



**A REVIEW OF METHODS FOR MEASURING
SMALL DIMENSIONAL CHANGE
DUE TO THERMAL EXPOSURE
IN MMC AND CMC**

by

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ABSTRACT

This review addresses some of the issues associated with the measurement of dimensional stability in MMC and CMC operating in thermal environments. It forms part of a more general review of methods for measuring small dimensional change and thermal properties of composites for the MTS DCC2 project on the *Design of Composite Components* and is the deliverable for Task 1.1.2 in this work. The review concentrates on the techniques for measuring dimensional change in composites as a consequence of constant or cyclic thermal exposure, and covers some of the merits and practical issues of the different techniques, which are suitable for testpieces and components. In-situ tests can be used to examine the behaviour of the testpiece or component under actual operating conditions, whilst periodic inspection tests are designed to monitor any change in the integrity of a component after a specified time or number of thermal cycles.

It is difficult to recommend a single technique for any one application because a large number of factors must be considered. The review contains a number of tables to help in the selection process.

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1 INTRODUCTION

Changes in the dimensions of composite components subjected to prolonged thermal exposure can lead to poor performance, increased friction and wear, and premature failure; the changes may develop in service as a consequence of the particular operating conditions, or may arise because of poor design and incorrect material selection. In thermal environments, materials expand and contract as the temperature changes. The dimensional changes may be elastic or plastic, can develop during a single exposure or after repeated cyclic exposure, and may result from a variety of mechanisms, including plastic deformation, stress relaxation, creep, viscoelasticity, phase transformation, microcracking, wear and recrystallisation. The magnitude of the dimensional change is a function of the temperature change and number of heating cycles and, for composite materials, is keenly affected by the properties of the matrix and reinforcement.

The engineer will normally use thermal expansion data for designing components operating in thermal environments, but more information is required on the long term dimensional stability and performance of the component under operating conditions. A wide variety of techniques can be used to monitor and measure dimensional stability. Generally, for composite materials, the measurement techniques applicable to metals and other monolithic materials can be used, but the methods are often complicated by other factors, such as anisotropy and the diversity of composite types.

This review deals with some of the methods for measuring dimensional stability in metal matrix (MMC) and ceramic matrix composites (CMC) operating in thermal environments. It forms part of a more general review of methods for measuring small dimensional change and thermal properties of composites for the MTS DCC2 project on the *Design of Composite Components*. The review concentrates on the techniques for measuring dimensional change in composites as a consequence of thermal exposure. The suitability of the various methods are assessed for testpieces and components. Essentially, two types of measurements can be made - in-situ measurements on testpieces and components during operation or thermal cycling and the measurement of damage and permanent deformation after prolonged exposure, carried out on the component after it has been removed from service.

The review is not a comprehensive, detailed study of every available measurement technique. What it aims to provide are some guidelines on the merits and practical applications of a number of methods for measuring small dimensional changes in composites, with particular reference to the typical operating conditions experienced by MMC and CMC components. Practical considerations for each test method are discussed.

2 COMPOSITE TYPES AND PROPERTIES

The review will concentrate primarily on metal matrix and ceramic matrix composites of which there are a number of generic groups :

Particulate Reinforced MMC	PRM	eg SiC _p /Al
Fibre Reinforced MMC	FRM	eg SiC _F /Ti
Short-Fibre Reinforced MMC	SFRM	eg Al ₂ O ₃ /Al
Fibre Reinforced CMC	FRC	eg SiC _F /glass-ceramic

Subscripts P and F refer to particulate and fibre reinforcement respectively.

MMCs offer high specific strength and stiffness, increased wear resistance and improved high temperature properties compared with unreinforced monolithic alloys. Many of the

applications being considered for MMC exploit the high temperature capabilities, so clearly the response to thermal exposure is important. For many applications the increased high temperature strength and stiffness are important criteria for choosing MMC, but in thermal environments the ability to tailor the thermal expansion behaviour to match other materials and components by varying the type and volume fraction of reinforcement is of interest also.

Particulate reinforced MMCs with volume fractions as high as 50% are being considered for precision instrument parts and electronic substrates where the coefficient of thermal expansion (CTE) can be engineered to match that of a ceramic, but at a lower density. Aluminium based MMCs are being evaluated for pistons in automotive engines where they offer a good match to the CTE of the steel cylinder block and have shown increased weight savings, superior high temperature strength, and increased fatigue and wear resistance (1). There is increasing pressure to improve the efficiency of the new generation lean-burn combustion engines and, over the temperature range -20 to 200°C, dimensional stability is crucial for maintaining efficiency and reducing vehicle emissions. For operation at peak temperatures of up to 400°C, MMC automotive brake components are also being developed.

