

NATIONAL PHYSICAL LABORATORY

Centre for Materials Measurement and Technology

STRAIN GAUGE TECHNIQUES FOR MEASURING THERMAL EXPANSION

by

J D Lord, W Nimmo, D Cooper and R Morrell

SUMMARY

A novel strain gauge technique for measuring thermal expansion and dimensional change is discussed. The technique has been used to measure the thermal expansion coefficient 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. Values obtained from the strain gauge method for the thermal expansion coefficient, between 25-100°C, of copper and aluminium were 16.6 and $23.4 \times 10^{-6}/^{\circ}\text{C}$ respectively and these are in good agreement with typical handbook values.

Data from particulate reinforced MMCs are discussed and compared with conventional dilatometry. Also presented are results from thermal cycling tests on a variety of polymer composites. With some of these materials, in addition to measuring the traditional thermal expansion behaviour, the strain gauge method allows the dimensional changes which develop during processing (cure and postcure) of the material to be monitored. The behaviour measured is in good agreement with predicted behaviour.

More general issues relating to the practical aspects of the technique are discussed also.

The report describes the work carried out by NPL in Project DCC2 and meets one of the deliverables of the project.

© Crown copyright 1997
Reproduced by permission of the Controller of HMSO

ISSN 1361-4061

National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

Extracts from this report may be reproduced provided
that the source is acknowledged.

Approved on behalf of Managing Director, NPL, by Dr M K Hossain,
Director, Centre for Materials Measurement & Technology

CONTENTS

1. INTRODUCTION 1

2. STRAIN GAUGE TECHNIQUE 1

2.1 Test Procedure 2

2.2 Validation of the Strain Gauge Technique 3

2.3 Effect of Using Different Strain Gauges 4

3. MATERIALS AND TESTPIECES ... 4

4. RESULTS 5

4.1 Particulate Reinforced Metal Matrix Composites 5

4.2 UD Carbon Fibre/Epoxy 6

4.3 Random Glass Fibre/Polyester 6

4.4 Woven Polymer Matrix Composites 7

4.5 Other Polymer Composites 8

5. SUMMARY 9

ACKNOWLEDGEMENTS 9

REFERENCES . 9

TABLES

FIGURES

1. 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 technique for measuring thermal expansion using strain gauges has received relatively little attention despite its relative simplicity and a number of advantages over conventional dilatometry. The technique exploits the differential thermal expansion of identical strain gauges bonded to two different materials subject to the same temperature change, and some of the main advantages over dilatometry are the ability to carry out multiaxial measurements on relatively large testpieces or components, using relatively simple equipment readily available in most engineering test laboratories. Some basic knowledge of strain gauges, strain gauge installation and instrumentation is required, but the test method itself is relatively straightforward and can be applied to a wide variety of materials. 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. The technique therefore is ideal for many polymer composites where 200°C often represents the maximum operating temperature of the material or component.

This report describes the technique applied to a variety of materials and discusses the merits and application of the strain gauge method. Practical tips are given where possible and conventional dilatometry data is presented for some materials for comparison.

Work is currently underway to develop an accepted standard for the technique. Some technical procedures are already available [1,2], and a draft procedure has been proposed for measuring thermal expansion of printed circuit boards [3].

2. STRAIN GAUGE TECHNIQUE

The background to the strain gauge technique is detailed in Refs 1,2. 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 homogeneous reference material is well characterised, then the thermal expansion coefficient of the material under examination can be calculated using the following equation:

$$\alpha_{spec} = \frac{[\epsilon_{spec} - \epsilon_{ref}]}{\Delta T} + \alpha_{ref} \quad (1)$$

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.

Figure 1, which shows the variation in thermal output from a strain gauge installed on materials with different thermal expansion behaviour, illustrates the basics of the method. Strain gauges are usually provided compensated for use with a particular material (self temperature compensated or S-T-C gauges), for example steel or aluminium, and the thermal output of the gauge is designed to minimize temperature induced strains by being relatively insensitive to variations in temperature. Line A in Figure 1 shows the typical response for a gauge compensated for steel (S-T-C no. 11) bonded to steel over the temperature range -60

to 250°C. Between room temperature and 200°C the gauge is relatively insensitive to the variation in temperature and only at the temperature extremes outside this range does the output vary significantly. The effect of using a strain gauge which is compensated for steel on a material with different thermal expansion behaviour is to rotate this curve about the room temperature point. For example, if the gauge is compensated for use with steel and it is used with a material with a lower CTE (Line B), the curve rotates clockwise, if higher the curve rotates anti-clockwise (Line C). The strain gauge technique exploits this difference in thermal output of a strain gauge when bonded to materials of different thermal expansion to measure CTE. In theory any reference material can be used provided that the thermal expansion behaviour is well characterised, and any strain gauge can be used. 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.

2.1 Test Procedure

The preferred method of measuring the coefficient of thermal expansion is by taking the difference in strain readings at two temperatures, but additional information can be obtained by continuously monitoring the strain and temperature values during thermal cycling, throughout the heating and cooling stages. The first method gives a single value for thermal expansion coefficient between two temperature extremes, continuous monitoring of the strain readings allows the variation of thermal expansion to be assessed, and this may be important if the CTE behaviour is non-linear, if the material is visco-elastic or in special cases, for example monitoring the curing process in polymer composites where controlled heating rates are often used and large dimensional changes can occur. Typical heating profiles used in this work are shown in Figure 2 - stepped heating, and continuous heating. Figure 2a shows the stepped heating method where the materials are held at constant temperature for 10 minutes to allow the gauge readings to stabilize; Figure 2b shows a continuous heating cycle involving a uniform heating rate from room temperature to 200°C at 3°C/min followed by cooling at the same rate without any dwell at temperature.

Tests were carried out in an environmental test chamber with an operating temperature range of -70 to 400°C, and a maximum heating rate of 20°C/min. Controlled cooling rates were achieved using liquid nitrogen. Figure 3 shows the experimental setup with the environmental chamber, data logger and PC; Figure 4 shows in closer detail a typical strain gauge installation with a polymer composite and glass reference material. For all the tests the material used for the reference specimen was a block of 7971 ULE titanium silicate glass manufactured by Corning. This material is isotropic and has an average coefficient of thermal expansion over the range 0 to 200°C of $0.03 \times 10^{-6}/^{\circ}\text{C}$ [4]. One reason for using a reference material with a low CTE, is that the strain gauge output is large and this helps to reduce the errors in the measurement. However, although the silica block has an extremely low thermal expansion coefficient between room temperature and 200°C, it also has a low thermal conductivity and during thermal cycling care must be taken to ensure that the composite and reference material are at the same temperature when strain readings are taken.

Individual gauges were connected in a three wire quarter bridge configuration to a multi-channel data logger. The strain gauge resolution was typically 1 microstrain. The leadwires were 1m long of which approximately 200 mm was exposed to the temperatures in the chamber. The wire used was insulated with a PTFE coating and was capable of operating up

to 260°C. High temperature solder was used and all gauges were coated with a silicon rubber protective film prior to testing. Gauges were bonded to both faces of the specimens and averaged to avoid errors arising from bending induced by temperature changes. The temperature was monitored throughout the test using type K thermocouples attached to the specimen and reference material as close as possible to the gauge. Temperature measurements were accurate to $\pm 0.5^\circ\text{C}$.

The gauges were bonded to the reference block and the specimens using a two-part cold curing epoxy adhesive. A hot curing adhesive is probably preferable but could not be used with the polymer composites in this work because the properties of the materials being examined would be affected by the temperature cycle required to cure the adhesive. It is recommended practice to carry out three thermal cycles between room temperature and 20 °C above the maximum temperature of interest prior to taking measurements to reduce hysteresis and to relieve any residual stress in the strain gauge installation. This procedure was not followed for some of the polymer composites, and in such cases measurements were made during the first and subsequent thermal cycles.

2.2 Validation of the Strain Gauge Technique

To validate the strain gauge technique, measurements were made from room temperature to 200°C on a 6061 aluminium alloy and a copper specimen and compared with handbook values. To eliminate hysteresis in the gauge installation three thermal cycles were carried out between room temperature and 220°C, prior to the CTE measurement. Separate tests were carried out using both the “step” method and with continuous heating and cooling. The strain gauge used was a single grid design which was compensated for steel and designated Strain Gauge 1, and was bonded to the specimens using a cold cure epoxy adhesive.

Strain gauge data from the fourth thermal cycle (continuous heating and cooling) for the aluminium, copper and titanium silicate reference material is plotted against temperature in Figure 5. Plotted in this form all three curves show some non-linearity and this is a feature of the thermal output of the strain gauge and not the material. The values for CTE are given in Table 1, calculated according to equation 1 for the given temperature range, but the variation of thermal expansion is shown also as a continuous plot in Figure 6, simply by subtracting the reference material strain data from the aluminium and copper data at the same temperature. The thermal expansion behaviour shown in Figure 6 is linear with no hysteresis. Calculated CTE values vary slightly depending on the temperature range over which they are calculated, but for 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. Typical handbook values for aluminium and copper are 23 and $17 \times 10^{-6}/^\circ\text{C}$ respectively and these are in good agreement with the values obtained from the strain gauge method and this confirms the validity of the technique. It is good practice to carry out such validation exercises with a reference material or well characterised specimen whenever a different strain gauge type is used.

Figure 7 shows values for CTE for the aluminium and copper specimens calculated at 25°C intervals from the “stepped” heating and continuous tests. There is a small difference in the values calculated and those from the “stepped” heating generally show less scatter. For improved accuracy this method should be used.

Also, if a series of tests are being carried out using strain gauges from the same batch, it is not strictly necessary to use the reference material every time, but a calibration curve can be generated. Figure 8 shows such a curve for the ULE titanium silicate glass and Strain Gauge 1. The repeatability of the data is shown in Figure 9, where data from seven tests are plotted. Such calibration curves however should be treated with care because they are only valid for one particular strain gauge type, gauge installation and adhesive type. Even if identical

strain gauges from different batches are used there is no guarantee that the thermal behaviour is the same.

2.3 Effect of Using Different Strain Gauges

To examine the effect of using different strain gauges, tests were carried out up to 200°C on the aluminium specimen and three different types of strain gauge were used. Figure 10 shows the raw strain gauge data for one thermal cycle plotted against time for the aluminium testpiece and ULE titanium silicate glass reference material. In this case, the thermal cycle consisted of heating at 3°C/min followed by a dwell at temperature for 10 minutes at 25°C intervals. Both Strain Gauges 1 and 3 were compensated for steel but were different designs supplied by different manufacturers; Gauge 2 was compensated for aluminium. This figure clearly shows the importance of using identical strain gauges for a test or series of tests because there is a considerable difference in the magnitude of the thermal output of the strain gauges, even when they are compensated for use with the same material. The strain gauge data is plotted against temperature in Figure 11. Note the duplicated datapoints at 25°C intervals on the curve which indicate good repeatability and stable gauge readings. Also, there is generally good agreement between the heating and cooling cycle with little hysteresis. Considering Figure 10 in more detail, Strain gauges 1 and 3 show marked differences in output at each temperature interval but the behaviour of the gauges is consistent with that described earlier in Figure 1. Because aluminium has a higher CTE than steel, for the gauges compensated for steel, the absolute gauge readings on the aluminium specimen are positive. For the titanium silicate glass the opposite is true. In this case the strain gauge is trying to expand but is constrained by the silicate glass resulting in a compressive strain in the strain gauge (even though both the strain gauge and reference materials are expanding). For Strain Gauge 2, which was compensated for aluminium the gauge readings on the aluminium specimen should be nominally zero over the whole temperature range; those from the silicate glass block are still negative. Only above 150°C on the aluminium specimen is there any significant thermal output from the gauge bonded to the aluminium block, and this is close to the recommended temperature limit for these gauges. The thermal expansion behaviour measured using the three types of gauge is plotted in Figure 12. There are minor differences between the individual gauge readings, and the CTE values calculated are 23.4 , 22.3 and $24.2 \times 10^{-6}/^{\circ}\text{C}$ for strain gauge types 1, 2 and 3 respectively. The maximum difference between the three calculated values is about 10%, but the individual results do not differ by more than 5% from the handbook value. This gives some indication of the accuracy of the strain gauge method. For all subsequent tests, Strain Gauge 1 was used as this gave the most accurate results.

The results show clearly the importance of using identical strain gauges in the test. In theory any type of strain gauge can be used, but it is advisable to use good quality gauges with accurate gauge factors. For some materials gauge size may be important, particularly if there are local variations in structure at or close to the surface. A good example is with some polymer composites where the fibres are close to the surface and may influence the local strain field beneath the strain gauge. In such cases, large gauges could be used to take a global strain reading, whilst small gauges could pinpoint local differences in the strain field. The choice of strain gauge often depends on what is readily available, the ease of installation, and the cost. Useful information can be obtained from manufacturer's datasheets and catalogues.

3. MATERIALS AND TESTPIECES

One of the main advantages of the strain gauge technique over conventional dilatometry is the ability to carry out multiaxial measurements on large testpieces or components. A variety of materials have been tested in this report, including conventional alloys, metal matrix

composites (MMCs) and a number of different polymer composites. Some details are given in Table 2. For the MMC and metal specimens, testpiece blanks were used, approximately 100 x 12 x 3 mm; and for the polymer composites, sections, approximately 50 mm square and the thickness of the panel were used. Strain gauges were bonded to both sides to take account of any distortion or bending, and the average strain readings used to calculate CTE.

