Sensors & Transducers, Vol. 190, Issue 7, July 2015, pp. 86-91

Sensors & Transducers

http://www.sensorsportal.com

A Simple Method for Determining Thermal Expansion Coefficient of Solid Materials with a Computer-aided Electromagnetic Dilatometer Measuring System

[1] Z. EZZOUINE and [2] A. NAKHELI

[1] Spectrometry Laboratory of Materials and Archaeomaterials (LASMAR), Faculty of Science, Moulay Ismail University, BP 11201 Zitoune, Meknes, Morocco

[2] Electrical Engineering Departments, High School of Technology, ESTM, Moulay Ismail University, Meknes, Morocco

[1] Tel.: +212650844764

E-mail: ezzouine.zakaryae@gmail.com

Received: 23 June 2015 /Accepted: 27 July 2015 /Published: 31 July 2015

Abstract: In this study, we present a newly designed electromagnetic dilatometer with micrometer accuracy for the measurement of the coefficient of thermal expansion of a solid in the 30 °C – 96 °C temperature range .The device has a graphical user interface to view real time data measurement. Iron and copper were subjected to temperature change in the thermal expansion experiment causing them to expand linearly. The voltage delivered in the electromagnetic dilatometer system, which includes the information about linear expansion and temperature change were transferred to a computer via a data acquisition card, presented by a program created in the LabVIEW environment, and the amount of linear expansion was detected in real time. The minimal change in length of the sample that can be resolved is 5µm, which yields the sensitivity comprised between 10^{-4} µm and 10^{-5} µm. In order to calibrate the electromagnetic dilatometer, thermal expansion coefficients of copper and Iron have been measured. By this technique, the thermal expansion coefficient can be determined with an acceptable accuracy. The present results appear also to agree well with those reported previously in the literature. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Coefficient of thermal expansion (CTE), Low temperature, Electromagnetic dilatometer, Measurement, Accuracy, Characterization of materials, LabVIEW.

1. Introduction

The coefficient of linear thermal expansion (CTE) is a material property that is indicative of the extent to which a material expands upon heating. Different substances expand by different amounts. Over small temperature ranges, the thermal expansion of uniform linear objects is proportional to temperature change [1].

According to the previous formulae, determination of the average coefficient of thermal expansion requires the measurement of two physical quantities, displacement and temperature, which can be accomplished by means of different experimental methods. Standard methods include mechanical dilatometry [2-5], laser interferometry [6-8] and high magnification optical imaging [9]. The increasing use of computer-based thermo-mechanical models as well as specific requirements concerning isotropic materials has determined in the last few years a greater need for quantitative data, promoting the development of new full-field optical measurement techniques, such as those based on Electronic Interferometry [10-12], Laser Interferometers and Thermomechanical analysis measurements [13]. All these techniques differs from each other only for the way the material expansion is measured with, since the reference temperature is always determined by monitoring the air temperature inside the heating device used to exert thermal loading, rather than measuring it directly on the sample surface.

Being able to make correct and accurate small displacement measurements, an important industrial application has great importance in terms of acquiring the most precision in the measurement of expansion and shrinkage of industrial materials. In addition, as the demand for detailed information about the dimensional stability and thermal expansion of advanced technological materials has increased day by day, the accuracy of measurements is continually being improved [14].

In its simplest form, the average (i.e., defined over a temperature range) coefficient of linear thermal expansion (CTE) of any material can be defined as the fractional increase in length (linear dimension) per unit rise in temperature. The most general definition is the mean or average coefficient of thermal expansion as given by the following equation [15-16]:

$$\Delta L = \alpha \times L \times \Delta T \,, \tag{1}$$

where ΔL is the change in length due to a temperature differential, α is the average coefficient of linear expansion, L is the length of the sample at the initial temperature, and ΔT is the magnitude of the temperature differential.

The purpose of this paper is to present a simple and inexpensive electromagnetic dilatometer for the measurement of the linear expansion of aluminum, Iron and copper undergoing temperature change with a computer-aided measuring system having micrometer accuracy.