Other areas being considered, particularly for continuous fibre reinforced MMC, are for structural applications in the aerospace and satellite industries. In space, the thermal performance of components is critical, as the temperature can fluctuate from -150 to 150°C as a structure passes from sunlight to darkness. Typical CTE requirements range from zero or $0.1 \times 10^{-6}/^{\circ}\text{C}$ for instrument mounts, to $0.9 \times 10^{-6}/^{\circ}\text{C}$ for structural elements and $2.0 \times 10^{-6}/^{\circ}\text{C}$ for reflectors (2). Carbon fibre reinforced MMCs can be produced with very low thermal expansion, as the longitudinal CTE of the carbon fibre itself is approximately zero at room temperature, (the transverse CTE is quite large by comparison).

The main driving force for using ceramic matrix composites (CMC) is the superior damage tolerance over monolithic ceramics at higher operating temperatures; and most applications will include some thermal loading. Generally, as the tolerances on thermal expansion and dimensional stability become more stringent, there is greater emphasis on the ability to measure accurately any change in dimension, and such precision pushes the limits of the current practical measurement techniques. Clearly, for both MMC and CMC, the mechanical behaviour and dimensional stability are important for applications in thermal environments.

For information, Table 1 shows typical values of the thermal expansion coefficient for a range of composites and reinforcement-matrix combinations. The numbers should only be taken as global values because for most composites there is some degree of anisotropy and properties vary with orientation and composition. Also, for many of these materials, the thermal expansion coefficient is non-linear and has been shown to vary significantly with temperature (2-7). Table 2 shows the magnitude of deformations due solely to elastic thermal expansion, for different sized testpieces and components, for three different values of CTE and typical temperature ranges for MMC and CMC. This deformation is likely to be a lower limit, as other mechanisms may also contribute to the dimensional instability after prolonged thermal exposure or cycling. Table 3 gives details of typical thermal conditions experienced by particular MMC and CMC components, based on returns from a questionnaire from a separate task in the project.

3 PRACTICAL MEASUREMENT TECHNIQUES

A number of measurement techniques will be considered, and these are listed below grouped according to the measurement method, generally in order of increasing resolution and accuracy.

- **Basic mechanical measuring instruments**
 - steel rule
 - micrometers
 - vernier callipers
 - optical projectors
- **Electrical transducers**
 - strain gauges
 - capacitance probes
 - Linear variable differential transformers (LVDTs)
 - extensometry
 - stylus profilometry
 - coordinate measuring machines
- **Optical techniques**
 - fibre optic displacement probes
 - laser interferometry
 - confocal microscopy
 - laser profilometry
 - laser holography
 - moire interferometry
 - image correlation techniques

A summary of these and other measurement techniques is presented in Table 4 (8). In the table, the resolution is expressed as the smallest dimension that can be repeatedly detected, the range refers to the maximum dimension that can be measured before the instrument must be reset and the accuracy refers to the traceability to a standard. In the following sections, the principles and merits of some of the techniques are discussed, particularly with reference to their use for measurements of dimensional changes caused by thermal cycling and exposure of MMC and CMCs.

3.1 Basic Mechanical Measuring Instruments

Steel rule

The steel rule is probably the simplest measuring instrument used for engineering purposes. A reasonable quality rule can have marked divisions of 0.05 mm. The accuracy can be increased if callipers are used to transfer the dimension from the testpiece or component to the rule. Callipers are readily available in a variety of shapes and sizes and can be specially made to deal with complicated shapes.

Vernier Callipers / Height gauges

The vernier calliper is basically a steel rule and calliper combined in a single instrument. This, by itself does not give increased accuracy over separate steel rule and callipers, but can be improved by including a vernier scale. The vernier callipers and height gauges are robust instruments and the squareness, finish and parallelism of the measuring faces are such that measurements can be made to an accuracy of 0.15 mm over a 1 m length. Measurements can be made to an accuracy of 0.01 mm using electronic callipers.