The reference material used was a block of 7971 ULE titanium silicate glass, approximately 150x12x4 mm with 1 strain gauge and a type K thermocouple attached. The strain gauge installation and instrumentation used for measurements on the composite materials were identical to those described in sections 2.1 and 2.2 above.

4. RESULTS

4.1 Particulate Reinforced Metal Matrix Composites

Strain gauge tests were carried out on two metal matrix composites following the procedures outlined above. MMC1 is a 6061 aluminium alloy with 20% Al_2O_3 reinforcement, MMC2 is a 2124 alloy reinforced with 20% SiC. A modified Linseis dilatometer was used also to measure CTE for comparison with the strain gauge data.

For the dilatometer, testpieces approximately 6 mm square cross-section and about 25 mm in length were cut in the extrusion direction and placed in a specially constructed silica specimen holder. A flat-ended silica push-rod held in contact with one end of the specimen was used to transmit the changes in length to a linear displacement transducer as the specimen was thermally cycled. The specimen ends were gently rounded to give localised contact with the apparatus and the temperature of the specimen was measured using a type R thermocouple. The outputs of the thermocouple and the displacement transducer were recorded continuously on an X-Y chart recorder to give a direct indication of behaviour, and on a data logger for subsequent analysis.

The maximum cycle temperature was set at about 460°C with a heating rate of 2 °C/min. Results were calculated at 50 °C intervals for the separate heating and cooling parts of four consecutive thermal cycles, and the average results were calculated. (The strain gauge tests were carried out at a constant heating and cooling rate of 3°C/min up to 250°C, so comparisons between the two techniques can only be made up to this temperature). The overall accuracy of the measurement is controlled by the mechanical stability of the specimen in the apparatus. Assuming complete stability, the measurement accuracy is considered to be approximately $\pm 1\%$ or $\pm 0.1 \times 10^{-6}/^\circ\text{C}$ over a 100 °C temperature range, whichever is the larger.

The data from the dilatometer was processed with an off-line computer program to give corrected results for each datapoint, and the mean CTE values were calculated by linear interpolation over the required temperature ranges. Average values from two separate runs in the dilatometer up to 250°C together with results from the strain gauge technique are presented in Table 3 for the two materials, and plotted in Figures 13 and 14. The corresponding thermal expansion behaviour is plotted in Figures 15 and 16.

Generally there is good agreement between the dilatometer and the strain gauge technique. Mean values for CTE for MMC1, the 2124 alloy + 25% SiC, calculated 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; for MMC2 with 6061 + 20% Al_2O_3 , over the same temperature range the mean CTE values calculated using the two techniques were identical at $18.3 \times 10^{-6}/^\circ\text{C}$. The greatest difference occurs at the lower temperatures and this may be due to the difficulties of controlling the furnace temperature. Also, at these temperatures, the strain and

displacement readings are low and the uncertainties associated with the strain measurement are correspondingly higher.

As would be expected, MMC1 which has the higher level of reinforcement has the lower CTE, and this is significantly less than the aluminium matrix. The thermal expansion behaviour of particulate reinforced MMCs is an important parameter of interest to materials engineers and designers. In particular the ability to tailor the CTE value by varying the level of reinforcement allows MMCs to be used instead of steel and other materials in thermal environments where accurate tolerances must be maintained, with considerable weight saving and improved specific properties. A specific example of using MMCs with high volume fractions of reinforcement and low CTEs is in the electronics industry for instrument assemblies, and for instrument racking in aircraft where MMCs have replaced costly carbon fibre polymer composites.

4.2 Unidirectional Carbon Fibre/Epoxy Composite

Test 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; sub-zero temperatures were achieved using liquid nitrogen. The composite was made up from 16 plies of unidirectional T300 carbon fibre in a Fibredux 924C resin matrix. Three runs were carried out prior to taking the measurements to eliminate hysteresis in the material and gauge installation. The thermal cycle consisted of heating from room temperature to 70°C at 3°C/min followed by cooling to -20°C at the same rate. The raw strain data for each gauge is plotted in Figure 17 together with the data from the ULE 7971 titanium silicate glass reference material. 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. Because the reference material is isotropic the three readings from the strain gauge rosette were almost identical and the mean value is plotted. Note that the strains in the composite material along the fibre direction are almost identical to those measured in the reference material.

The thermal expansion behaviour is plotted in Figure 18. Of particular interest is the performance of the material along and perpendicular to the fibre direction. 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 $34.4 \times 10^{-6}/^{\circ}\text{C}$, and these are in reasonable agreement with the model predictions.

4.3 Random Glass Fibre/Polyester Composite

To illustrate further the application of the strain gauge technique to other composite systems, tests were carried out on a random glass fibre/polyester composite, code FHV, which is used for structural applications at ambient temperature. Two type 1 strain gauges were used, bonded to both sides of the specimen with a two part cold cure adhesive. The first two cycles were monitored and the raw strain gauge data is presented in Figure 19, together with the data for the silicate glass reference material. (Codes FHV1 and FHV2 refer to the individual strain gauges.) The thermal cycle consisted of continuous heating at 3°C/min to 200°C, followed by a dwell at temperature for 10 minutes and cooling to room temperature at the same rate. The thermal expansion behaviour is plotted in Figure 20. The material exhibits two regions of linear expansion with the change in temperature either side of the glass transition temperature of the matrix. From the strain gauge data the glass transition temperature, T_g , was identified as lying between 100 and 110°C. The CTE value below T_g was $22.3 \times 10^{-6}/^{\circ}\text{C}$ and above T_g , when the matrix material becomes less viscous, this increased to $62.2 \times 10^{-6}/^{\circ}\text{C}$.

°/°C. Although the absolute value of the glass transition point is difficult to identify, continuous monitoring of the strain data reveals how the material is behaving with a change in temperature, and normally such information can only be obtained using expensive specialized techniques such as differential scanning calorimetry (DSC).

Referring to Figure 20, the material exhibits some hysteresis in the first cycle with a small amount of contraction on cooling to room temperature, but on repeated cycling the material is fairly stable. During the dwell at 200°C in the first cycle, there is some contraction and reduction in the strain readings on the composite material. It is not clear what this mechanism is, but it may be a feature of the adhesive system used to mount the strain gauges which is curing at this temperature. This does not occur on repeated cycling or exposure at this temperature.

4.4 Woven Polymer Matrix Composites

Tests were also carried out to measure the dimensional change and thermal expansion behaviour of a number of woven carbon fibre polymer matrix composites. The materials had different lay ups and were in two conditions - with either an initial cure or full postcure treatment. The results are given below for two of the materials, coded FKM and FKP, which have the same 0/90 lay up but different thermal treatments. FKM had an initial cure for 10 hours at 60°C, whilst FKP had been fully postcured for 8 hours at 190°C. Specimens approximately 50 mm square were used with strain gauges bonded to both faces to take account of any bending or distortion.

Identical testing conditions were used for both materials which involved heating from room temperature to 200°C at 3°C/min followed by a dwell at temperature for 10 minutes and then cooling back to room temperature at the same rate. Figure 21 shows the raw strain gauge data plotted against time for the titanium silicate glass reference material and composite FKM (with an initial cure only) for the first thermal cycle. Data from both strain gauges are plotted (as FKM1 and FKM2) and there are small differences between them. The individual strain outputs are plotted against temperature in Figure 22. Initially the two strain gauge readings are identical, but above about 75°C the slope changes and the readings diverge, indicating that the gauges are being put further into compression and the composite is contracting. On cooling back to room temperature the material response is almost linear with a permanent offset in the gauge readings indicating a contraction. The slope of the curves is similar to the initial slope at the start of the cycle.

Figure 23 shows the thermal expansion behaviour of composite FKM as a function of temperature for the first cycle. The data points plotted have been calculated by subtracting the output of the gauge bonded to the reference material from the mean of the outputs of the gauges bonded to the composite. The CTE can be calculated from the slope of the curve in Figure 23 or from the raw strain gauge data. In this case there is a clear advantage in using continuous monitoring of the strain gauges because of the complicated thermal behaviour, if data had been recorded only at 25°C intervals the full behaviour of the material could not be established.

Examination of Figure 23 gives useful information about how the material is behaving. With the initial cure, the composite is stable up to 60°C and the composite expands linearly to this point. In fact for this material, the expansion is linear up to about 75°C at which point the matrix begins to cure and shrink. This cure shrinkage dominates the thermal expansion of the material until the temperature exceeds 100 °C. Between 100 and 200°C the dimensional changes are governed by a mixture of cure shrinkage and thermal expansion. On cooling to room temperature the behaviour is linear with a large permanent offset - the material has contracted. The corresponding plot for a second identical thermal cycle is given in Figure 24. In this case the strain gauge readings have been reset to zero at the start of the test. The

material is now stable and the CTE is approximately constant over the whole heating cycle indicating full cure of the material. The hysteresis loop at the maximum temperature in both cycles is probably caused by curing of the adhesive used to bond the strain gauges to the composite. It does not appear with the strain gauge bonded to the reference material because this has been subjected previously to a number of cycles to higher temperatures and is fully stable.

Figure 25 shows the data from the first thermal cycle for composite FKP which is identical to FKM except for a full postcure for 8 hours at 190°C. After exposure at this temperature the composite should be fairly stable. Between 60-75°C on the heating cycle there is a small change in slope, with some hysteresis at higher temperatures probably associated with the cure of the strain gauge adhesive, but the behaviour is fairly stable and the thermal expansion is reasonably constant over the whole heating and cooling cycle. Figure 26 shows the corresponding plot for the second thermal cycle on the same scale.

The variation of CTE, calculated over 25°C intervals from the strain gauge data for the FKM composite for the two cycles presented above, is presented in Figure 27. As described earlier, most of the changes occur during the heating phase of the first cycle and after this the calculated CTE is roughly constant, at $\sim 3.0 \times 10^{-6}/^{\circ}\text{C}$. Figure 28 shows the corresponding plot for the postcured material over the first two thermal cycles, plotted on the same scale. Again, the CTE is calculated over 25°C intervals from the raw strain gauge data. The mean value of CTE is approximately $3 \times 10^{-6}/^{\circ}\text{C}$, comparable with that for the FKM material with the initial cure only. The tabulated values of CTE the two cycles for both materials is given in Table 4.

Because of the 3D nature of the weave, local variations in the material are inevitable and this may contribute to differences in strain gauge readings. If the carbon fibres are close to the surface the strain gauge readings can be appreciably different to the case if very few fibres are present close to the gauge. Larger gauges could be used to reduce the scatter in the measurements. Also, the strain gauges were bonded to the material after the initial cure or postcure and the measurements were made during the first thermal cycle. It is normal practice to carry out at least three thermal cycles prior to making the measurements to eliminate hysteresis, but this was not possible because the initial behaviour of the unstable material, (before postcure) could not be observed. Continuous monitoring of the data has proved invaluable in this case in understanding the behaviour of the material.

4.5 Other Polymer Composites

A variety of other polymer composites have been tested (5) to develop a database of polymer properties for modelling predictions. Table 5 gives experimental values and theoretical predictions for the materials examined. The CTE measurements were made using the strain gauge technique, using "step" heating up to 200 °C, and the values presented are average values calculated from room temperature to 200 °C. Generally the results are in reasonable agreement with the predicted values. However, for tests on anisotropic materials such as fibre reinforced composites, it is possible and preferable to correct the raw strain data for transverse sensitivity effects, and this will improve the accuracy of the measurements. Transverse sensitivity varies with the individual material and the strain gauge type. In this work the data has not been corrected, but the appropriate equations and details on the corrections are presented in Ref. 1.

5. SUMMARY

The strain gauge technique has been used successfully to monitor dimensional change and thermal expansion behaviour in 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. Some of the practical issues have been covered but further work is still required before a standard test method can be issued.

At this stage it is difficult to comment on the absolute accuracy of the measurements and 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%. For future work, a well characterised material could be used to develop an uncertainty budget for the technique and a systematic assessment of the errors involved in the CTE measurement. Data could be compared with dilatometry.

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. For the greatest accuracy "step" heating is preferable, but the continuous heating cycle combined with continuous monitoring of the data can provide additional information on the behaviour of the material. In this work a heating rate of 3°C/min is the recommended maximum heating rate.

ACKNOWLEDGEMENTS

This work was supported by the MTS Programme on Advanced Materials, a programme of underpinning materials measurement research financed by the EAM Directorate, UK Department of Trade and Industry.

REFERENCES

- 1 Measurements Group Tech. Note TN-513-1 *Measurement of Thermal Expansion Coefficient using Strain Gauges*.
- 2 Poore, MW and Kesterson, KF. *Measuring the Thermal Expansion of Solids with Strain Gauges*, JTEVA, Vol. 6, No.2, March 1978.
- 3 The Institute for Interconnecting and Packaging Electronic Circuits. *IPC-TM-650 Test Method (Proposal) - Coefficient of Thermal Expansion - Strain Gauge method*
- 4 Corning Glass Works. *Materials for the Design Engineer. Properties of Corning's Glass and Glass Ceramic Families*.
- 5 Broughton, WR and Cooper, D. NPL Report. To be published June 1997.

