

Measurement Note

Validation of Strain Gauge, Digital Image Correlation and Dilatometry Procedures for Measuring CTE

Abstract

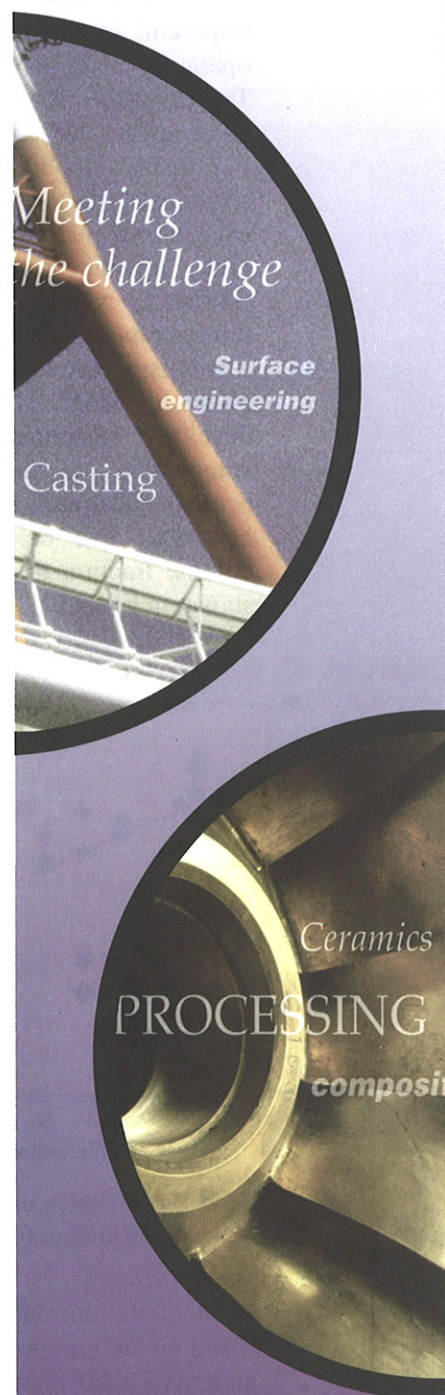
Accurate values for the coefficient of thermal expansion (CTE) are crucial in the design of many components operating in thermal environments. In electronic systems for example, CTE mismatch is a key driver for thermally induced mechanical stresses, which can lead to premature component failure.

Conventional dilatometry is an accepted method for measuring CTE, but it cannot be readily used for large components or for electronic systems such as printed circuit boards (PCBs). Procedures have been developed at NPL to determine the CTE of such components using strain gauge techniques and digital image correlation (DIC). This note summarises some of the results that have been produced, together with some practical tips and issues that should be considered using these novel techniques.

The work described in this Measurement Note provides validation data on 3 MMC candidate substrate materials, in advance of more detailed studies applying the techniques developed to measure CTE at the system level. For the materials examined, the results for the strain gauge and image correlation and dilatometry techniques were in good agreement, validating the procedures that have been developed.

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BACKGROUND

The coefficient of linear thermal expansion (CTE) is a basic physical property that is important in many designs and components operating in high temperature environments. Typical values for the CTE (α) of metals and alloys are in the range $10\text{--}30 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ [1,2]. For many applications in the electronics sector, material developments are focusing on using novel multilayer metallic laminates and high volume fraction metal composites (HVMC), which can contain up to 70% reinforcement. Electronic packaging has been a promising and rapidly developing market for Al-based MMC, based on the ability to develop materials with CTE values comparable to electronic materials and ceramic substrates. In these materials the CTE behaviour can be tailored by varying the volume fraction of ceramic reinforcement, as shown in Fig. 1 [2].

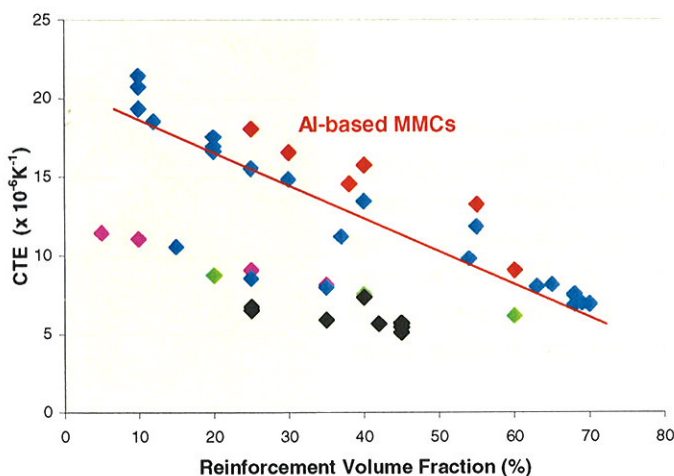


Fig 1 – Variation of CTE with reinforcement volume fraction for a variety of MMCs [2]

Most of the currently available materials are based on aluminium alloys that are lightweight and have good thermal conductivity. A range of reinforcement types is used but mostly it is either SiC or Al₂O₃, up to volume fractions of 70%, and in fact the industry has labelled the commercially available products with a high volume fraction of reinforcement collectively

as “AlSiC”. Such materials can offer a combination of significant weight and cost savings and attractive mechanical and thermal properties.