Micrometers

The micrometer in its simplest form is an instrument which measures between two anvils, one of which is fixed and the other which moves by rotation of a thimble along a screw thread. The movement of the anvil is directly related to the pitch of the thread. For a metric micrometer, the pitch of the thread is likely to be 0.5 mm and the circumference of the thimble is divided into 50 equal parts, so that each division on the thimble represents a change in length of 0.01 mm. If the micrometer incorporates a vernier scale, measurements can be made to an accuracy of 0.001 mm.

Scanning laser micrometers have recently become available with a maximum resolution of 0.1 μm , depending on the measurement range and type of sensor head used.

Optical Projectors

Optical projectors provide a convenient and effective method of checking the profile and dimensions of small objects. In their simplest form with a magnification of $\times 50$, the object can be measured to an accuracy of 0.5 mm on the screen which translates to an accuracy in the measurement of the component of 0.01 mm. Some projectors can be used to measure contoured surfaces. Recent developments have seen stepper motor control, LVDT digital displays and high magnification video cameras which give a resolution and accuracy of 1-2 μm . The technique is non-contact, cannot be carried out in situ and is essentially two dimensional. If a component is thick, the sides must be perfectly parallel to avoid errors in measurement and blurring of the edges of the image.

3.2 Electrical Transducers

Strain Gauges

A huge variety of resistance strain gauges are available for quite specific applications, but the principle of operation for them all is the same. A resistance strain gauge is basically a metal foil formed into a grid, bonded to an adhesive backing which is then bonded to the structure of interest. The strain gauge uses the change in electrical resistance of a metal subjected to tension or compression to measure the equivalent strain. When pulled, a metal's electrical resistance increases, the magnitude of which is proportional to the applied strain.

The most widely used gauges use a nickel-copper foil alloy and have an operating temperature range of -70 to 200°C. Special high temperature gauges, which use a platinum-tungsten alloy wire grid, can go up to 650°C and are bonded to the surface with a hot curing adhesive or ceramic cement. In thermal environments, self temperature compensating gauges must be used to take into account the inherent change in resistance of the metal gauge with temperature.

The temperature coefficient of the strain gauge should be matched as closely as possible to the linear thermal expansion of the material to be measured. This is difficult for MMC and CMC as the thermal expansion coefficients vary with material type and composition. At room temperature, gauges designed for steel or aluminium ($\text{CTE}=11$ and $23 \times 10^{-6}/^{\circ}\text{C}$ respectively.) have been used successfully with minimal error. In thermal environments however, where there is a large temperature change, it becomes more important to match the thermal expansion behaviour of gauge and specimen, and this may be a problem. Compensations for temperature-induced gauge resistance changes can be made using the Wheatstone's bridge, but this will not account for induced strains due to CTE mismatch between gauge and specimen.

Strain gauges are relatively inexpensive and are very versatile. They can be applied equally to testpieces and components, in locations inaccessible to other techniques and respond quickly to dynamic strains. The strain gauge measurement resolution depends to a large extent on the instrumentation, but at its best can be of the order of $0.5 \mu\epsilon$. This corresponds to a dimensional change of $0.5 \mu\text{m}$ over a 10 mm gauge length. The strain gauge measures local deformation under the grid but there is an integrating effect, different sizes are available and strain measurements can be made in three directions using a strain gauge rosette. The main drawbacks with using strain gauges are the limited temperature operating range, temperature induced errors and the problems of calibration and traceability.

Semiconductor strain gauges use silicon and germanium which have a sensitivity some 65 - 130 times that of other metals. Essentially the semiconductor strain gauge works in the same way as the foil gauges. The increased sensitivity however has a number of drawbacks including the dependence on the nonlinear crystallographic direction, the dependency of resistance and gauge factor on temperature, limited strain range and high cost. They are also fragile.

Capacitance probes

Capacitance probes measure displacement by monitoring the capacitance change when the separation of two plates attached to the sample under test are altered. With appropriate electronics and design of the probes, measurements with a sensitivity up to 0.1 nm can be made. Probes can also be optimised for ranges up to several millimetres with reduced sensitivity. Capacitance probes are, by their very nature, averaging devices, and cannot be used to measure the movement of a localised point without the use of extensometry.

Some precautions are necessary to achieve the best performance such as the use of guard rings around the active elements of the probes. These reduce measurement artefacts that occur because of edge effects. Capacitance probes are calibrated by conventional means, and normally have high stability and low noise.

LVDTs

The linear variable differential transformer (LVDT) is an example of an inductive displacement transducer. Essentially it is a transformer which provides an accurate voltage output as a function of the displacement of a moveable magnetic core. The amplitude of the output voltage depends on the coupling of the primary and secondary windings and the position of the core.

