Final Report

for

COMPOTOOL LTD

THERMAL EXPANSION MEASUREMENTS OF CT850 TOOLING BOARD SPECIMENS

July 30, 2014

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PURCHASE ORDER NUMBER PO-0012

TESTING SERVICES PROVIDED BY
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THERMAL EXPANSION MEASUREMENTS OF CT850 TOOLING BOARD SPECIMENS

WORK CONDUCTED FOR COMPOTOOL LTD
PURCHASE ORDER NUMBER PO-0012

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Precision Measurements and Instruments Corporation determined the coefficient of thermal expansion of CT 850 Tooling Board test specimens. Measurements were made with a Michelson laser interferometer measurement system (ASTM E 289 - 04) performed under vacuum. Results are presented in the table and the following graphs. Michelson laser interferometry measurement techniques are described in the enclosed document, “PMIC Michelson Laser Interferometer.” A brief description of the test procedure, data analysis and comments on the results follow.

Specimen Description

CompoTool Ltd provided the test specimens as listed below:

Specimen ID	Description	Length	Width	Thickness
1	CT850 Tooling Board	~101.6mm	~1016mm	~50.8mm
2	CT850 Tooling Board	~101.6mm	~50.8mm	~50.8mm

The specimens were measured in the length direction.

Test Procedure

¨ Specimen Check-In

The specimens were hand delivered at the SAMPE Seattle show. The specimens were inspected for damage. No specimen damage was observed. The specimens were stored in a secure environment. After selecting and cutting the test specimens and prior to measurement, the specimens were placed in a 60ºC vacuum oven.

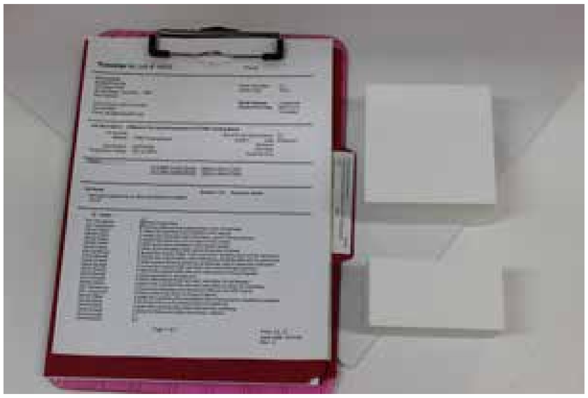


Figure 1, specimens as received.

¨ Specimen Set-up

Vertical, Three Piece Method: Vertical, Three Piece: A group of three specimens were placed on fused silica chips that were positioned every 120 degrees within a 3” circle on a silica support plate (see figures 2 and 3). Thermocouples were attached to the specimens and/or support plate. A mirror was positioned to be in the same plane as the bottom of the specimens. Three more fused silica chips were placed on top of the specimens with a mirror place on top of the chips. The laser interferometer was aligned to follow the distance change between the upper and lower mirrors. At the end of the testing any errors from extra fused silica in the measurement path were removed from the measurements. The chamber was evacuated to below 200 mTorr. Specimens were heated to 300^{o}C and held until their length was stable.

Figure 2, test setup with top mirror removed.

Figure 3, Specimen group installed in a vertical interferometer.

¨ CTE Measurements

Length change measurements were taken as the specimen temperature was cycled between 300°C and 23°C for at least 1 full temperature cycle. Specimen length change and temperature were continuously recorded during the tests.

Thermal Expansion Test Results

The results are presented in the table and graphs of microstrain vs. temperature. The CTE and estimated uncertainty values shown on the table and graphs were calculated over the full temperature range. The CTE values were first calculated by a least squares regression analysis and then reported as the slope of the chord evaluated at the temperature extremes.

Microstrain is calculated as follows:

$$\Delta L = \frac{N\lambda}{2L_0}$$

Where,

N is the total number of fringes that are measured while changing the temperature from $\mathbf{T_1}$ to $\mathbf{T_2}$

λ is the wavelength of the laser light used to produce the fringes (24.912 micro-inches for a He-Ne laser)

$\mathbf{L_0}$ is the initial specimen length

CTE is calculated by dividing the measured microstrain by the temperature range over which it was recorded.

$$\alpha = \frac{\Delta L}{\Delta T}$$

The reported CTE measurement description and the initial specimen length (L_0) are listed in the lower left-hand corner of each graph.