Temperature Interval (°C)	6061 Aluminium (x 10 ⁻⁶ /°C)	Copper (x 10 ⁻⁶ /°C)
25-50	23.0	16.8
50-100	23.2	16.6
100-150	23.9	17.1
150-200	25.4	17.8
25-100	23.4	16.6
25-200	24.1	17.1

(Typical handbook values for aluminium and copper are 23 and 17 x 10⁻⁶/°C respectively)

Table 1: Values for CTE for aluminium and copper calculated from the validation exercise

Reference Material	7971 ULE Titanium Silicate Glass
Calibration and Validation	6061 Aluminium Copper
Metal Matrix Composites	MMC1: 2124 + 25% SiC MMC2: 6061 + 20% Al ₂ O ₃
Polymer Composites	Unidirectional Carbon fibre/epoxy Random glass fibre/polyester Woven carbon fibre/resin

Table.2: Details of the materials tested

MMC1 : 2124 Al + 25% SiC			
Temperature Interval (°C)	Specimen 1 Dilatometer	Specimen 2 Dilatometer	Strain Gauge
25-50	12.3	12.5	15.1
50-100	17.3	17.2	15.7
100-150	17.0	16.9	16.4
150-200	17.3	17.5	17.2
200-250	17.0	17.8	17.5
25-100	15.6	15.6	15.5
25-200	16.5	16.5	16.1

Table 3a: Comparison of CTE values ($\times 10^{-6}/^{\circ}\text{C}$) for MMC1 using Dilatometry and Strain Gauge

MMC2 : 6061 Al + 20% Al_2O_3			
Temperature Interval (°C)	Specimen 1 Dilatometer	Specimen 2 Dilatometer	Strain Gauge
25-50	14.9	12.9	15.6
50-100	17.6	19.2	17.9
100-150	19.1	19.6	18.5
150-200	19.9	20.5	19.4
200-250	21.2	21.6	19.3
25-100	16.7	17.1	17.5
25-200	18.3	18.8	18.3

Table 3b: Comparison of CTE values ($\times 10^{-6}/^{\circ}\text{C}$) for MMC2 using Dilatometry and Strain Gauge

Material		Temperature Interval							
			25-50	50-75	75-100	100-125	125-150	150-175	175-195
FKM	cycle 1	heat	3.0	2.9	-5.2	1.0	0.4	0.7	4.8
		cool	3.0	2.5	2.4	2.7	3.0	2.9	1.1
	cycle 2	heat	1.9	2.3	2.4	2.2	2.8	3.2	4.1
		cool	2.8	2.4	2.7	2.7	2.8	2.6	1.6
FKP	cycle 1	heat	2.8	2.3	2.3	2.9	3.3	3.0	2.3
		cool	2.9	2.9	3.1	3.1	3.2	2.8	1.0
	cycle 2	heat	2.5	3.0	3.2	3.2	3.4	3.1	3.2
		cool	3.9	3.1	3.1	3.1	3.2	2.9	1.2

Table 4: CTE values ($\times 10^{-6}/^{\circ}\text{C}$) for woven carbon fibre/epoxy composites

Material	CTE ($\times 10^{-6}/^{\circ}\text{C}$)	
	Measured	Theory
Continuous random glass fibre mat/polypropylene (30%)	31.3	37.1
Continuous random glass fibre mat/polypropylene (40%)	20.6	24.2
Aligned carbon fibre/epoxy (L)	-0.1	-0.2
Aligned carbon fibre/epoxy (T)	36.0	34.0
Aligned glass fibre/epoxy (L)	6.6	6.5
Aligned glass fibre/epoxy (T)	21.0	28.9
Discontinuous glass fibre/nylon 66 - as received (T)	58.1	-
Discontinuous glass fibre/nylon 66 - dry (T)	81.0	93.3
Discontinuous glass fibre/nylon 66 - dry (L)	23.3	30.9
Sheet Moulding Compound	20.8	-
Pultruded glass fibre/polyester	37.2	-
Chopped Strand Mat	28.9	27.6
3/1 twill glass fibre woven fabric/vinyl ester	17.1	-
2/2 twill glass fibre woven fabric/polypropylene	20.1	22.2
2/2 twill glass fibre woven fabric/epoxy	14.5	16.3
Plain glass fibre woven fabric/epoxy	14.4	18.2

Table 5: CTE values for a number of polymer composites (Ref. 5)

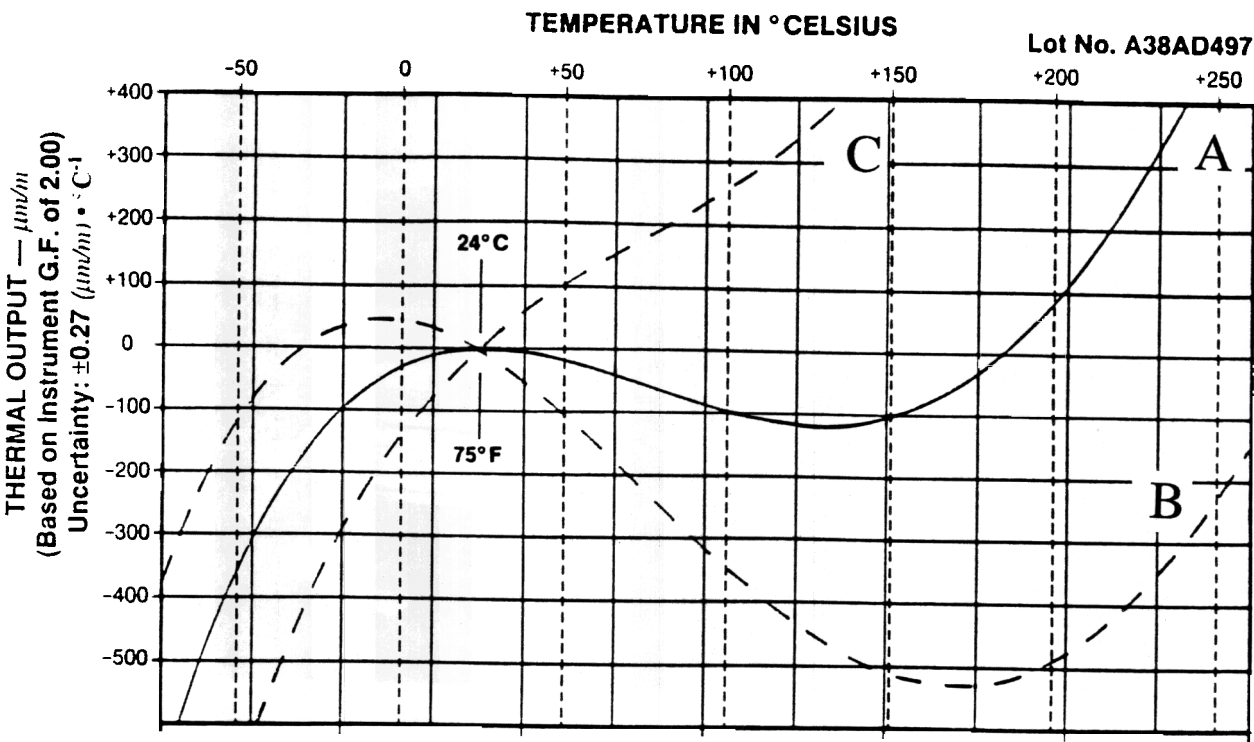


Figure 1: Thermal output characteristics of a strain gauge (Ref 1)