Movement of the core from the central position increases the coupling to one of the secondary coils, while reducing coupling to the other. The difference in the outputs from the secondary coils is then proportional to the movement of the core. LVDTs are available in a wide range of sizes with full scale displacements from 1 mm to several metres, and have potentially infinite resolution since the signal output is limited only by the ability to measure DC voltages and the stability of the core. Because there is no friction between the core and the coil, the input impedance is very low and such devices are reliable and have a long lifetime.

Extensometry

The wide range of extensometry available includes contact and non-contacting designs, but essentially all are designed to operate in-situ on a simple testpiece to measure strain during a test. Mechanical extensometers are usually attached to the testpiece via metal knife edges or quartz rods and measure an average strain over a fixed gauge length. Conventional

mechanical extensometers use strain gauges mounted on the extensometer arm to monitor deformation, they are available in a range of gauge lengths with single or double sided designs, and generally operate in the temperature range -70 to 200 °C. Combined longitudinal and transverse extensometers are also available for measuring Poisson's ratio. Up to 500°C, water cooled titanium alloy or nimonic extensometers can be used. For testing at higher temperatures, quartz rods are used to transfer the axial strain to the extensometer body, which is now some distance from the testpiece outside the furnace. Such systems are relatively expensive and difficult to set up.

Non-contacting optical extensometers have been developed for testing elastomers and highly extensible materials, but they do not have sufficient resolution for MMC and CMCs which are brittle and often fail at strains below 1%. Higher resolution digital systems claim accuracies of $\pm 2.5 \mu\text{m}$ and a resolution of $1 \mu\text{m}$, but they are expensive and are restricted to low temperature testing. Scanning laser extensometry offers a potential solution to these problems.

Typically a scanning laser extensometer consists of a laser and a rotating mirror and a receiver containing a photodiode which is linked to a digital processor. The laser is mounted on the test machine such that the plane of the laser beam intersects flags mounted on the testpiece. The laser light and shadows from the flags are monitored by the receiver. Typically, these instruments have a quoted resolution of $0.2 \mu\text{m}$ with a repeatability of $\pm 0.4 \mu\text{m}$ over a 15 mm gauge length. Examples of the application of scanning laser extensometry to MMC and CMCs are given in Refs 9 and 10.

There are a number of advantages and disadvantages of using extensometry over other techniques. Among the advantages are the relatively low cost and simplicity, and the fact that extensometers can be readily calibrated via a laser interferometer, which can be traceable to national standards. Disadvantages of using them for MMC and CMCs are that extensometers are really only designed for in-situ tests, they measure an average strain over the gauge length and, in the case of contacting extensometers, may initiate premature failure in notch sensitive materials such as CMC and some MMCs. Scanning laser extensometers which are non-contacting can operate at temperatures up to 1500 °C and are potential solution for strain measurements under these conditions.

Profilometry

Conventional stylus profilometry is normally used for surface finish and flatness measurements. The principle of the profilometer is to obtain a magnified output of the movement of a diamond stylus as it traverses the surface of a component. The horizontal and vertical magnifications can be varied independently, but the maximum resolution is usually in the vertical plane, and is typically of the order of $1 \mu\text{m}$. Flatness measurements can be made by moving the stylus against a datum surface within the machine itself. In this case the component or testpiece must be level and the maximum vertical travel is somewhat limited. Profilometry could be used as a technique for monitoring distortion of FRM sheet material for example. In many cases, during the manufacture of FRM sheet, residual stresses cause the sheet to bow. With thermal cycling the stress distributions within the sheet will change with subsequent distortion. If large changes occurred, flatness measurements over the length of a testpiece could be made on a simple stylus profilometer by comparison of the output before and after thermal exposure.

Coordinate Measuring Machines

Traditional measurement instruments are available for measuring the dimensions, flatness, roundness etc of a component; a coordinate measuring machine (CMM) can, in principle,

combine all these requirements in a single instrument. In the simplified form, a CMM works in the same way as a digital dial gauge, with some form of probe following the contours of the component, but offers a larger travel and multi axis measurements. The measurement characteristics of a CMM are highly dependent on the probe used which may be a contact or non-contact variety. In many cases a probe which registers contact with the component gives the most consistently accurate results. This probe is called a 'touch trigger' probe, since it has no measuring capability itself, but triggers an electrical signal at the touch position. The contact probe has a stylus which should be kept as short as possible but long enough to access all the features of the component. It should be stiff with a small tip diameter. A reading is taken when the probe touches a surface of the component and the machine head is moved until contact occurs with another surface. The dimension required is the difference between the two readings minus the diameter of the probe stylus. The accuracy of this form of measurement depends largely on the machine used, but probe indications are repeatable to within 0.1 μm .