Measurement Uncertainty

The uncertainties associated with temperature, fringe spacing and initial specimen length measurement can be combined and expressed as a total uncertainty $\mathbf{E_\alpha}$.

$$E_\alpha = \alpha\sqrt{\left(\frac{E_L}{\Delta L}\right)^2 + \left(\frac{E_T}{\Delta T}\right)^2 + \left(\frac{E_{L_0}}{L_0}\right)^2}$$

Where,

$\boldsymbol{\alpha}$ is the calculated CTE over the whole temperature range.

$\mathbf{E_T}$ is the uncertainty in the absolute temperature measurement over $\Delta\mathbf{T}$

$\mathbf{E_{\Delta L}}$ is the uncertainty in the fringe spacing that is measured between temperatures $\mathbf{T_1}$ and $\mathbf{T_2}$

$\mathbf{E_{Lo}}$ is the uncertainty in the measured initial specimen length

Observations

No out of plane motion was observed for the reported data. Dwell periods of at least 20 minutes are used to eliminate and reverse the gradients in the specimen, thus fixing two points on the curve at which there is no error due to thermal gradients. The secant fit used to calculate the CTE value uses only the two end points where the thermal gradients are minimized.

Please contact our technical staff at (541) 753-0607 if you have any questions or require any additional information regarding these measurements.

Contents:
- 1 table of average CTE values
- 2 graphs of microstrain and CTE versus temperature
- 1 composite graph of microstrain versus temperature
- "PMIC Michelson Laser Interferometer" supplemental procedures

Submitted by:

Darrell Oakes Primary Project Engineer/Laboratory Manager	Eric Henthorne Secondary Project Engineer	David Stumpff Test Technician

Precision Measurements and Instruments Corporation hereby claims that test results are obtained by techniques based on relevant ASTM standards, calibrations with NIST standard reference materials and/or published procedures. Thus, we accept no liability for test results beyond the cost of the contract rendered.

Quality Statement:

At PMIC, our policy is to consistently provide the maximum possible accuracy and reliability for materials properties test data, as requested by our customers. This level of quality is achieved through the adoption of a Quality Management System that reflects the competence of PMIC to existing customers, potential customers and independent auditing authorities.

TEST RESULTS - TABLE OF CTE VALUES

Contract:	**14525**	**Status:**	**Final**
Customer:	**CompoTool Ltd**	**Version:**	**29.07.14.A**
Material:	**CT850 Tooling Board**	**Revised:**	**29-Jul-14**