In addition to the family of “AlSiC” materials, other materials are being developed for electronic substrates and thermal restraint cores in printed circuit boards (PCBs). Some of these new systems are based on novel laminates, which offer a solution to surface mount assembly problems because the coefficient of thermal expansion of the board can be matched more closely to the device mounted on the surface. This is an attractive solution because low cost, off the shelf IC devices and assemblies can be used, which could not have been considered previously in advanced military systems where the electronics are subject to stringent vibration fatigue acceptance tests, and heat dissipation, thermal expansion mismatch and weight reduction are important issues. In comparison to traditional thermal core materials such as copper clad molybdenum and Invar, these new material systems can reduce the assembly weight by as much as 80% and increase the overall specific stiffness by a factor of three or more. With their combination of low mass, high thermal conductivity and high stiffness, they are well suited for military avionics systems and other critical high value electronic circuitry.

CTE MISMATCH

CTE mismatch is a key driver for component failure, particularly where thermal cycling exists, and it is important both at the component and system level.

As the power handling requirements, operating temperatures and packing densities of electronic systems increase, the task of reducing thermal mismatch strains and improving the thermal management capability of these devices poses an increasingly important challenge. It is crucial that the CTE is accurately determined, and any CTE

mismatch reduced. Electronic packages consist of various conducting and insulating materials, all of which have different values of CTE. Fig 2 illustrates a cross-sectional view of a typical multi-chip ceramic ball grid array (CBGA) package assembly, where a silicon chip is mounted on a multi-layer ceramic module and the module is attached to a PCB through solder ball interconnections. An aluminium metal heat sink is attached to the module to dissipate the excessive heat. The bold numbers in Fig 2 indicate the typical CTE values of each component.

When the chip is powered up, the package is subjected to a thermal cycle and the various components expand at different rates. Any CTE mismatch can lead to large thermally induced mechanical stresses within the package assembly, which can cause reliability problems via premature failure and a reduction in the lifetime of the device.

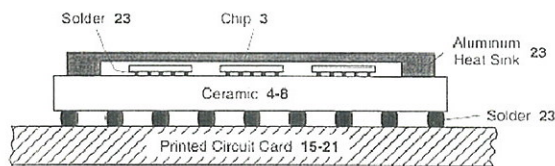


Fig 2 – CTE distribution of a typical CBGA package assembly [3]

The induced thermal strains can operate at both a global and local level, as shown schematically in the following figures. Globally, there may be a mismatch between the module and the PCB (Fig 3a), which causes large-scale distortion. Locally, there might be differences between materials at the interface (Fig 3b), which might lead to the failure of solder joints or individual connections and components.

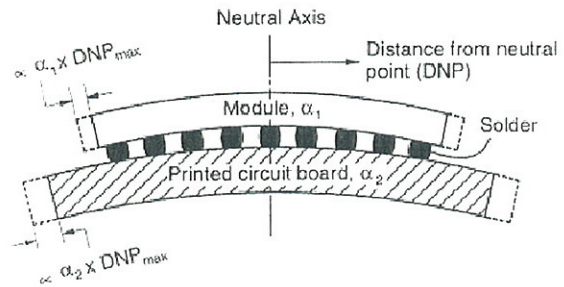


Figure 3a – Global CTE mismatch [3]

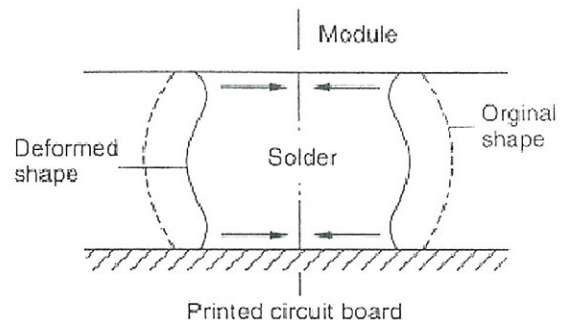


Figure 3b – Local CTE mismatch [3]

MATERIALS EXAMINED

The work described in this Measurement Note provides validation data on 3 MMC candidate substrate materials, in advance of more detailed studies applying the techniques developed to measure CTE at the system level. The materials are detailed in Table 1 below.

Material	Details
AMC640xa	40% SiCp/Al 6061 T1
Denka	70% SiCp / Al
CPS	70% SiCp / A356

Table 1: Details of materials examined

Micrographs are presented in Figs 4a-4c. It is clear from the micrographs that the AMC 640xa is very different to the CPS and Denka materials. The volume fraction of SiC reinforcement in the CPS and Denka MMCs are ~65 and 70% respectively, compared with 40% for the AMC640xa.