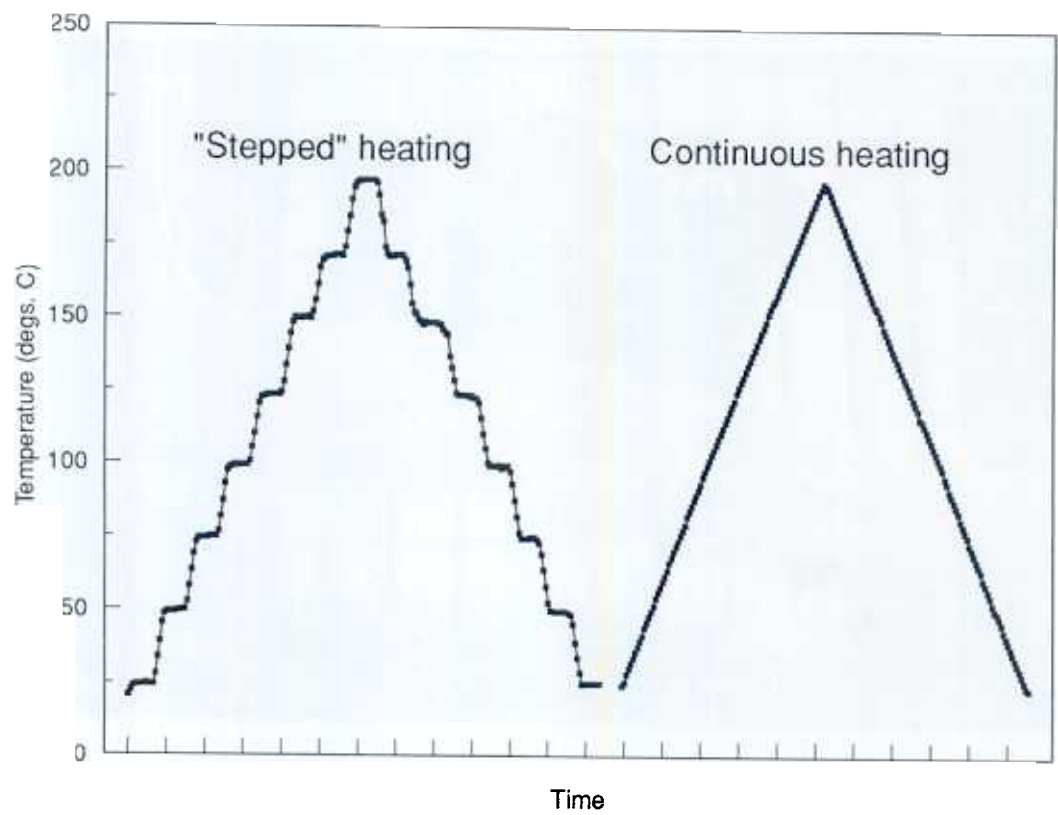


Figure 2 : Typical thermal profiles used in the strain gauge tests



Figure 3: Thermal expansion equipment

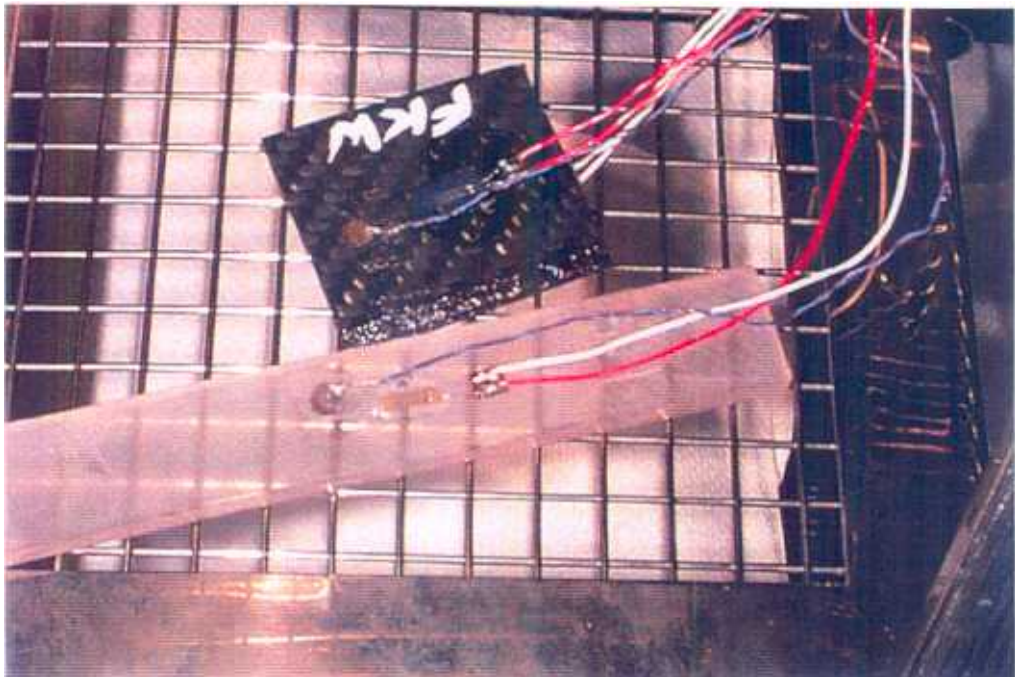


Figure 4 : Typical strain gauge installation

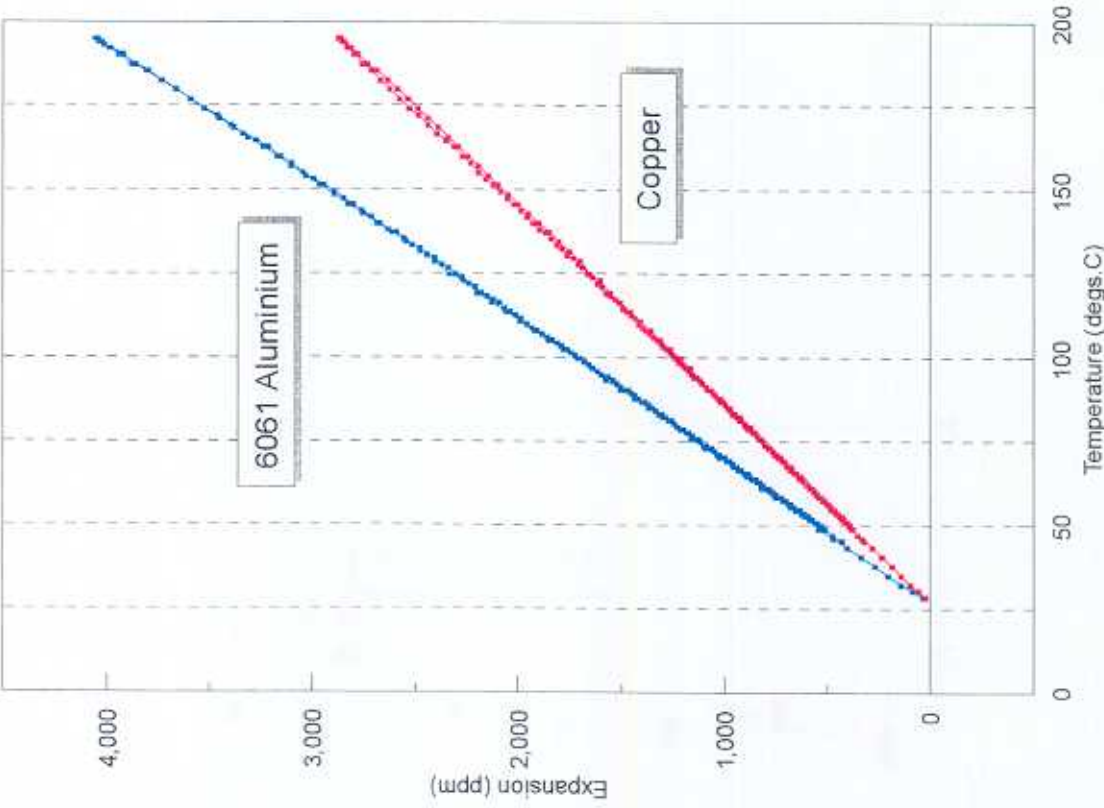


Figure 6 : Thermal expansion behaviour of the aluminium and copper specimens

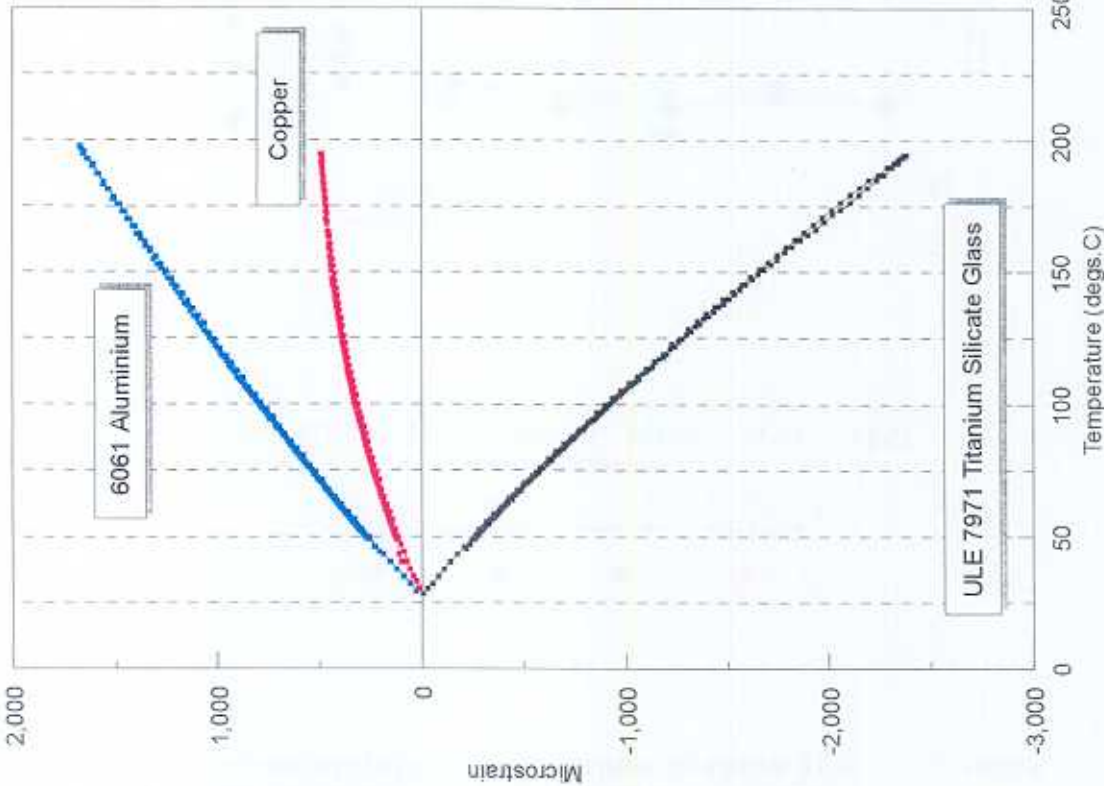


Figure 5 : Validation data from the aluminium and copper specimens.

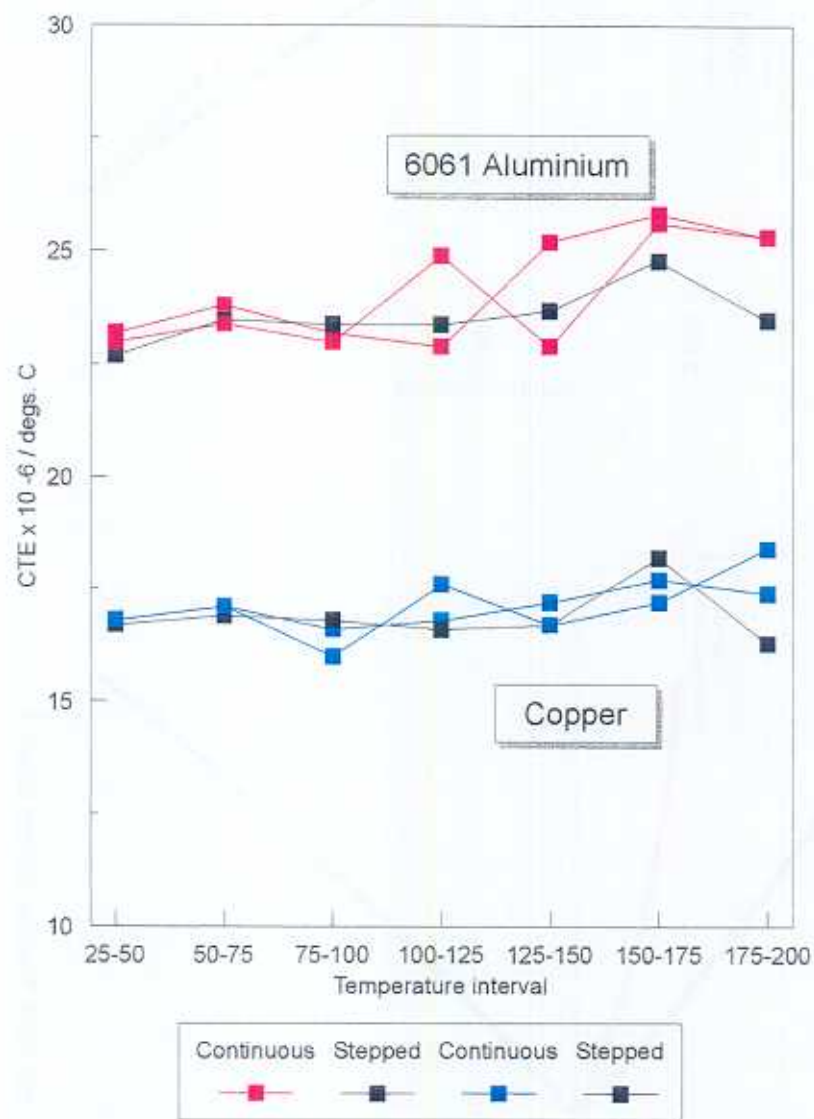


Figure 7: CTE values for aluminium and copper specimens - comparison of “Stepped” and continuous heating tests