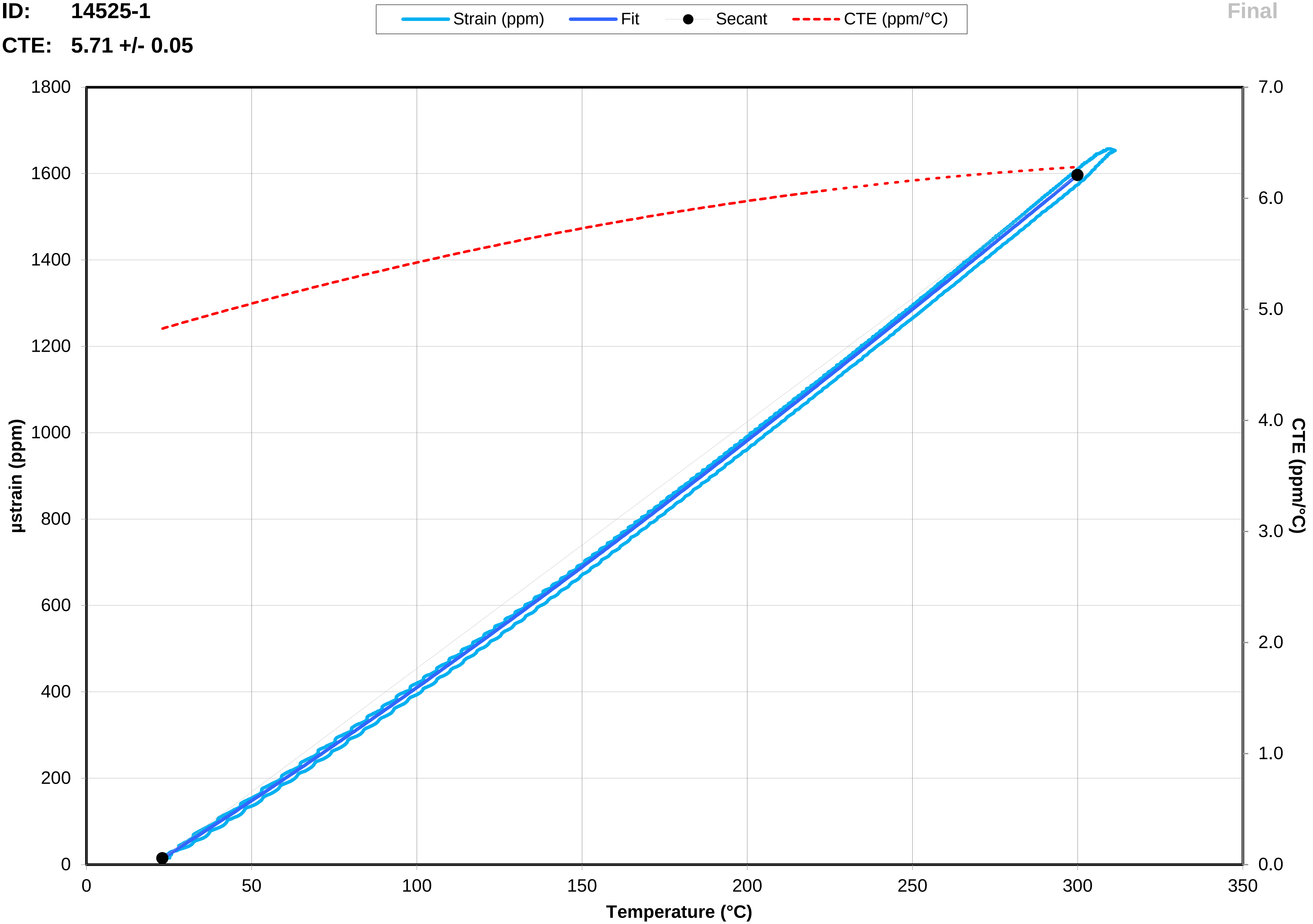
PMIC ID	Specimen Description	Measurement Direction		Temperature (°C)		Strain (ppm)		Avg. CTE (ppm/°C)	Cycle #
		(units = inches)		T1	T2	S1	S2	T1:T2	
14525-1	CT850 Tooling Board	Length	0.975	23.00	300.00	14.44	1596.59	5.71 +/- 0.05	4
14525-2	CT850 Tooling Board	Length	0.946	23.00	300.00	14.52	1622.92	5.81 +/- 0.05	2

1) The reported average CTE is calculated as an average slope of the polynomial regression evaluated over the temperature range.
2) The expanded measurement uncertainty (±U) is calculated for the full temperature range.
3) Measurements performed by PMIC in a Michelson interferometer in vacuum according to ASTM E289-04