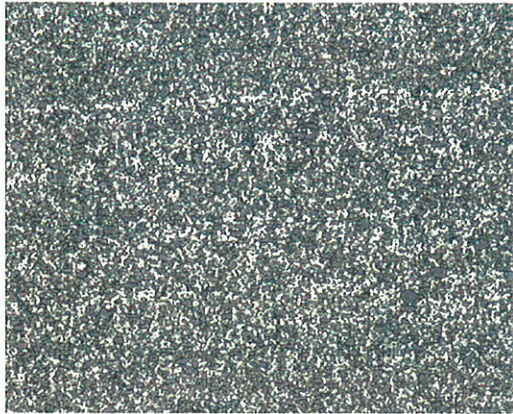


Fig 4a: Microstructure of AMC 640xa (x500)

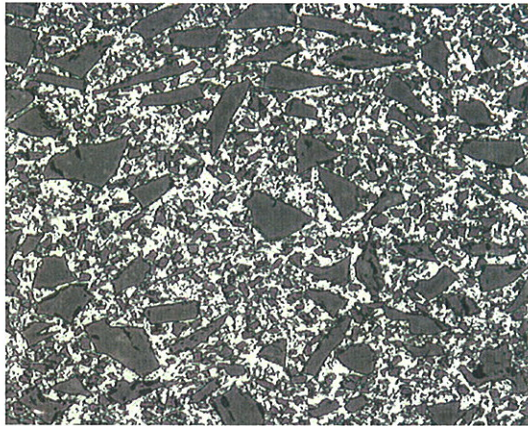


Fig 4b: Microstructure of CPS AlSiC-9 (x200)

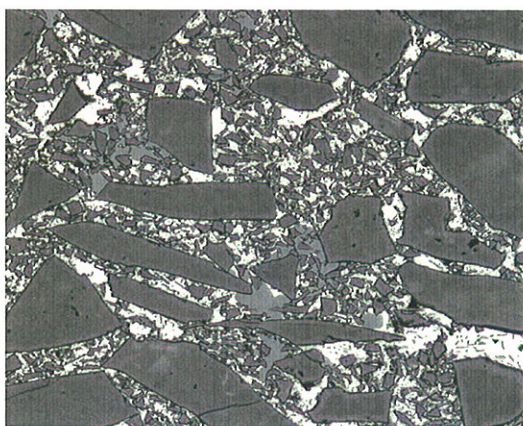


Fig 4c: Microstructure of DENKA MMC (x200)

The size of the distribution is also an important factor – the AMC material contains a very fine

(3 μ m) and uniform distribution of SiC particulate, whereas the CPS and Denka materials both contain bimodal particle size distributions, with the largest SiC particles approximately 50-100 μ m in size.

VALIDATION OF CTE MEASUREMENT METHODS

Although a variety of techniques are available for measuring CTE, in this study the focus has been on comparing mechanical dilatometry, strain gauging and digital image correlation.

Dilatometry

Mechanical dilatometry is a well-established technique for measuring CTE [4,5,6], but making measurements with the dilatometer is a delicate, demanding task. The test uses a testpiece in the form of a simple round or flat bar, which is held against a stop in a support tube, with its free end contacted by a push rod. As the testpiece is heated and cooled its changes in length are transmitted by the push rod to a measurement device, usually a linear variable differential transformer (LVDT).

The CTE can be calculated directly from the slope of the change in length vs temperature graph.

Calibration routines for dilatometry are well established. The key factors in calibration are the absolute sensitivity of the displacement measuring device, the temperature homogeneity of the system, which can lead to a "baseline" shift (positive or negative apparent displacements with no testpiece present), and the correction for the expansion of the apparatus itself, the part against which the testpiece length is compared. Details of the calibration routine and procedure used in this work are given in Ref 6.

Crucially, for many of the applications being considered in this report, only linear expansions on relatively simple specimen geometries are possible and full-field

measurements on the components themselves are impossible.

Dilatometry tests carried out as part of this study have been made according to a validated NPL procedure [6]. With appropriate care and attention the measurement procedure can achieve a reproducibility of about $\pm 0.2 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ measured over a range of $100 \text{ }^{\circ}\text{C}$, with an absolute accuracy of about $\pm 0.2 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$. Over larger temperature ranges the absolute accuracy can be better than this, but the range $100\text{-}200 \text{ }^{\circ}\text{C}$ is typical of that encountered in the electronics applications being considered.

Strain Gauge Method

The measurement of CTE via the use of strain gauges is a little-used technique, yet it offers considerable potential. It has been reported in a number of studies [7-12], and there is already an industry standard test method available for using the technique for PCBs [12]. Measurements made within this study have been carried out according to a new NPL procedure [13], which builds on previous work [11], developing the technique for composite materials. The strain gauge method is relatively straightforward but does require some operator knowledge and skill. Contrary to most strain gauge applications, which seek to minimize the effects of temperature on the output, the CTE strain gauge technique exploits the response of the gauge to temperature. The method relies on the differential output between identical gauges on the component of interest and a well-characterised reference material. The CTE can be calculated from the following equation:

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

where α_{spec} and α_{ref} are 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.

The main advantages of the strain gauge technique over conventional dilatometry includes the ability to carry out multiaxial measurements on relatively large testpieces or components, using relatively simple equipment readily available in most engineering test laboratories. However, 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.

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, the material and the thermal output of the gauges. The strain readings typically have a resolution of $1\mu\epsilon$, but the uncertainties associated with the measurements are typically 5-10%.

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 material 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.

These are covered in more detail in Ref 13.

Digital Image Correlation

Digital Image Correlation (DIC) is a non-contact full field strain measurement technique. Recent work described in this Measurement Note has been carried out at NPL to develop a procedure for using DIC to measure thermal expansion [14]. The basic concept of DIC is to compare two images of a component, before and after deformation. The basic experimental set-up used at NPL is shown in Fig 5. In this case the specimen has been heated via a hot plate placed on a copy stand and images input directly into the computer for analysis. Full resolution images of 1268×1204 pixels were used to maximise the accuracy and measurement resolution.