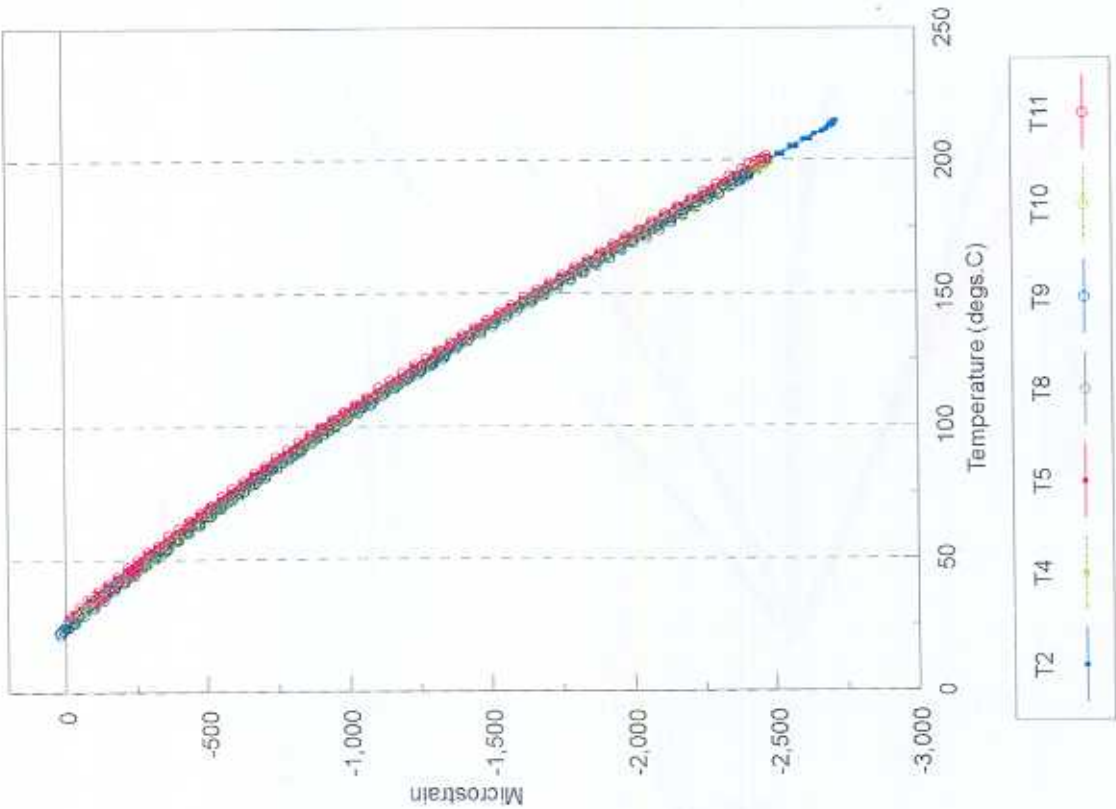


Figure 9 : ULE 7971 Titanium silicate glass
- Comparison of 7 separate tests

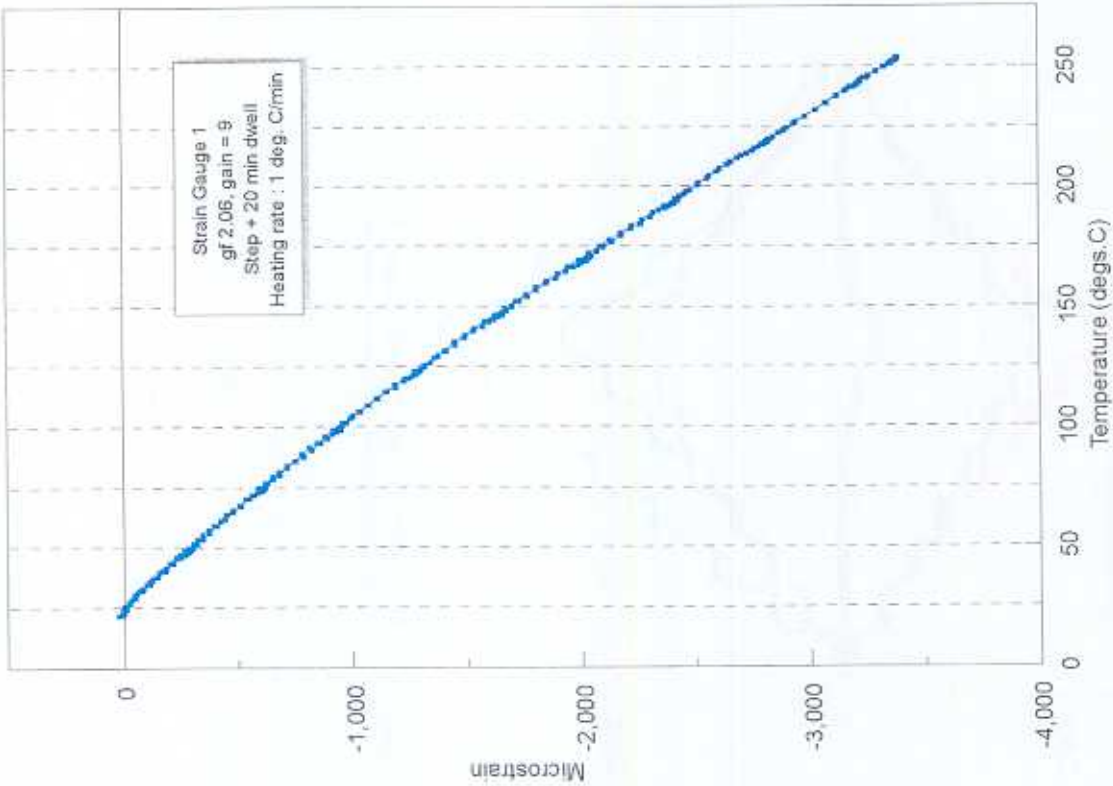
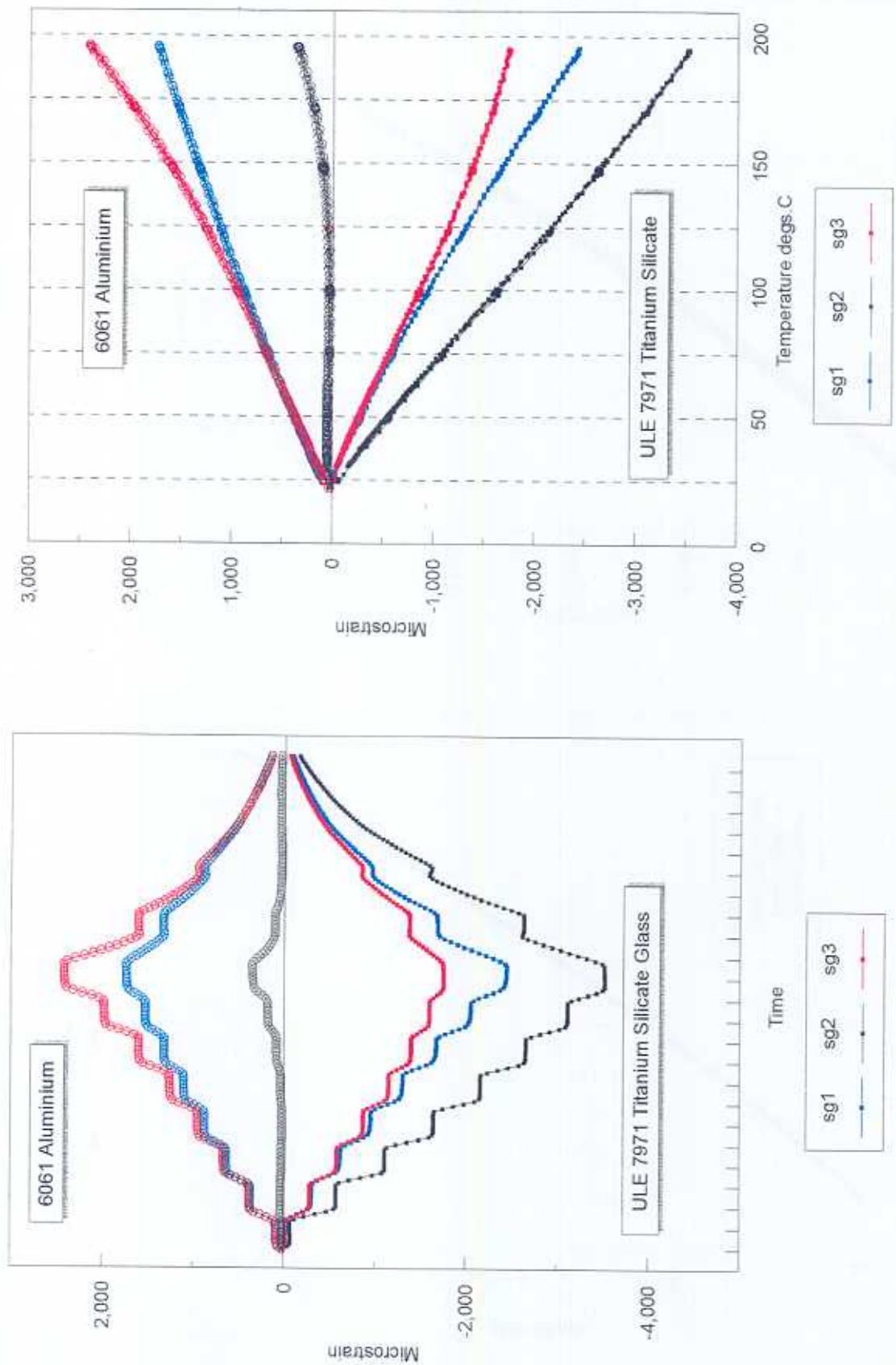


Figure 8 : ULE 7971 Titanium silicate glass
- Calibration curve for Strain Gauge 1



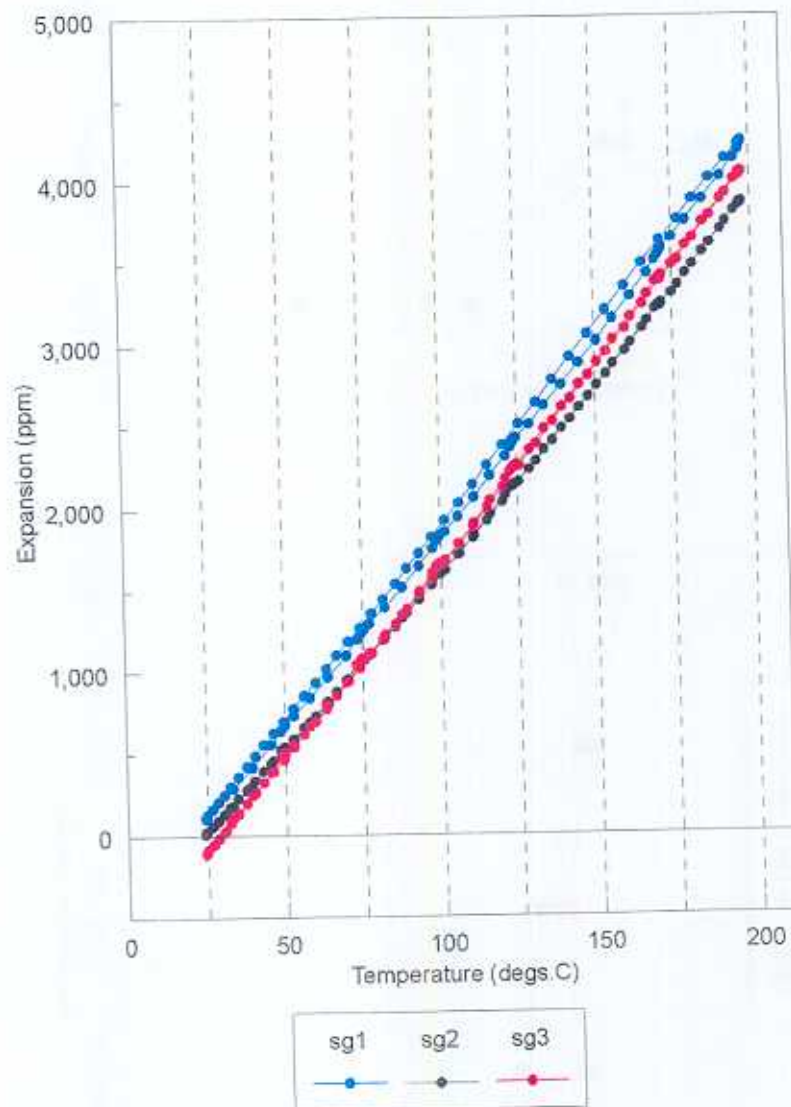


Figure 12: Thermal expansion behaviour for the aluminium specimen
- comparison of 3 different strain gauges

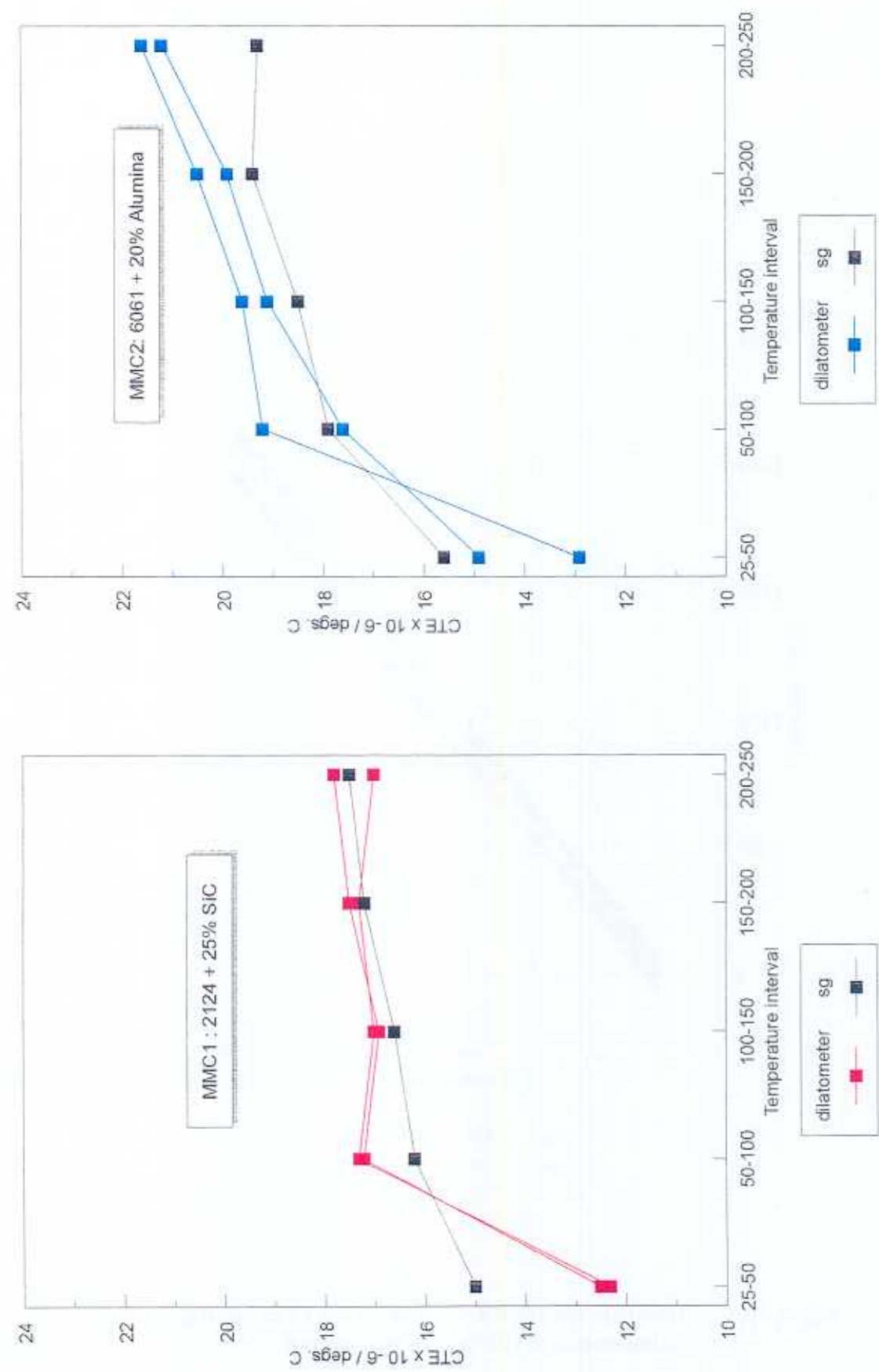


Figure 13: CTE values for MMC1 (2124 + 25% SiC)
- comparison of strain gauges & dilatometry

Figure 14: CTE values for MMC2 (6061 + 20% Alumina)
- comparison of strain gauges & dilatometry

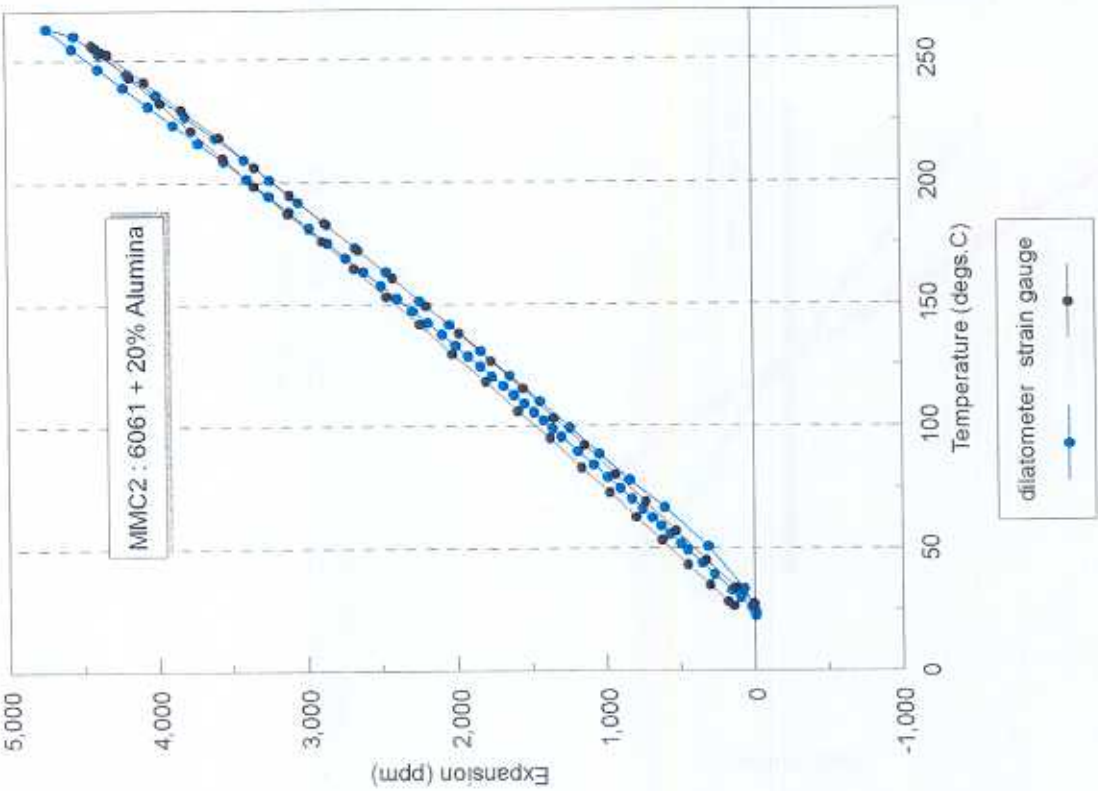


Figure 16: Thermal expansion behaviour of MMC2
- comparison of strain gauges & dilatometry