ID: **14525-1**

CTE: **5.71 +/- 0.05**

Final

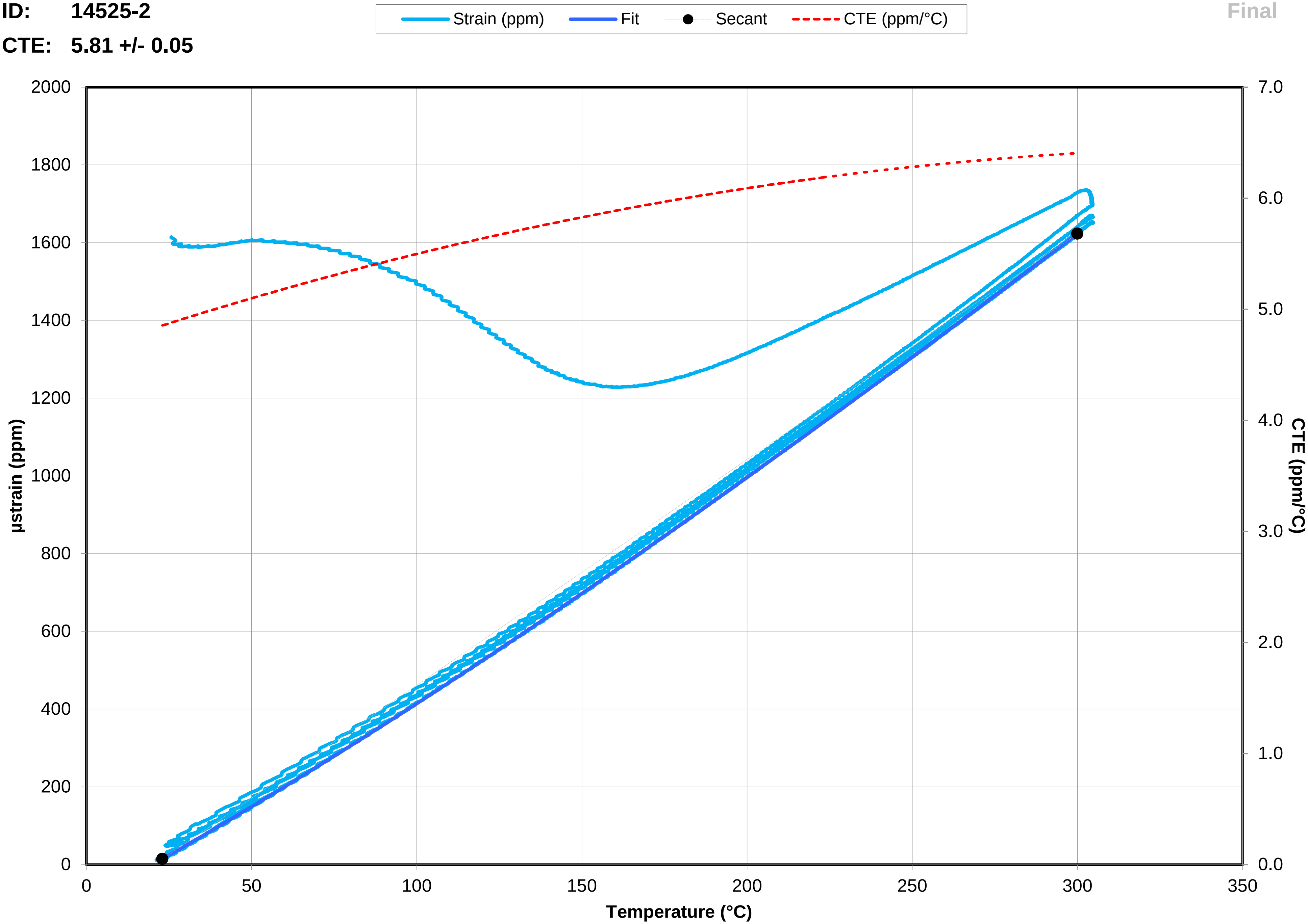


0.975 **14525-1ABC-b** **CTE_4A** **22-Jul-14**

ID: 14525-2

CTE: 5.81 +/- 0.05

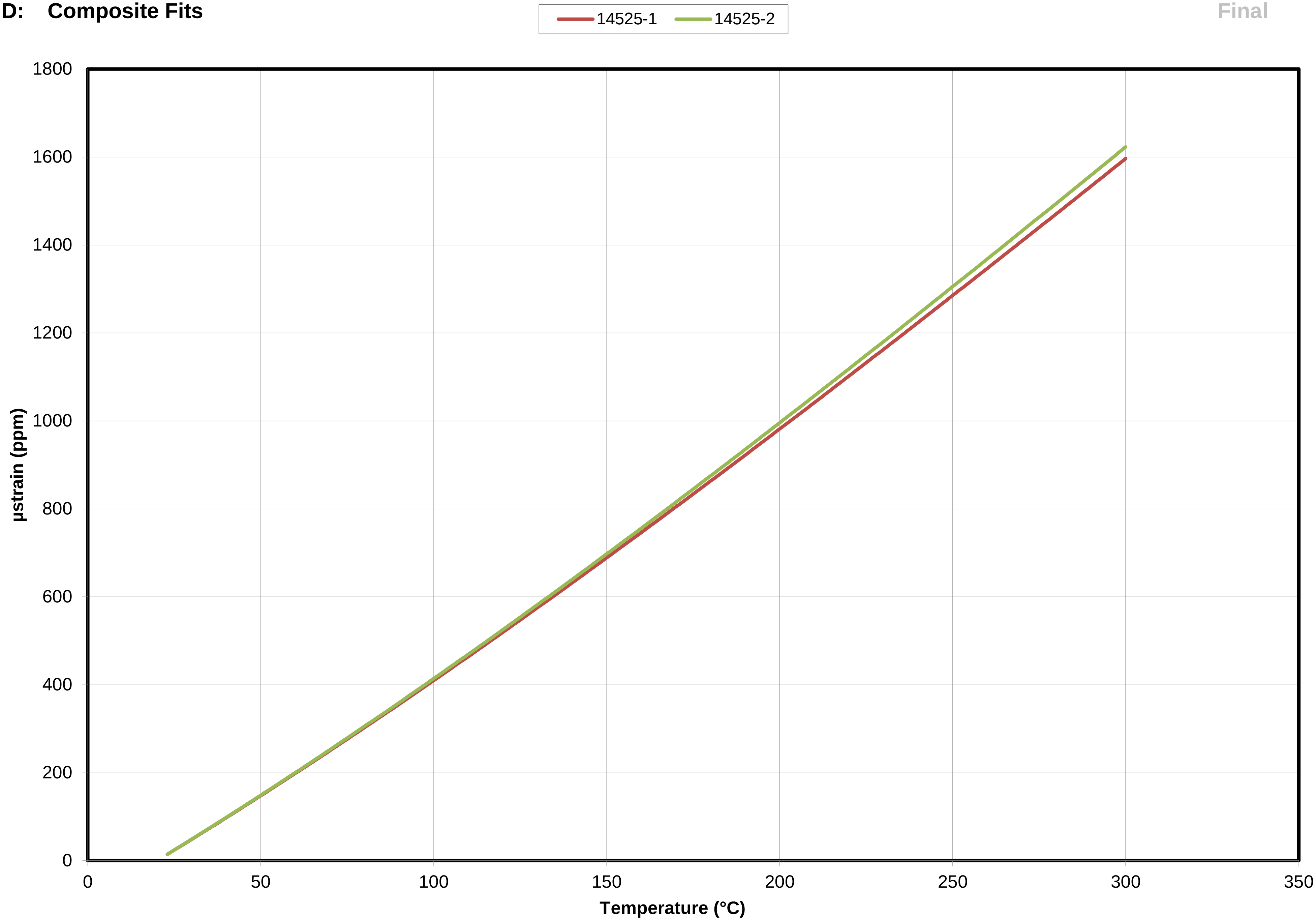
Final



0.946 **14525-2ABC-a** **CTE_4A** **25-Jul-14**

ID: Composite Fits

Final



CTE_4A 22-Jul-14

PMIC
Precision Measurements and
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PMIC PROPRIETARY INFORMATION

Precision Measurements and Instruments Corporation
Michelson Laser Interferometer

Precision Measurement and Instruments Corporation can determine the linear coefficients of thermal expansion (CTE) of plate, tube and honeycomb specimens. The strain measurements are made with a Michelson laser interferometer. This system is suitable for real time displacement measurements of components with CTE values as low as 10^{-9}/ K. Components of arbitrary size and shape can be accommodated. Temperature can be accurately cycled between ≤30K and 1000K. A component's CTE can be measured in two or more directions at once.

Figure 1 illustrates the basic features of a Michelson laser interferometer. A helium-neon laser provides a stable single frequency beam, which is then split by a beam splitter (BS). One beam is reflected off the mirror (on a PZT) and passes into the vacuum chamber where it is reflected off the left specimen mirror. A second beam passes straight through the beam splitter (BS) and into the vacuum chamber where it is reflected off the right specimen mirror. These beams return along their respective paths and interfere, forming a fringe pattern. Each shift in the fringe pattern corresponds to a change in specimen length equal to one half the wavelength of the laser light (12.456 micro-inches or 0.316μm for a He-Ne laser). Photo-detectors are used to sense shifts in the fringe pattern. The SP beam splitter separates the 0° and 90° components of the elliptically polarized fringe pattern light and directs them into the photo-detectors PD1 and PD2.