In-plane displacements and strains are determined by correlating the position of pixel subsets or blocks in the original and deformed image, normally based upon contrast (grey levels). The size of the pixel block can be varied, thus allowing many random patterns to be correlated. In order to identify if there is any movement between the two blocks there must be sufficient detail for it to be considered unique. It may be the case that the specimen or component already has a suitable level of surface features which can be imaged directly, but if not, some form of spray paint or coating or scratches on the surface can be used. For best results a good distribution of intensity values must be obtained. The deformations of the specimens are then calculated by correlating the positions and displacements of pixel subsets or blocks in the original and deformed image to produce a vector map. This is then analysed further to produce a full field strain map, shown schematically in Fig 6.

Figure 7 shows a high magnification image of a typical coated specimen, showing a good range of pixel intensities, separate (8x8) pixel blocks and the corresponding vector calculation points.

For the DIC CTE measurements carried out as part of this study, the specimen geometry and test set up was chosen to give uniform

expansion in all directions from a central point. This is reflected in the vector plots shown in Fig 8a and 8b, which were both generated from the same set of images. For the test at least 2 images are required (taken at the temperature extremes) to calculate the vector and strain plots. If required a series of images could be captured during the heating cycle but care must be taken to ensure that temperature equilibrium is reached across and through the thickness of the component.

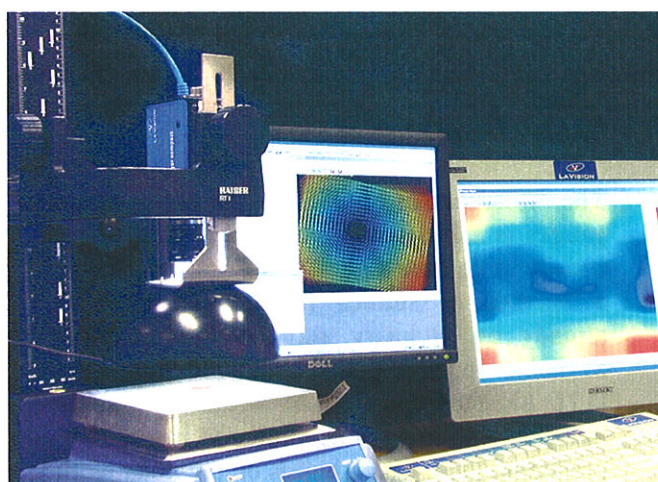


Fig 5 – NPL image correlation CTE set-up

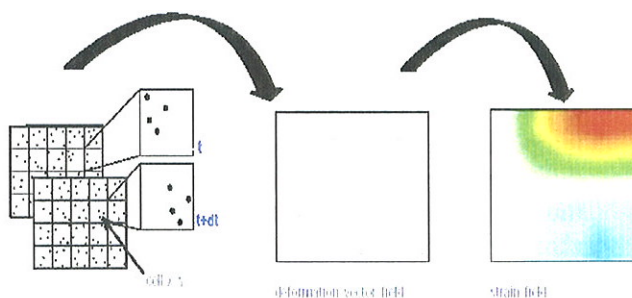


Fig 6 – The principle of digital image correlation [15]

One of the key issues is the size of the interrogation window – i.e. the size of the pixel subset used for the correlation. The effect of changing the size of the interrogation window can be seen in Figure 8. Both diagrams show vector displacement maps from

a correlation of the same two images for the CPS material. However, Fig 8a was analysed using a 16x16 interrogation window and Fig 8b using a 256x256 window.

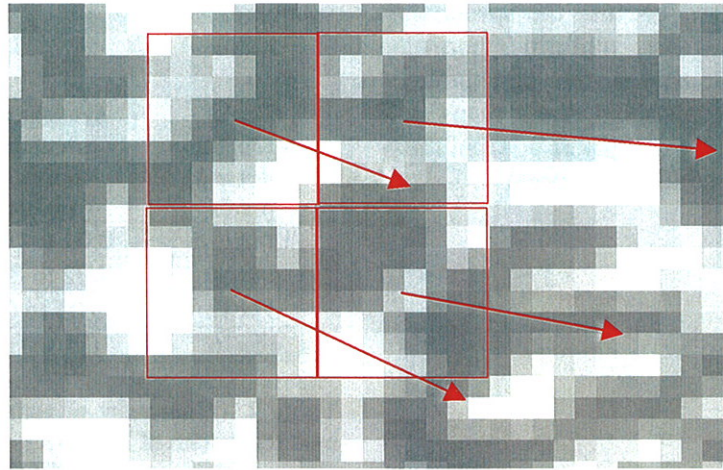


Figure 7: Typical coated specimen showing a range of pixel intensities, a (8x8) interrogation window and vector calculation points