A survey of current coordinate measuring machines is presented in Ref 11. One clear advantage of using a CMM for monitoring dimensional changes is the ability to measure real components which are complex in shape and to monitor distortion in a number of directions, typically to an accuracy of 1 μm . Modern designs are generally very rigid, use low mass moving parts and provide fast and accurate probe movement; most machines use computer control and are interfaced to CAD/CAM packages. Standards do exist for the calibration of CMMs and these are used together with acceptance tests on reference artefacts. The major disadvantage is cost - with all but the most basic machine costing in the region of £30-100k, and this restricts their use to industrial measurement labs. Resolution is not as good as optical methods but three-dimensional measurements of real components can be made.

3.3 Electro-Optical Techniques

Fibre optic displacement probes

Fibre optic displacement probes offer a potentially high resolution and cost effective measurement system. They work by bundling sets of light receiving fibres and light emitting fibres together into a measurement probe. There are three different possible configurations - random, hemispherical and concentric - which are optimised for different applications. In most cases the random fibre distribution is most appropriate.

As the probe is moved away from the target surface, the amount of light reflected into the receiving fibres initially increases as the gap increases because of the increased possibility of reflection from emitting fibres into receiving fibres. With further separation between target and probe, the output from the device reaches a maximum and then declines with further separation as the amount of light reflected into the receiving probes decreases. Obviously, when the probe is remote from the target surface, no signal is observed. The region of increasing signal which is found when the probe is relatively close to the target surface gives a more sensitive response than the region of decreasing signal further away from the target surface.

Probes are available with a range of tip sizes from 0.5 mm up to 3.2 mm. For the best systems, the probes have a nominal measurement sensitivity of a few nm, but in practice the probes are more limited by the generation of electrical noise which limits their fundamental resolution to about 15 nm. However, in most circumstances this performance can be improved by time averaging, since these probes have an upper frequency capability of about 200 kHz.

The probes are calibrated by making use of the peak in the output response. The major problem with calibration is due to the fact that the output is dependent on the reflectivity of the surface. However, the position of the peak is not dependent on reflectivity, so for every new surface, the peak can be found and the output adjusted to the appropriate calibrated value.

Laser interferometry

Laser interferometry is an excellent method for measuring displacement. The major advantages are that it is inherently traceable to national standards, can be very stable, has excellent sensitivity and can give very fast measurements. The major drawback with the method is that it is relatively expensive.

Interferometry works through the interference of two beams of laser light, one of which is reflected off the target surface, the other off a reference mirror. When the optical path lengths of the two arms are equal, or differ by an integral number of wavelengths, constructive interference occurs with a consequent increase in the signal detected. When the optical path lengths are exactly out of phase, ie a half wavelength (or multiple) apart, then destructive interference occurs and no signal is received at the detector. In fact modern interferometers measure intermediate values of displacement so that much higher resolutions can be achieved.

One drawback with the conventional (Michelson) interferometer described above occurs if the measurement points are more than one wavelength of light apart (in terms of the difference in optical paths), then there is some ambiguity in the measurements since the output from the interferometer recurs for every wavelength shift. A good way of overcoming this problem is to use two sets of interfering beams in a single system with the two sets shifted optically with respect to one another by a quarter of a wavelength. When the signals from the two sets are combined, this results in a steadily varying signal which can be followed to give an absolute measure of target surface movement. This technique is termed quadrature measurement.

Another concern with interferometry arises because the reference light beam covers a different optical path from the measurement beam, and errors in measurement can occur from path differences that arise from thermal fluctuations or movements in the air through which the beam passes. This can be overcome by the use of common path interferometry which ensures that the reference beam passes as close as possible to the measurement beam, and in fact in some interferometer designs a full common path strategy can be achieved.

Calibration is simple with interferometers as the measurements that are obtained are immediately referenced to the wavelength of the laser light that is used. Thus, as long as the wavelength of the laser has been calibrated (normally this is very stable) the calibration of interferometers needs very little attention.