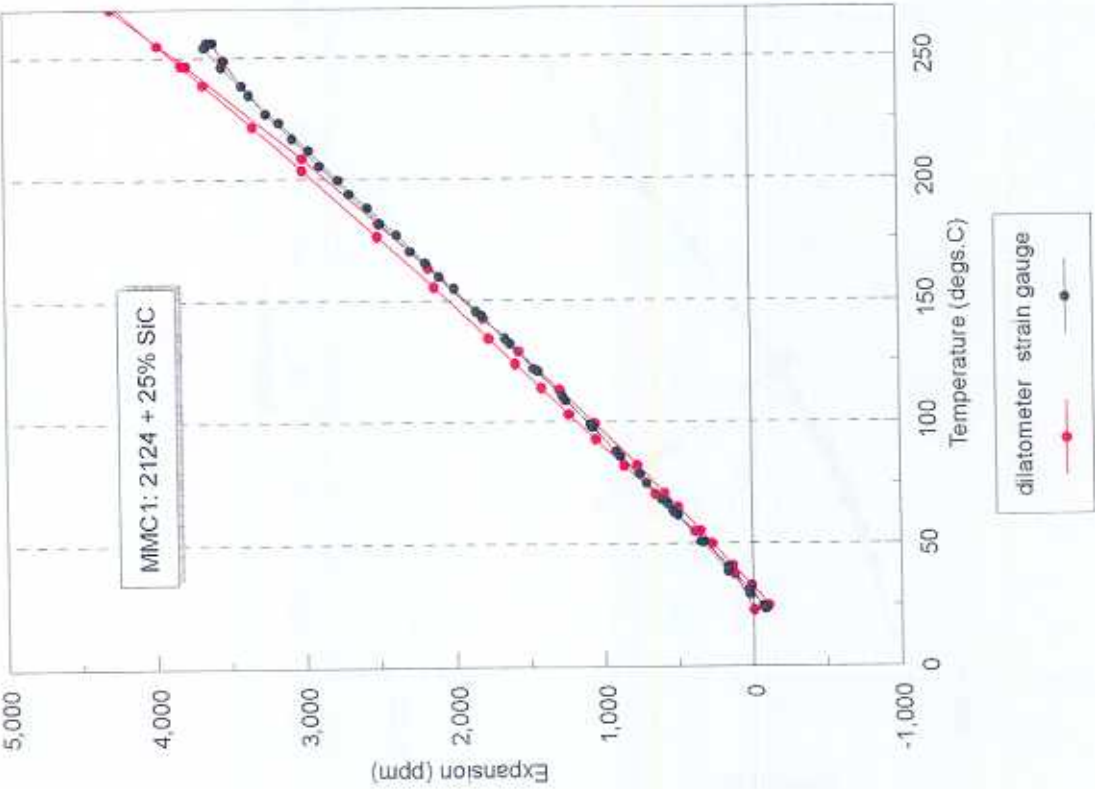


Figure 15: Thermal expansion behaviour of MMC1
- comparison of strain gauges & dilatometry

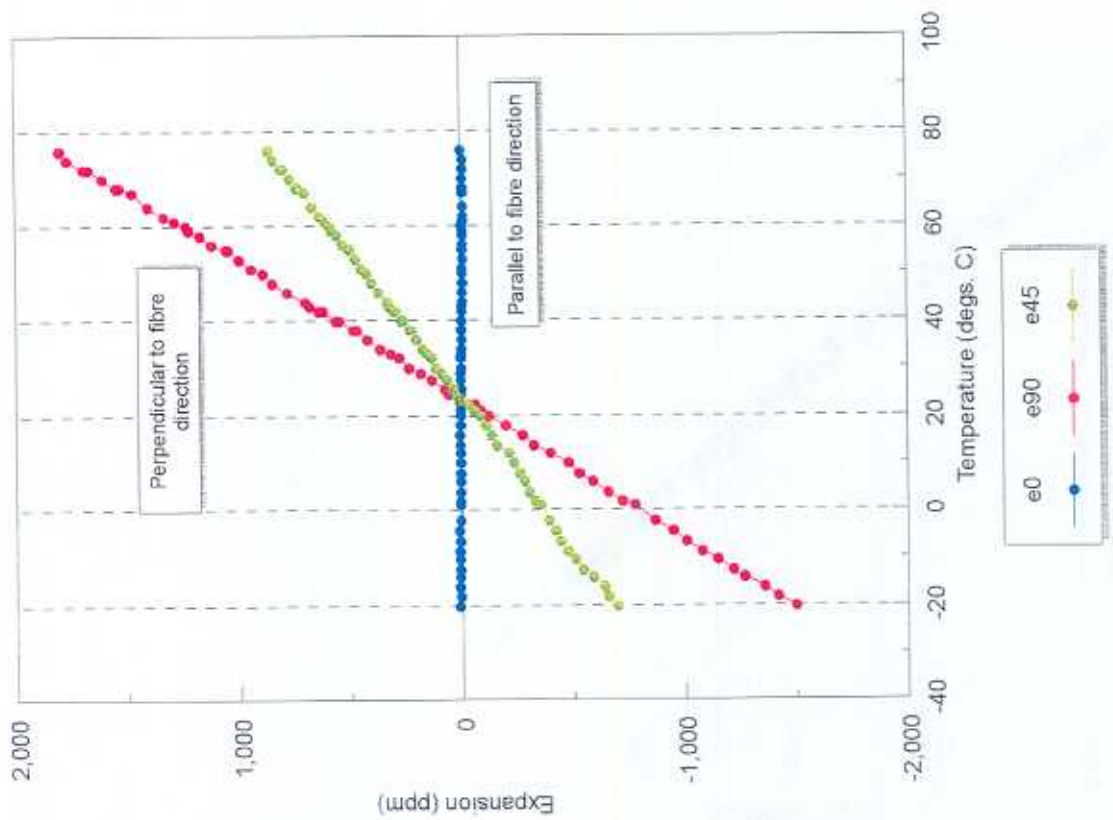


Figure 18 : Thermal expansion behaviour of UD carbon fibre/ epoxy composite

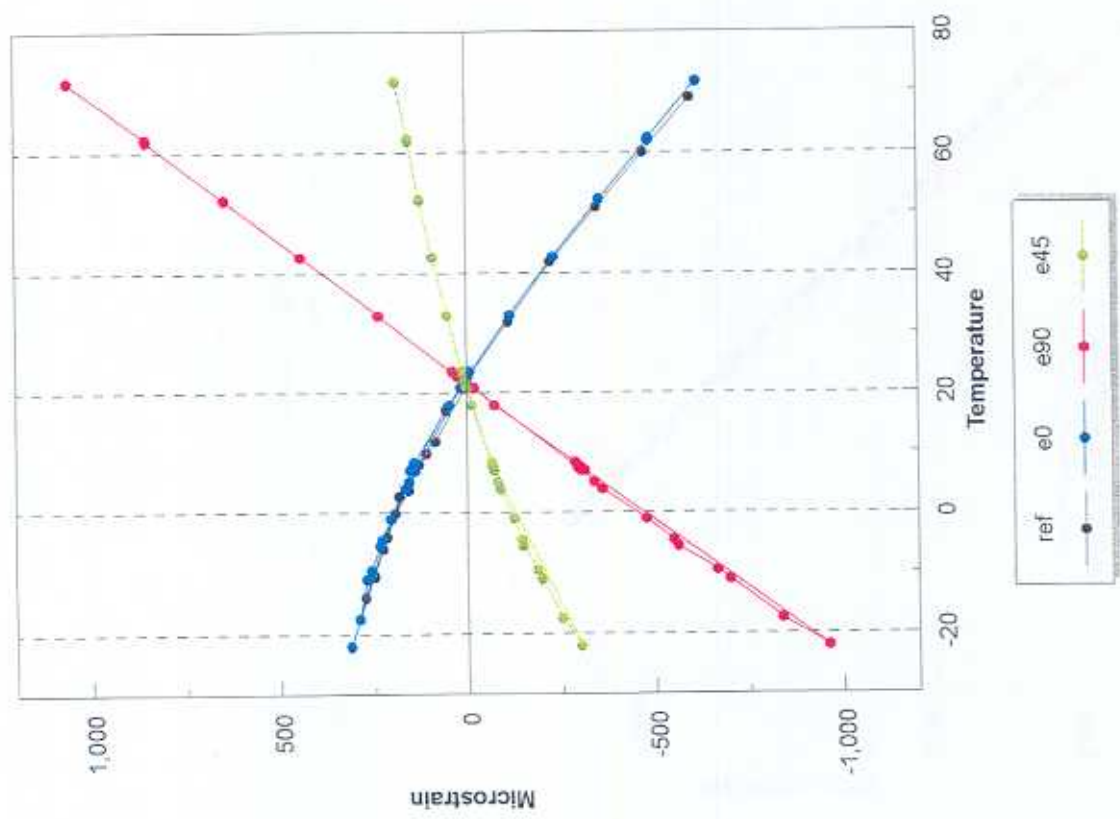


Figure 17 : Raw strain gauge data for reference material and UD carbon fibre/epoxy composite