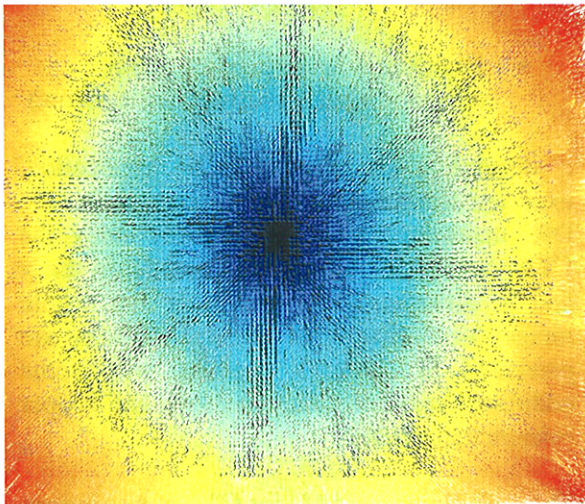


Fig 8a – Vector plot calculated from the (16 x 16) interrogation window (CPS material)

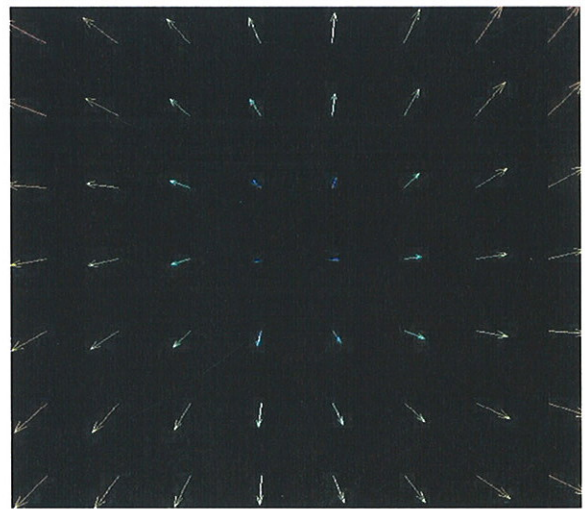


Figure 8b – Corresponding Vector plot calculated from the (256 x 256) interrogation window (CPS material)

Careful consideration must be given to the size of this window as it has important implications on the spatial resolution and accuracy of the measurement. For all the measurements carried out in this study a large (512 x 512) window size was used because the specimen was assumed to have uniform thermal expansion and this offered the best strain resolution. The corresponding strain maps in Figs 9a and 9b, which were generated from the vector plots in Fig 8 confirm this point.

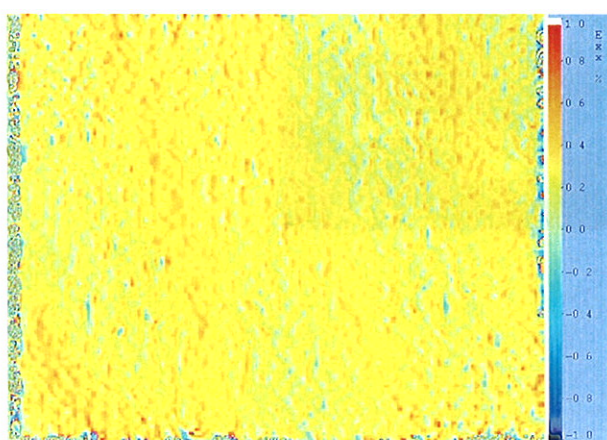


Fig 9a – Strain field calculated from the (16 x 16) interrogation window

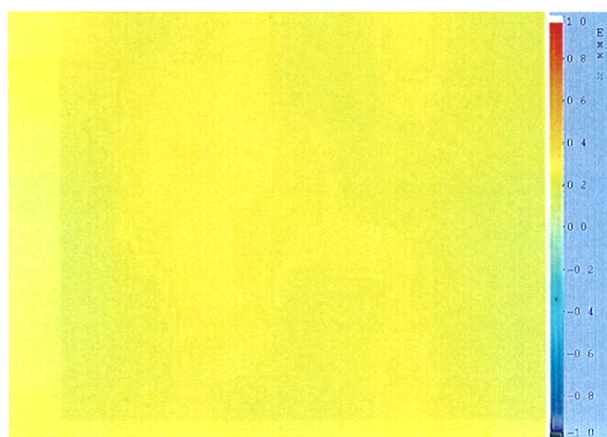


Fig 9b – Strain field calculated from the (256 x 256) interrogation window

Table 2 summarises the estimates of the uncertainties and accuracies of the DIC setup. It can be seen that the accuracy (and strain resolution) increase with larger interrogation window sizes, but with a corresponding loss of spatial resolution.

Size of interrogation window in pixels	Accuracy of calculated vectors in pixels	Accuracy of calculated strain values
128x128	0.01 to 0.03	0.094%
64x64	0.02 to 0.05	0.3%
32x32	0.05 to 0.2	1.25%
16x16	0.1 to 0.3	5%

Table 2 – Summary of estimated uncertainties and accuracies of DIC [15]

It is clear from the images and information detailed above that a compromise is needed between:

- High spatial resolution (small interrogation window)
- High strain resolution and strain accuracy (large interrogation window)

.. depending on the particular application, expected strain field and data required. For the DIC measurements in the current study the CTE was calculated from the strains in the x and y directions averaged over the whole image (excluding edge effects). Results are presented in Table 3, together with some additional validation data on the Al and copper reference materials.

The specific use of DIC for CTE measurement is a novel technique, and as such has not been considered before. Most of the applications of DIC reported in the literature are for room temperature situations and there are a number of complications that must be addressed when considering its use at elevated temperatures. For the CTE work in the current project these include....