Non-contacting probes

In addition to laser interferometers, there are several other types of optical measurement probes which can also be used for displacement measurement. These can be split into two groups - single point devices, and devices which give a full field of view. The former type, like the interferometer, essentially give a measurement of a single point and require the use of an auxiliary scanning stage to produce a displacement map of a complete surface. Full field instruments are based on optical microscope technology and can give a very rapid measure of a complete field of view. However, this can be restrictive if measurements over an extended distance are required.

A common type of single point device is based on the auto focusing mechanism found in compact disc (CD) heads. This forms an image of a laser spot on the target surface onto a photo-diode, and then either adjusts the position of a focusing lens until the size of the image is reduced to a minimum, or uses the error signal derived directly from the photo-diode to give a measure of the displacement. These devices have good speed (up to about 10 kHz) and high sensitivity (down to a few nm), with a spatial resolution of a few micrometres. They can be calibrated by making measurements of a calibrated grating or step.

Another type of probe uses triangulation with the small spot produced by a laser to give a measure of probe to target surface. These devices can have a displacement sensitivity of a few tens of nm, but with a higher spatial resolution of about 50 μm than the autofocus devices.

Laser profilometers use these type of probe to measure fine displacements or surface texture with typical accuracies down to 0.1 μm . Interchangeable probes allow a measuring area ranging from 100 μm to 100 mm in size with corresponding accuracies of 0.01 to 6 μm . Small components can be scanned in their entirety with cross section profiles and real time display of x, y, z coordinates. Because the images are stored digitally, it is possible to compare a measured component with a master reference component to allow dimensional differences to be highlighted, and software is available for producing colour three dimensional images of components and surfaces.

Instruments which give a full field of view are based on the on-line analysis of interference fringes produced in an optical microscope by techniques such as Mirau interferometry. A normal optical microscope can be adapted fairly readily for use for measurements by this route. The technique suffers from the same ambiguity mentioned earlier for the laser interferometers arising from ambiguities in fringe counting, but this has recently been alleviated by the development of white light fringe techniques which rely on the use of modern workstations to provide the computational power necessary to determine surface height accurately across a full field of view.

Similar computational power is needed for the measurement of displacement across a surface by use of a confocal optical microscope. This relies on the optical sectioning abilities that come from confocal microscopy, with analysis of a set of these slices taken at different heights to achieve a full map of surface height across a specimen.

Laser Holography and Moiré interferometry

Equipment has been developed at NPL for carrying out in situ measurements of the deformation of components at temperatures up to 600°C. Holographic interferometry methods can measure out of plane deformations of 0.01 μm . The laser holographic technique involves recording photographically the diffraction pattern produced by laser illumination of a component, and later reconstructing its image from the diffraction pattern. The holographic pattern is in the form of displacements and the technique can be used for monitoring damage accumulation in composites and NDT flaw detection. Laser speckle photography can be used for large components to a precision of 1 μm .

Moiré interferometry uses a diffraction grating bonded to the surface of a component. When a laser interferometer containing a reference grid is used to illuminate the surface, fringe patterns are revealed when the component is loaded. The technique can only be used on flat surfaces and the accuracy is related to the hole density of the grating. The high density gratings required for sensitive measurements are expensive and must be bonded to the surface of the component which may affect the properties of the surface itself. Generally these techniques allow critical points of stress and deformation to be located, and can be used to

complement other displacement measurement methods.

Image Correlation

Digital imaging techniques have developed over recent years and are a potential method for measuring in-plane surface displacements at elevated temperatures. The image correlation technique compares images of surfaces before and after deformation and, by means of a suitable correlation algorithm computes the strains or displacements by comparing the relative locations of a pattern or features on the testpiece surface.

The technique has been used for strain measurement at high temperature (12). Surface preparation is important. One method is to apply a coat of white heat resistant paint to the surface and spray onto this a randomly distributed speckle pattern. Images are compared and the displacement of individual points on the surface can be measured. The resolution of the system depends on a number of factors including the magnification and resolution of the video camera and lens and the number of pixels in the image window. Higher resolution images have been reported from tests on CMCs at elevated temperatures (13), using in situ measurements in a loading stage in an SEM and concentrating on surface features rather than an artificial surface pattern. Disadvantages of the image correlation methods include the need for considerable computing power, and measurements are restricted to flat surfaces because of the limited depth-of-field of the imaging equipment. The advantages are that it is a technique which can be used in situ, over a wide temperature range, providing full field multiaxial displacement measurements.