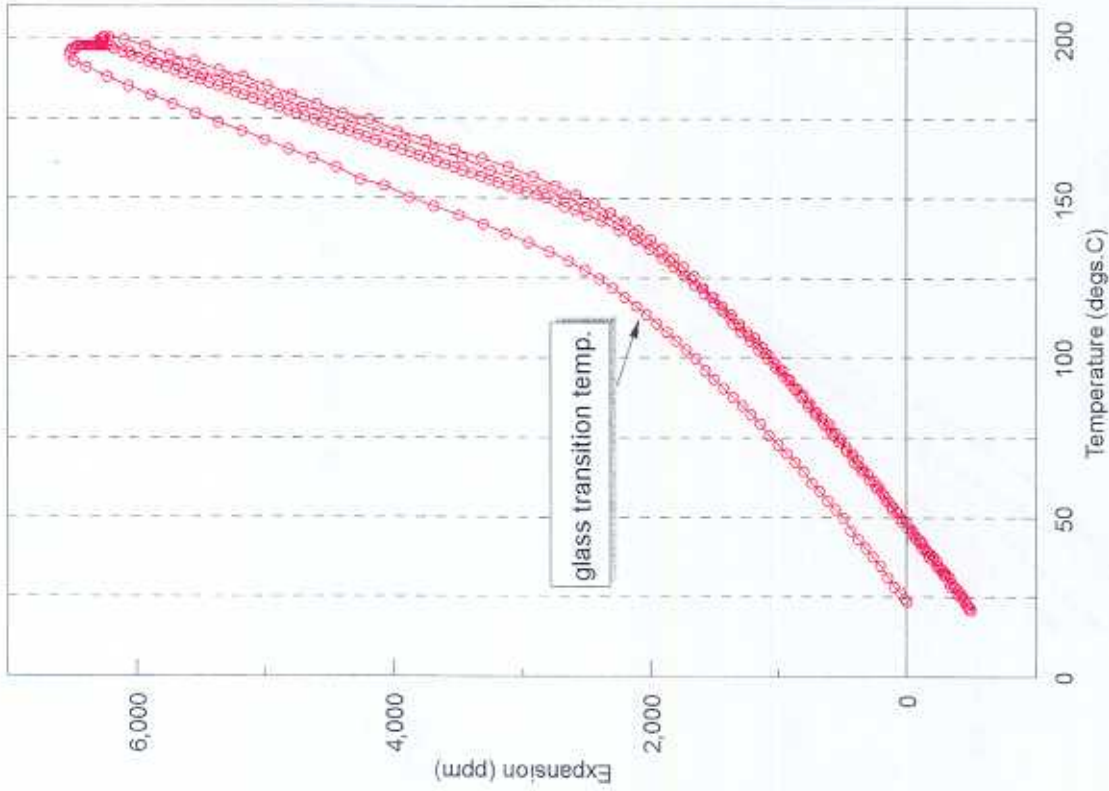


Figure 20 : Thermal expansion behaviour of glass fibre/polyester composite

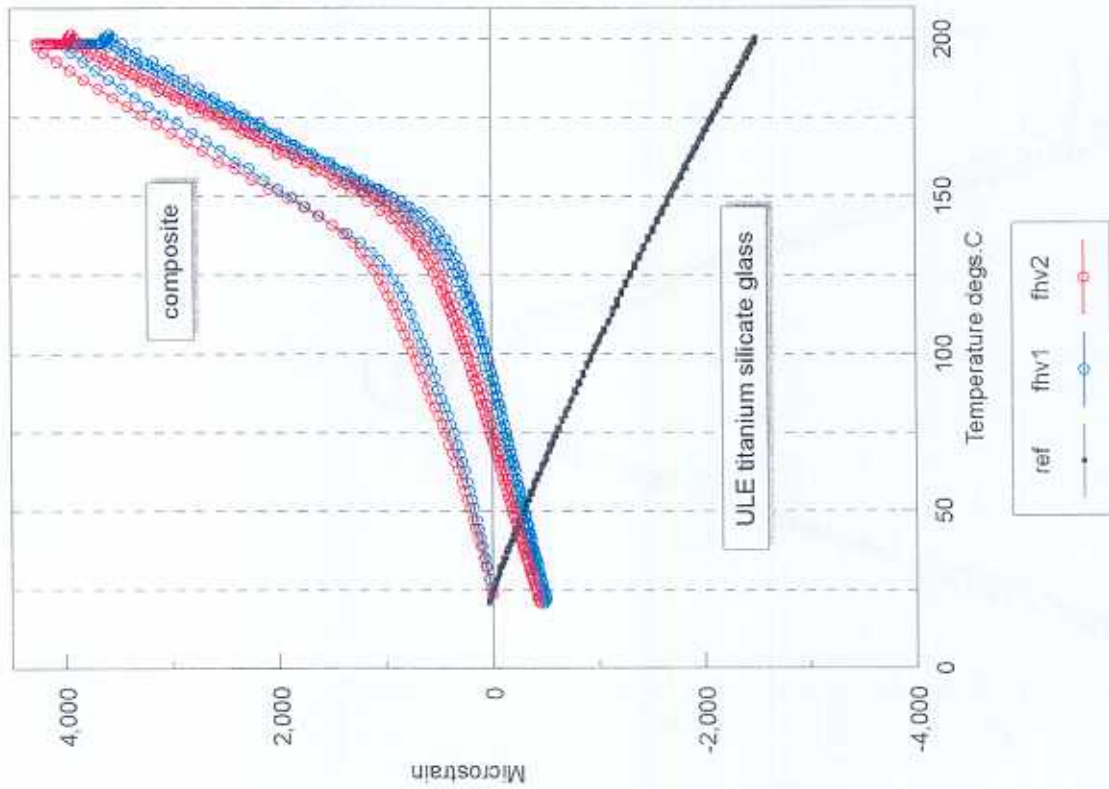


Figure 19 : Raw strain data for reference material and glass fibre/polyester composite

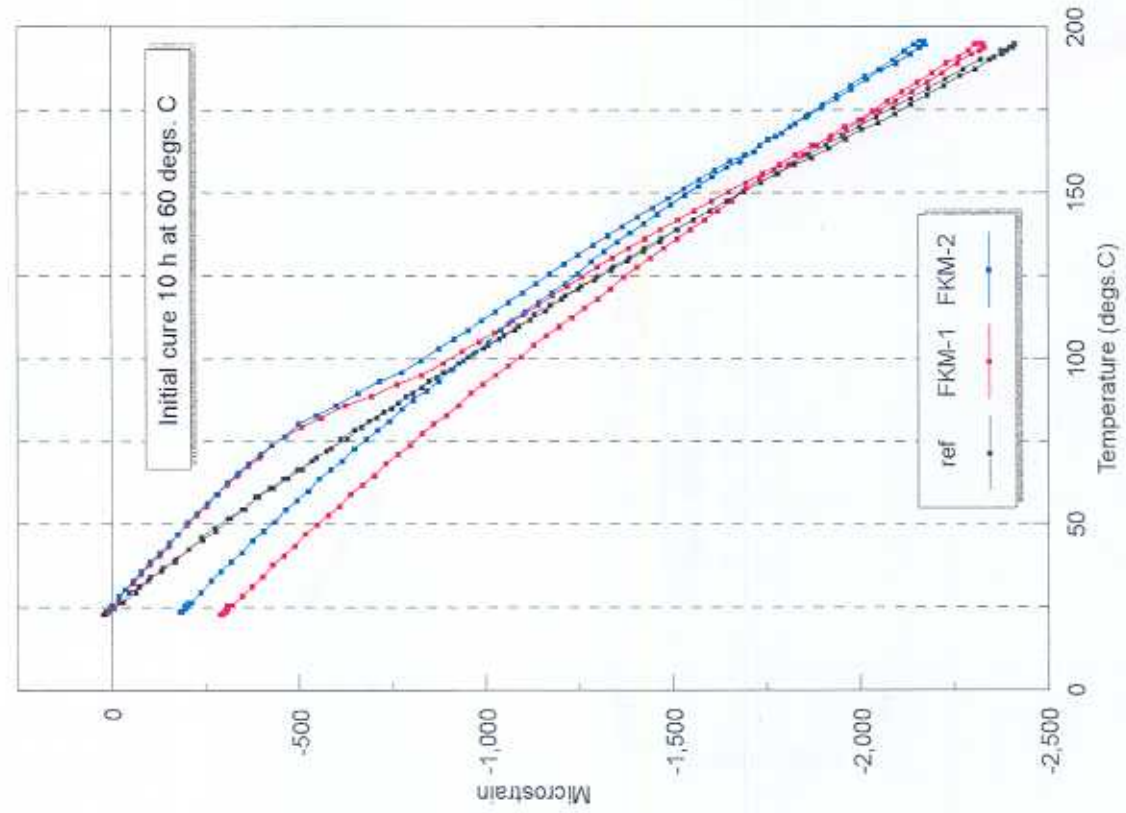


Figure 22 : Strain data plotted against temperature - reference material and woven composite

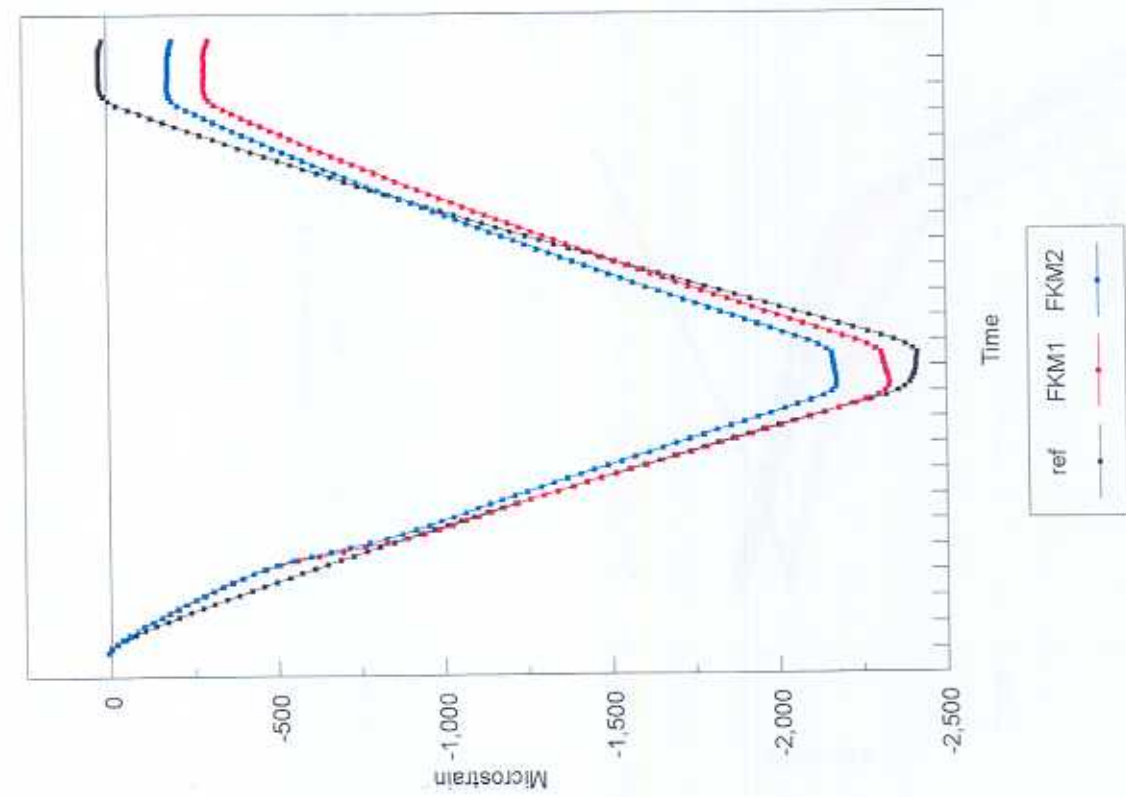


Figure 21 : Raw strain data for reference material and woven composite

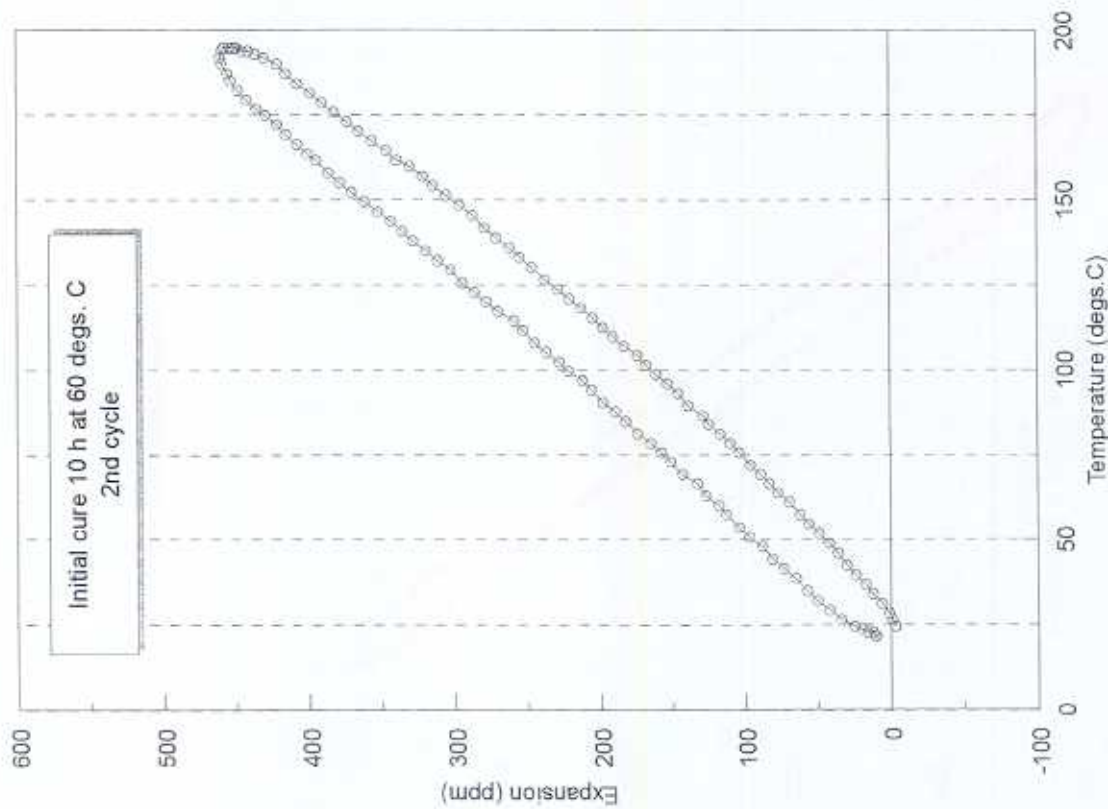


Figure 24 : Thermal expansion behaviour of the woven composite - initial cure only, 2nd cycle