- Maintaining the integrity of the applied speckle pattern at elevated temperatures
- Practical access to the component in a furnace or temperature cabinet
- Potential effect of thermal currents on image quality
- Thermal gradients across the specimen
- Translation of mount /reference point
- Image distortion
- Image processing considerations

Further information on the technique is available in NPL Measurement Note (MN)28 [17] and measurement procedure [14,15] .

The quality of the results obtained using image correlation is also directly affected by a number of parameters. These can be divided into two main categories: practical considerations and factors associated with the image analysis and processing.

Practical Considerations

To obtain accurate and meaningful measurements, it is crucial that high quality images with appropriate surface features are used for image analysis. Lighting is a key factor in optimising this - over-saturated images do not allow adequate detail to be seen whilst under-saturated images do not provide enough contrast for 'good' correlation. Care must also be taken when lighting the sample as reflections can directly interfere with the measurement. Consistent lighting between capturing the images is important, as is the need to eliminate vibration or gross movement of the specimen or component.

Image Processing Considerations

Many parameters must be considered when carrying out the processing and analysis of the images. The user must have a good understanding of the software as this can have an important effect on the quality of the results and the values measured.

RESULTS

Table 3 below shows a summary of the results obtained for the 3 MMC materials and eth aluminium and copper "reference" specimens, using the techniques described in this report.

Material	Dilatometry (0-200 °C)	Strain Gauges (0-150 °C)	DIC (50-200 °C)
Al	23.4	24.0	23.0-26.1
Copper	16.6	16.8	16.1-18.3
AMC640	13.5	12.6	11.2-12
CPS	9.5	9.1	10.1-10.5
Denka	7.4	6.5	6.8-7.4

Table 3 – Mean CTE values ($\times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$) for the 3 MMCs and reference materials tested

It is important to note that the values in Table 3 are not expected to be identical, as the tests have been carried out over different temperature ranges.

Representative plots of the data obtained from the different methods are given on the following pages.

Dilatometry Results

Results for the 3 materials of interest in this study are presented below.

**Fig 10a -
Dilatometer data
for AMC 640xa**

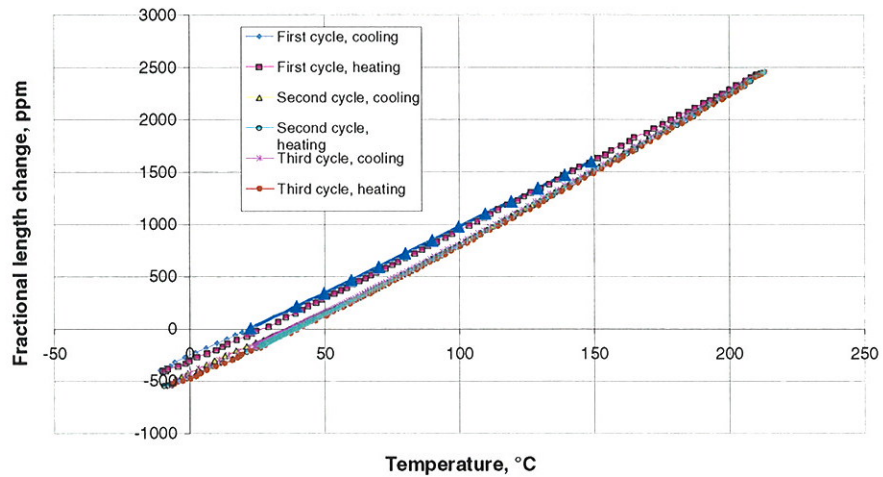


**Fig 10b -
Dilatometer data
for CPS Material**

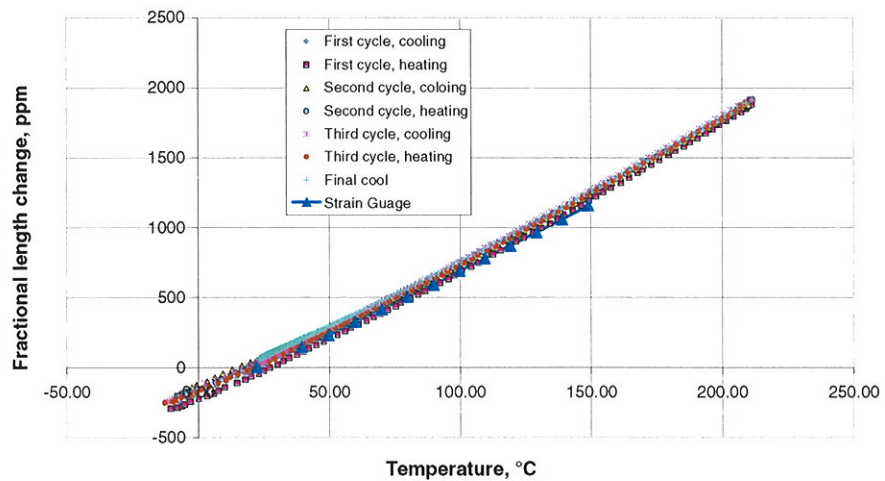
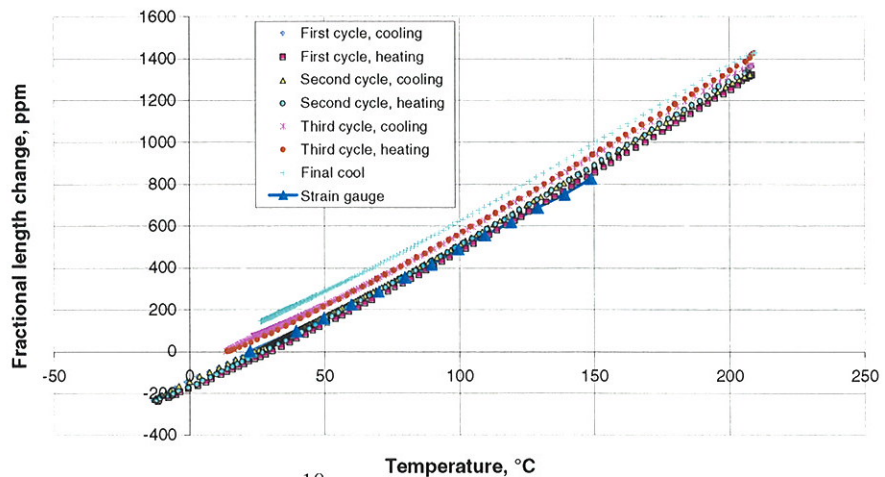