4 SUMMARY AND RECOMMENDATIONS

It is difficult to recommend a single technique for any one application because a large number of factors must be considered. Table 6 attempts to simplify the selection procedure by breaking down the measurement requirements into in-situ monitoring and periodic inspection, and this can be used in conjunction with Tables 4 and 5 which give more specific details on each technique. In-situ tests can be used to examine the behaviour of the testpiece or component under actual operating conditions, whilst periodic inspection tests are designed to monitor any change in the integrity of a component after a specified time or number of thermal cycles. The particular test method can then be subdivided further into techniques suitable for testpieces or components. Typical practical considerations for each test mode are given in Table 6, together with a list of suitable measurement methods.

For in-situ testing, consideration must be given to the practicalities of making measurements at temperature, and accessibility to the component or testpiece may be a problem. The temperature range of interest is also important as this may affect the feasibility of using a particular technique and the measurement device itself. Surface preparation must be carried out carefully to avoid damage to the testpiece or component and, for similar reasons, for notch-sensitive materials non-contact methods are preferable. For tests on components, the interface with other components should be considered.

For out-of-service inspection tests, measurements are compared with the original component and for this an accurate reference point or image must be available. Ideally the technique should be non-destructive so that the component can be returned to service. The frequency of inspection and the associated downtime are important considerations if the tests are carried out on working components.

For all the measurement methods the cost of equipment, ease of use, accuracy and resolution, calibration, standards are important issues to consider. If full field, multiaxial measurements

are required then this will determine to a large extent which techniques are suitable. The choice of method is very much dependent on the particular test requirements, but ultimately operators are likely to consider techniques with which they have some experience.

At NPL, tests are currently in progress under a separate task in DCC2 to develop and compare some of the methods described in this report. Particular effort has been spent on developing suitable methods for fibre optic probes, laser interferometry, laser profilometry and strain gauges. Periodic inspection measurements are being made on thermally exposed testpieces which have not been loaded, and on testpieces kept under a sustained load during thermal exposure or cycling. Results will be reported in a separate report.

5 ACKNOWLEDGEMENTS

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<i>Matrices and Fibres</i>		<i>Composites</i>	
6061 Al alloy	23.6	10% SiC _p /2124	21.7
Mg	26	20% SiC _p /2124	18.7
Ti alloy	9	30% SiC _p /6061	14.8
Borosilicate glass	3.5	50% SiC _p /6061	
Glass-ceramic	1.5	20% Al ₂ O ₃ /6061	11.9
SiC whisker	4.3	10% SiC _w /6061	20.3
SiC fibre	1.5	20% SiC _w /6061	18.4
SiC particulate	4.8		
Al ₂ O ₃ (saffil) fibre	5.4	C fibre/Al UD	0.19
		C fibre/Al 0/90	0.76
		C fibre/Cu UD	0.81
		C fibre/Cu 0/90	1.92
		B fibre/Al axial	1.8
		trans	6.0

NB Values for CTE are $\times 10^{-6}/^{\circ}\text{C}$

Table 1 : Typical CTE values for MMC and CMC

Composite type, and typical CTE	$\Delta T (^{\circ}\text{C})$	Deformation (in μm) in testpiece/component of dimension (mm)		
		1	10	100
Particulate reinforced MMC $\alpha = 15 \times 10^{-6}$	200	3	30	300
	400	6	60	600
Fibre reinforced Ti MMC $\alpha = 5 \times 10^{-6}$	650	3.25	32.5	325
Fibre reinforced CMC $\alpha = 2 \times 10^{-6}$	1000	2	20	200

Table 2 : Magnitude of deformations for different values of CTE and testpiece sizes

Application	Material type	Min Temp	Max Temp	No. of cycles	Heating or cooling rates
Auto components	Particulate Al MMC	-40	400	5000	
Aero engine components	Ti- based FRM	-50	600	50000	10-100°C s ⁻¹
	Mg MMC	-20	120	10000	5°C min ⁻¹
Gas turbine components	CMC	20	1600		300°C min ⁻¹
	SiC-SiC	20	1300	10000	100°C s ⁻¹
Brake discs	C-C	-50	1200	4000	200°C s ⁻¹