2. Fundamentals of the Electromagnetic Sensor

The proposed sensor is a displacement electromagnetic sensor. Its operating principle is based on the phenomenon of influence with magnetic induction between two flat coils of the same diameter (2 cm) and having the same number of coil turns (30) made by a copper conductor wire of a section 0.06 mm, placed in parallel. One of the flat coils (Fixed Coil) is fixed on an insulating horizontal support and the other flat coil (Moving Coil) is wound on an insulating cylinder of 2 cm in diameter, the lower extremity passes through the free surface formed by the coil fixed, and the upper extremity is connected to a spring which is itself attached to a fixed support. At the lower end of the cylinder that acts as a guide, we set a hook for hanging masses.

The entire system formed (fixed flat coil, guide roller, spring and moving flat coil) is aligned on the same vertical axis (Fig. 1).

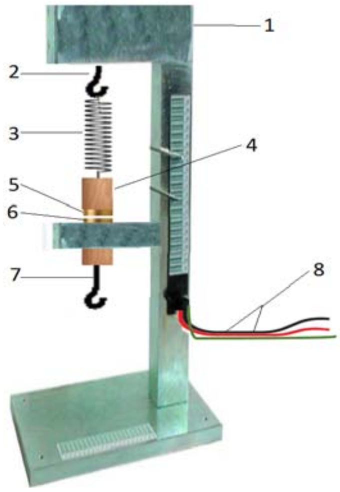

Fig. 1. Displacement electromagnetic sensor: 1 - Fixed support; 2 - Hook; 3 - Spring; 4 - Guide cylinder; 5 - Receiver coil (Moving coil); 6 - Transmitter coil; 7 – Hook.

The cylinder is movable vertically upwards or downwards virtually without friction, when we exert a force on its lower extremity [17-18], which has the effect of extending or compressing the spring, it bring closer or away the guide cylinder (moving coil) from the fixed coil.

The fixed coil is supplied by a low frequency generator of a frequency f_0 = 16 kHz whose phase conditions and amplification are satisfied; therefore, it is traversed by a sinusoidal current which creates a sinusoidal magnetic induction variable along its axis (Fig. 2).

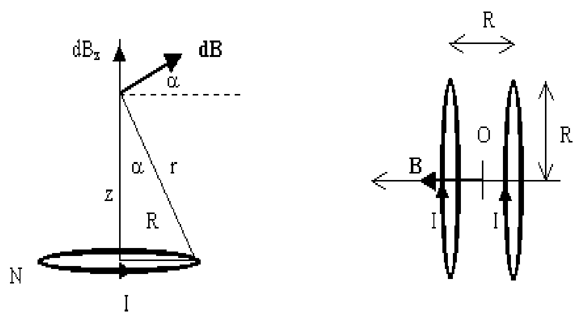

Fig. 2. Illustration of coil conductivity principle.

This induction produces a variable flux Φ and a variable induced electromotive force (EMF) on the electrons of the other coil (moving coil) equal to:

$$e = -\frac{d\Phi}{dt} \quad (2)$$

The maximum value of the EMF induced depends on the distance z between the two coils, the flux Φ is proportional to the magnetic induction B that changes as a function of z are given by the following relation:

$$B(z) = \frac{\mu_0 \times N \times I \times R^2}{2 \times (R^2 + z^2)^{3/2}}, \quad (3)$$

where I is the maximum amplitude of the current flowing through the coil, R is the coil radius and z is the distance between the two coils. The magnetic field created by the transmitter coil is at a maximum at the center of the coil z = 0, the above formula became simple:

$$B(0) = \frac{\mu_0 \times N \times I}{2R} \quad (4)$$

The induced voltage is sinusoidal and its amplitude is low, so it has been necessary to introduce circuits for amplification, rectification and filtering to make this voltage usable, the corresponding sensor output signal conditioning circuit is as it is shown in Fig. 3.

More details about the electromagnetic sensor system can be found elsewhere [17-18].

3. Method

The thermal expansion experiment, based upon the principle of the Electromagnetic dilatometer measurement system as shown in Fig. 4, consists of Electromagnetic displacement sensor used in detecting the changes length of a test specimen, on the simple principle that moving coil will shift vertically, depending upon the expansion or contraction of the specimen.

This change in position is interpreted and processed by a computer to obtain the actual thermal expansion of the specimen. The National Instruments NI USB-6281 data acquisition card used in transferring these values to the computer, and the program created in LabVIEW 10, used in analyzing the data and calculating the linear expansion amount. This technique is capable of measuring resolutions of 10^{-7} millimeters currently limited to very small test samples; this method shows promise for more widespread applications after further development.

