirement that it should be stable and the thermal behaviour must be repeatable. The titanium silicate glass used in this work is ideal because the CTE is very nearly zero, but the main problem with this material is its low thermal conductivity and extra care should be taken to ensure that strain measurements on both materials are taken at the same temperature. Invar has been used in other work, and this has a much higher thermal conductivity, but similar problems can exist should the material have a large thermal mass.

Acknowledgement

This work was carried out as part of the 'Materials Measurement Programme', a programme of underpinning research financed by the UK Department of Trade and Industry.

References

1. Strain Gauge Techniques for Measuring Thermal Expansion. NPL Report CMMT(A)68, April 1997; J D Lord, W Nimmo, D Cooper and R Morrell.
2. Measurement of Thermal Expansion Coefficient using Strain Gauges. Measurements Group Tech. Note TN-513-1
3. Measuring the Thermal Expansion of Solids with Strain Gauges, JTEVA, Vol. 6, No.2, March 1978; M W Poore and K F Kesterson.

For further information contact:

Dr J D Lord
Centre for Materials Measurement and Technology
Tel: 020 8943 6340
Email: Jerry.Lord@npl.co.uk

Experts

[Link to Expert](#)

National Physical Laboratory
Queens Road
Teddington
Middlesex
United Kingdom
TW11 0LW

Tel: 020 8977 3222
Fax: 020 8943 6458
Email: materials@npl.co.uk

CMMT(MN)012

Strain Gauge Techniques for Measuring Thermal Expansion

August 1997

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