Table 3 : Typical thermal environments for MMC and CMC applications

Technique	Resolution (m)	Range (m or $\Delta\epsilon$)	Accuracy (m or %)	Contact **
Mechanical Instruments				
Micrometers	3×10^{-5}	10^{-1}	10^{-4}	C
Vernier Scales	3×10^{-5}	1	2×10^{-5}	C
Dial Gauges	10^{-5}	10^{-2}	10^{-5}	C
Profile Projectors	8×10^{-6}	1	10^{-5}	NC
Telemicroscopes	10^{-6}	1	10^{-6}	NC
Electrical Transducers				
Resistance Strain Gauges	10^{-7} (ϵ)	20%	10^{-7} (ϵ)	C
Semiconductor strain gauges	10^{-9} (ϵ)	1%	10^{-8} (ϵ)	C
Capacitance	10^{-11}	10^{-4}	10^{-10}	SG
LVDT's	$< 10^{-8}$	10^{-2}	10^{-8}	SG
Resistance Transducers	10^{-5}	3	1%	C
Variable Impedance	10^{-8}	10^{-2}	0.01%	SG
Electro-Optical Techniques				
Fibre Optics	10^{-8}	10^{-2}	10^{-7}	SG
Detector Arrays	10^{-6}	$> 10^{-1}$	10^{-5}	NC
Photoelectric Microscopes	10^{-9}	10^{-4}	10^{-8}	SG
Michelson Interferometry	$< 10^{-9}$	10^{-3}	10^{-8}	NC
Fizeau Interferometry	10^{-8}	10^{-3}	10^{-8}	C
Holographic Interferometry	10^{-7}	10%	10^{-7}	NC
Speckle Interferometry	10^{-7}	1%	10^{-7}	NC
Moiré Interferometry	10^{-7}	1%	10^{-7}	NC
Sub-surface methods				
X-ray diffraction	10^{-14}	$< 10^{-10}$	10^{-13}	NC
Electron diffraction	10^{-14}	$< 10^{-9}$	10^{-13}	NC
Neutron diffraction	10^{-14}	$< 10^{-9}$	10^{-13}	NC
Ultrasonics	10^{-5}	10^{-1}	10^{-4}	C
Acoustic Emission	10^{-3}	> 1	10^{-3}	C

** C - Contacting
 NC - Non-contacting
 SG - Small Gap ($< 10^{-1}$ m)

Table 4 Summary of Length Measurement Techniques (Ref 8)

	Mode	Capital Cost	Ease of Calibration	Temp range (°C)	Measurement range	Resolution	Features
Micrometers	C	Low	Simple	room temp	0-100 mm	0.001 mm	Simple operation. Limited accuracy and resolution. Restricted to simple shapes
Strain gauges	C	Low	Difficult	-70 to 200	4%	0.5µe	Use on components and testpieces. Multiaxial measurements possible. Calibration difficult, surface preparation required. Limited temperature range.
Capacitance probes	NC	Low	Moderate	-20 to 500	few mm	0.1 nm	Excellent resolution. Use restricted to testpieces.
LVDTs	C	Low	Simple	-20 to 500	10s mm	0.1 µm	Simple to set up and use.
Mechanical extensometry	C	Low	Simple	-50 to 1600	10%	0.5µe	Relatively inexpensive and simple to operate. Use restricted to testpieces. Non-contact optical systems do not have sufficient resolution for MMC
Laser extensometry	NC	Low/Med	Simple	-50 to 600	50%	0.1 µm	Excellent resolution. Use restricted to testpieces.
Profilometry	C	Low/Med	Moderate	room temp	few mm	1 µm	Use on complex components. Multiaxial measurements
CMMs	C/NC	High	Moderate	room temp	10 m	1 µm	Multiaxial measurements on complex components. Expensive.
Fibre optic probes	NC	Low	Moderate	-50 to 600	0.5%	10 nm	High resolution
Laser interferometry	NC	Low/Med	Simple	-20 to 300	few mm	0.1 µm	Easy to calibrate. Relatively expensive.
Non-contact probes	NC	Med	Moderate	-20 to 500	few mm	10 nm	Some devices give full-field measurements.
Image correlation	NC	Med/High	Moderate	-20 to 1500	few mm	0.1 µm	Multiaxial measurements possible. Good resolution, in-situ measurements on both components and testpieces
Laser Holography	NC	Low/Med	Moderate	-50 to 600	few mm	0.01 µm	Use on components and testpieces, full- field measurements.
Moire interferometry	NC	Low/Med	Moderate	-50 to 600	10s mm	10s mm	Use on components and testpieces. Requires grating bonded to component.

Table 5 : Characteristics of the Measurement Method