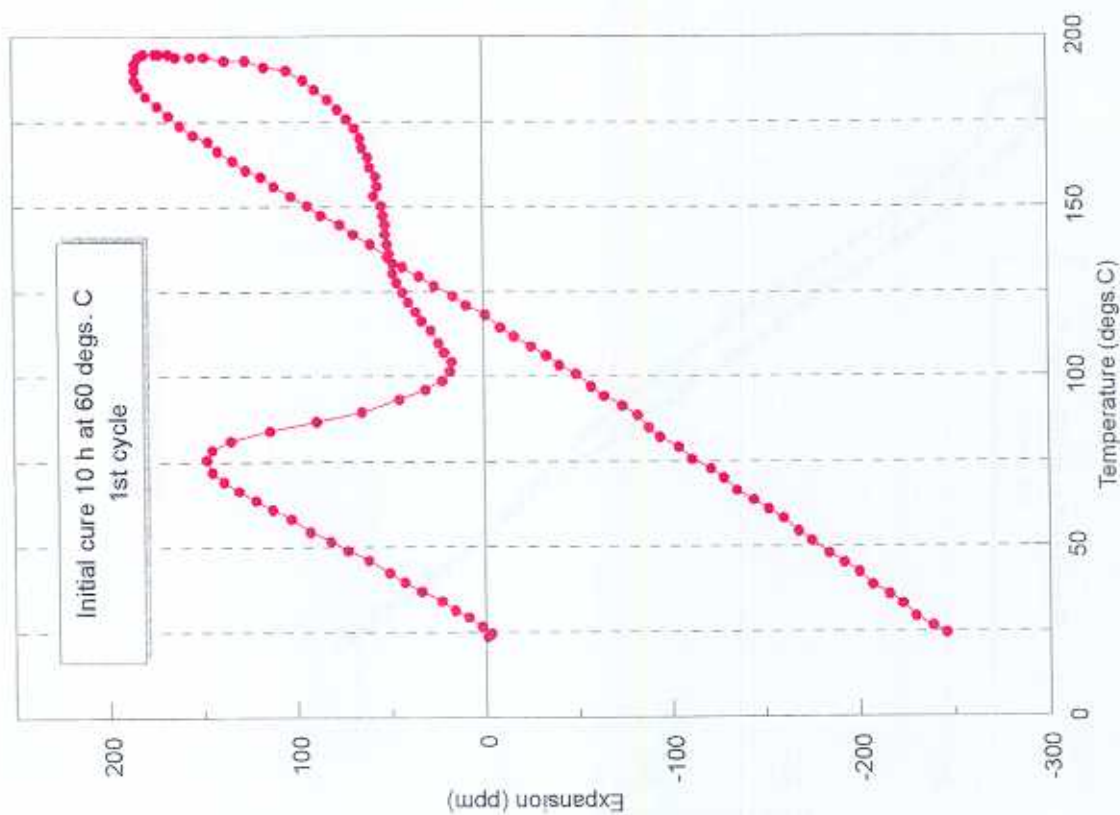


Figure 23 : Thermal expansion behaviour of the woven composite - initial cure only, 1st cycle

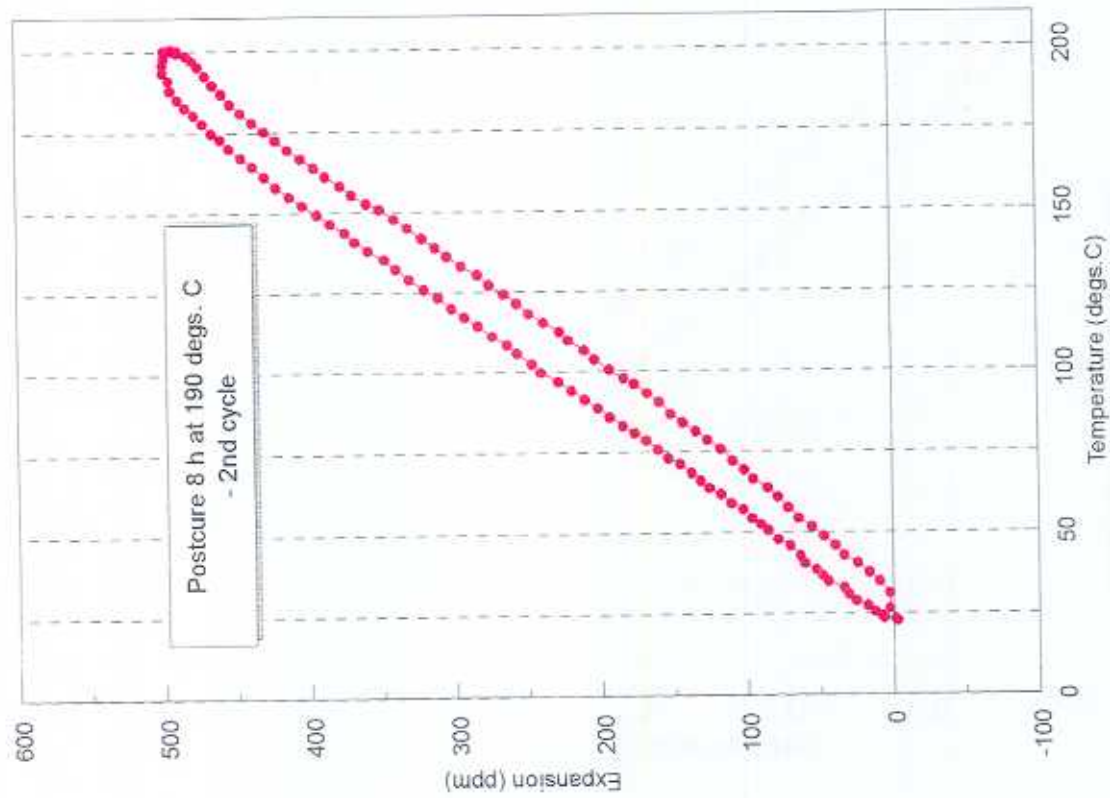


Figure 25 : Thermal expansion behaviour of the woven composite - postcured, 1st cycle

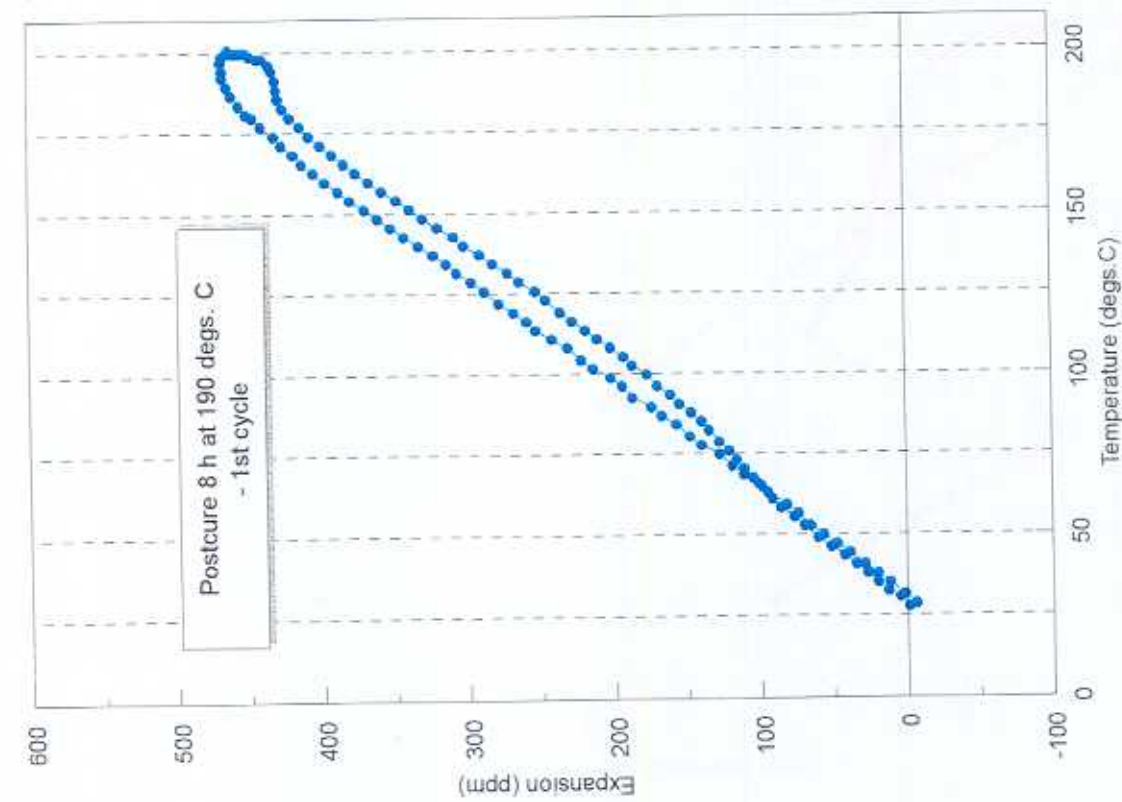


Figure 26 : Thermal expansion behaviour of the woven composite - postcured, 2nd cycle

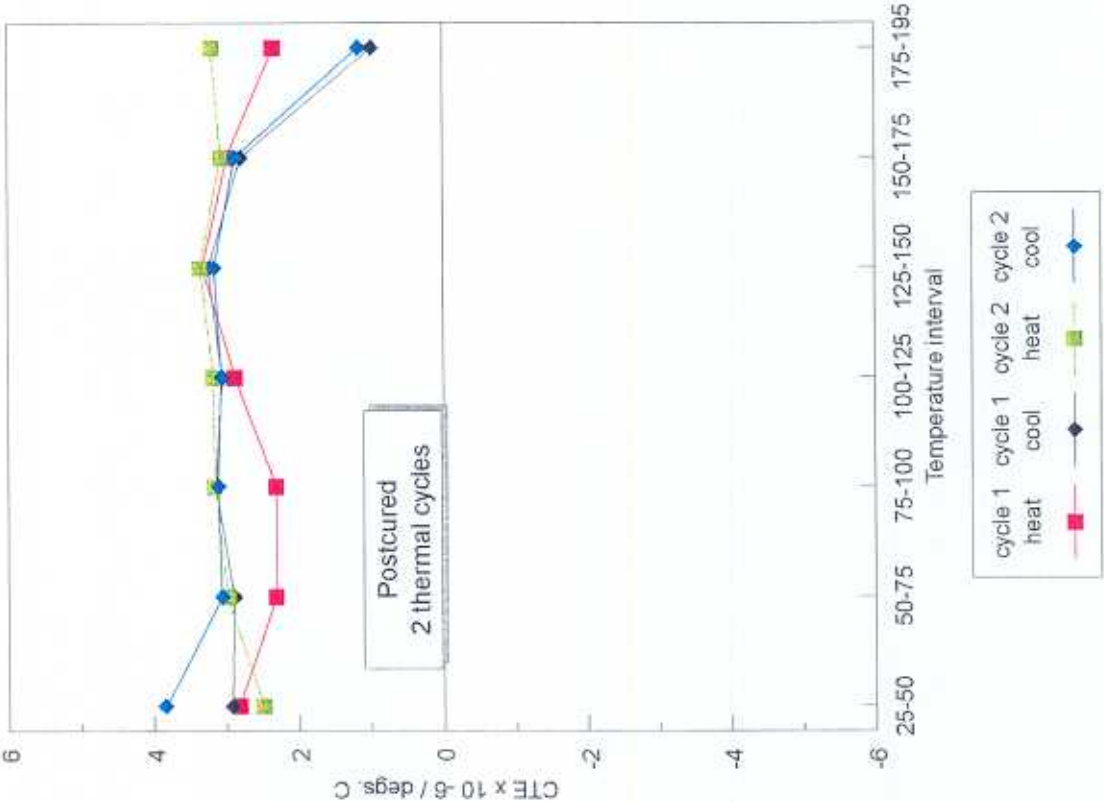


Figure 28 : CTE values for postcured woven composite

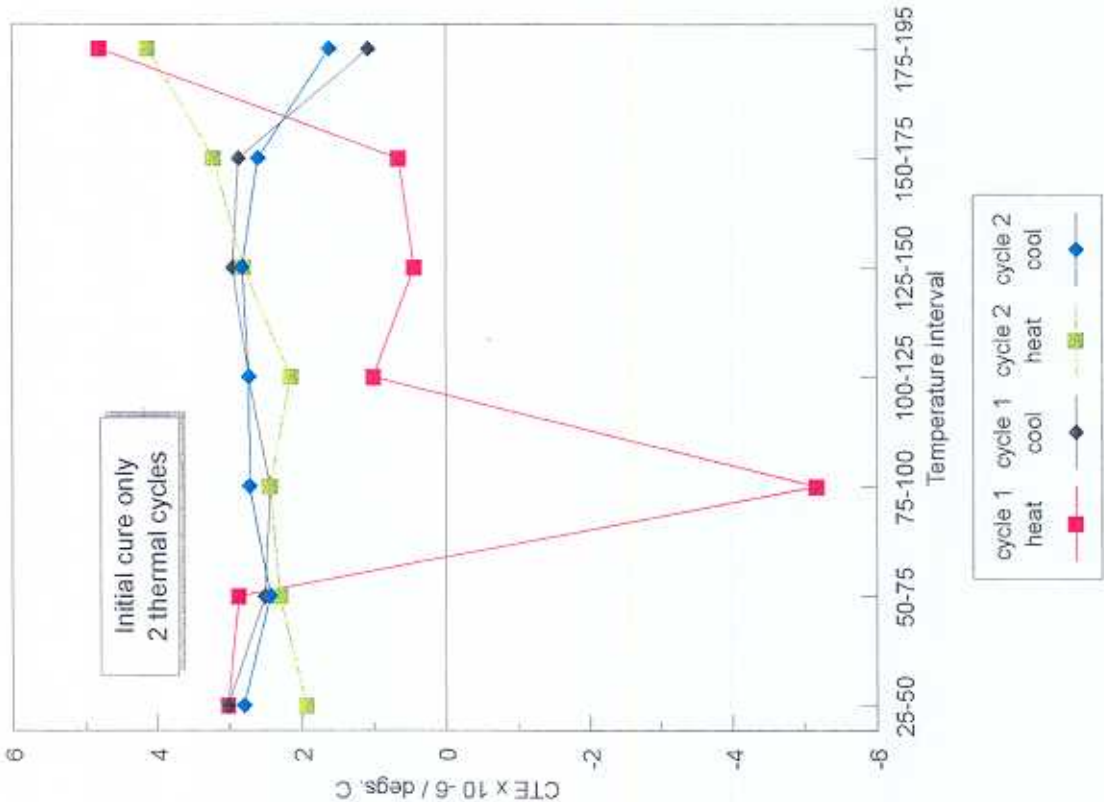


Figure 27 : CTE values for woven composite with initial cure only