The two photo-detector signals are applied to the X-Y inputs of an oscilloscope to determine the direction of specimen strain as either expansion or contraction[1]. One photo-detector signal is recorded on a strip chart recorder along with the output of thermocouples and/or silicon diode temperature sensors that monitor specimen temperature. The current thermocouple and/or silicon diode temperature sensor value and photo-detector output are continuously transferred to a computer spreadsheet. These data and the room temperature specimen length are used to produce a graph of micro-strain versus specimen temperature. The slope of this graph is the coefficient of thermal expansion of the specimen. Accurate measurements of materials with CTEs less than 10 ppb/ K are made with these instruments.

Two quartz rods running parallel to the measurement direction support plate/honeycomb structures as well as single plate specimens. Specimens lie horizontally on the rods. Thin

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laminates are restricted from out-of-plane motion by placing two additional quartz rods on top of them. The top two rods are weighted as necessary to limit specimen bending.

The left and right specimen mirrors are connected to the specimen in one of two ways. Specimen mirrors are attached directly to the specimen's surface or attached to a guide that is then connected to the specimen by a knife-edge. The knife-edge method increases the accuracy of plate/honeycomb strain measurements. The knife-edge method avoids errors caused by distortion of the face sheets between honeycomb cell walls. Errors caused by specimen bending are reduced. Edge effect errors caused by incomplete honeycomb cells at the ends of specimens are completely eliminated.

The knife-edge is connected to the specimen by placing it on a scribed line that is perpendicular to the measurement direction. The line is well away from the edge of the specimen. The blade to specimen contact is a single line so specimen bending cannot rotate the reflective surfaces. Rotation of these surfaces leads to large errors in interferometer length change measurements. For more information, refer to references 1, 2, 3 and 4.

Test Procedure

Specimens are held initially at a constant temperature (in vacuo) to establish a zero strain state. It is necessary to establish a zero strain to assure that moisture content change will not affect the thermal strain data. Materials with large moisture contents are dried at elevated temperatures until stable. Specimens are then cycled through their temperature range one or more times while data are collected. Specimen temperature is computer controlled. The rate of temperature change is controlled in order that no significant gradients form in the specimen.

References

1. G. S. Peng & E. G. Wolff "Processing of Interferometric Signals for a CTE Measurement System." Thermochimica Acta. Vol., 218, 1993, pp101-112

2. E. G. Wolff and R. C. Savedra "Precision Interferometric Dilatometer", Rev. Sci. Instr. 56(7), (July 1985), p 1313-1319

3. E. G. Wolff, B. K. Min, M. H. Kural "Thermal cycling of a unidirectional graphite-magnesium composite" J. of Mat. Sci. 20, (1985), p 1141-1149

4. E.G. Wolff and S.A. Eselun "Thermal expansion of a fused quartz tube in a dimensional stability test facility", Rev. Sci. Instr. 50(4), Apr. 1979, p 502-505

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October 2005
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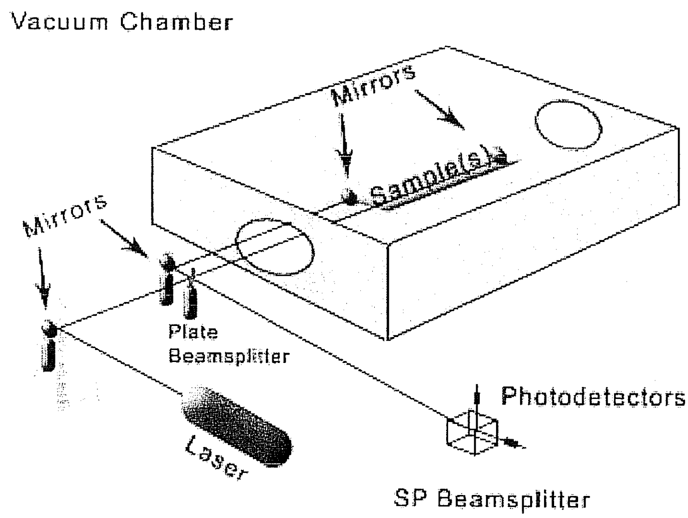
Vacuum Chamber
Mirrors
Sample(s)
Mirrors
Plate
Beamsplitter
Photodetectors
Laser
SP Beamsplitter