**Fig 10c -
Dilatometer data
for Denka Material**



Values for the CTE calculated from the slopes, together with additional calibration measurements carried out on an aluminium and copper samples are given in Table 3.

Strain Gauge Results

Fig 11a shows the raw strain gauge data generated during heating of the 3 materials and reference specimen. These are represented in Fig 11b as differential outputs by subtracting the reference material readings.

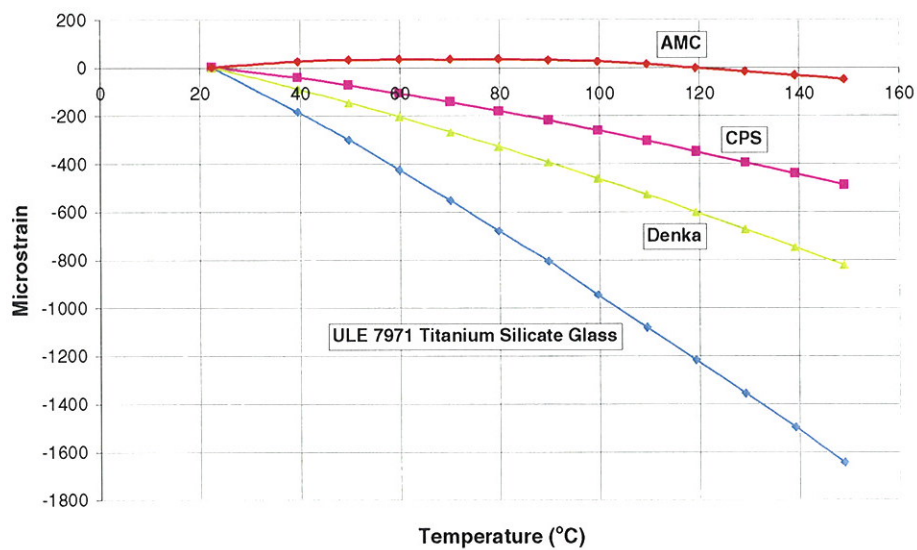


Figure 11a – Raw strain gauge data

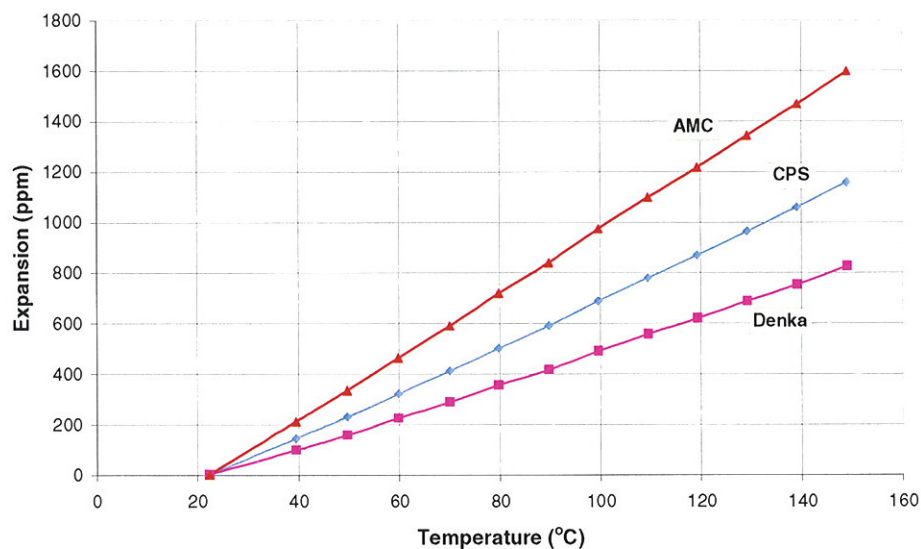


Figure 11b – Thermal expansion behaviour

And because the titanium silicate glass reference specimen has effectively zero CTE, the CTE values can then be calculated directly from the slopes of the graphs in Fig 11b. CTE values measured are given in Table 3, together with the results from additional calibration measurements carried out on aluminium and copper samples.

The data shows some scatter, with the calculated range of CTE values in the range $20\text{--}26 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$.

Image Correlation Results

Using the procedures described above, the Image Correlation CTE measurements were made on flat plates approx $\sim 50 \text{ mm} \times 50 \text{ mm}$. Each specimen was coated with white paint and a black speckle pattern applied. Care was taken to ensure that the coating remained integral with the specimen and did not detach during heating, as this would result in misleading and meaningless data.

Figure 12 below shows data calculated from 6 repeat measurements on an aluminium plate. In each case the whole of the plate was imaged, and images captured at approximately 20°C intervals.

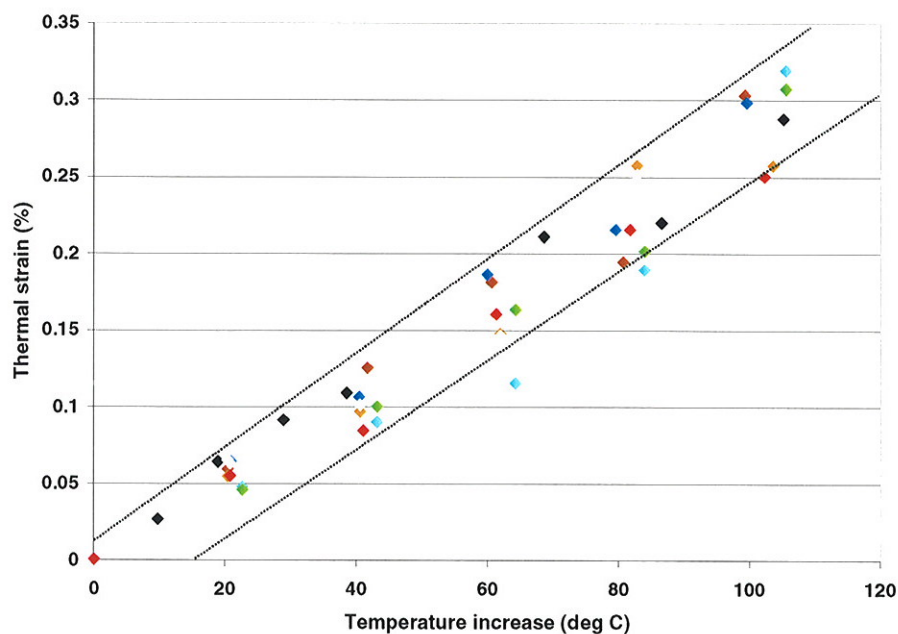


Fig 12 – Thermal expansion behaviour of an aluminium specimen, measured using DIC

UNCERTAINTY IN THE MEASUREMENT

The scatter and uncertainty in the calculated values using DIC were larger than the other two methods, but it gave comparable mean results. Particular care must be taken in both the practical set up and in analysing the images. Typical uncertainty values for the NPL test procedures [6,13,14] and equipment are given in the Table below.

Method	Uncertainty
Dilatometry	Less than $\pm 1\%$
Strain Gauges	$\pm 5\%$
Image Correlation	$\pm 10\%$

Table 4: Summary of typical uncertainties (2 SD) associated with the techniques.

Information on the factors contributing to the uncertainty in the calculated CTE values is detailed in Refs 6,13 and 14. The uncertainty budget for the strain gauge CTE method used at NPL is shown below for reference.

The user should consider their own experimental set-up and quality system in developing their own uncertainty budget for the measurements. It is an essential exercise and can help to identify particular areas of the test method and equipment that make the most significant contribution to the overall uncertainty.

SUMMARY

All three methods have been successfully implemented to measure the CTE of three MMCs and 2 conventional “reference” materials. Dilatometry is a well-established technique and the most reliable and accurate of the methods examined. The strain gauge method is being used more frequently and is capable of producing reliable, repeatable CTE values. DIC has not been used previously for measuring CTE and results from this study show some promise, although the scatter and uncertainty in the calculated values for CTE were the highest.

Source of Uncertainty	Uncertainty	Measured value *	Uncertainty (%)	Probability distribution	Divisor	Standard uncertainty u_{CTE} , (%)
Resolution of strain gauge instrumentation	$\pm 2 \mu\epsilon$	750 $\mu\epsilon$	0.3	Normal	1	0.3
Operator skill/quality of installation	$\pm 10 \mu\epsilon$	750 $\mu\epsilon$	1.3	Rectangular	$\sqrt{3}$	0.75
Accuracy of temperature measurement	$\pm 0.5 ^\circ\text{C}$	75 $^\circ\text{C}$	0.7	Rectangular	$\sqrt{3}$	0.4
Resolution of temperature measurement	$\pm 0.2 ^\circ\text{C}$	75 $^\circ\text{C}$	0.2	Normal	1	0.2
Uniformity of Temperature (ref & spec)	$\pm 1 ^\circ\text{C}$	75 $^\circ\text{C}$	1.3	Rectangular	$\sqrt{3}$	0.75
Strain gauge drift and stability	$< 5 \mu\epsilon$	750 $\mu\epsilon$	0.7	Rectangular	$\sqrt{3}$	0.4
Calculation of slope (Method B)	± 0.25	23	1	Normal	1	1
Combined Standard Uncertainty						2.6
Expanded Uncertainty (k=2.00, 95%)						5.2

Table 5: NPL Uncertainty budget for strain gauge CTE method

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