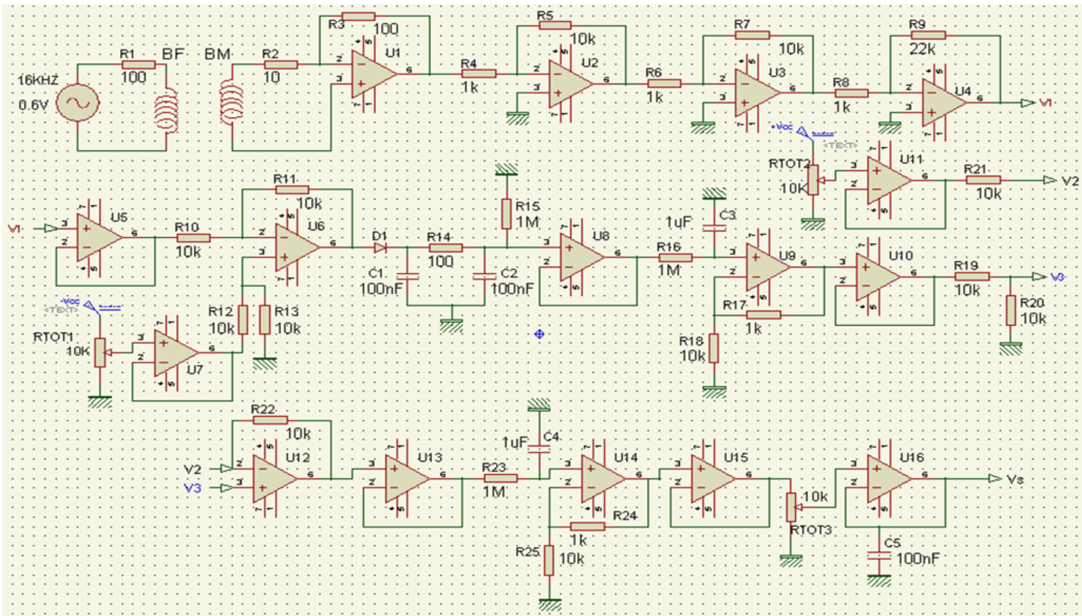

Fig. 3. Conditioning circuit.

4. Electromagnetic Dilatometer Calibration

The characteristic curve of the sensor shown in Fig. 5 is obtained by hooking high-precision masses from 0 g to 3 g in steps of 1 g, and we note the voltage values corresponding to each mass with a voltmeter of precision 0.1 mV. The curve response is not linear; it is rather parabolic in relation with the sensor sensitivity as a function of the distance between coils.

The electromagnetic sensor is comprised of a converter (a calibrated spring) that allows the Conversion of the masses in displacements. The curve of Determination of the displacement d=f (V) obtained by conversion the masses in displacement while using the characteristic for spring K (Fig. 6).

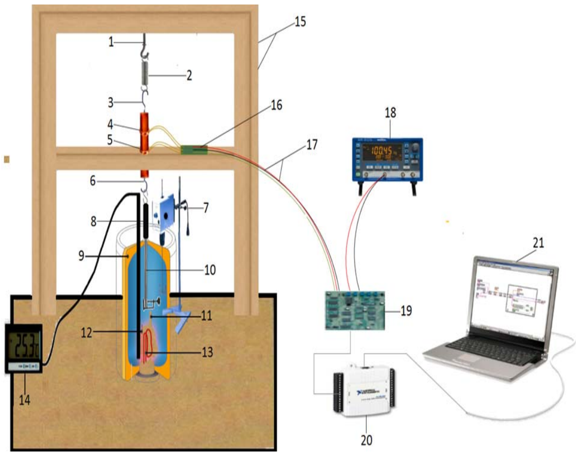

Fig. 4. Experimental setup for determining the thermal expansion coefficient: 1 - Hook; 2 - spring; 3 - Hook; 4 - Moving coil; 5 - Fixed coil; 6 - Hook; 7 - Agitator; 8 - Fixation cylinder; 9 - Insulating foam; 10 - Test Tube fixed by a Mounting bracket in lower extremity; 11 - Magnesium anode; 12 - Thermostat; 13 - Heating resistor; 14 - Thermometer; 15 - Fixed support; 16 - Printed circuit board; 17 - Wire connections; 18 - Low frequency generator; 19 - Conditing circuit; 20 - Acquisition card; 21 – Computer.

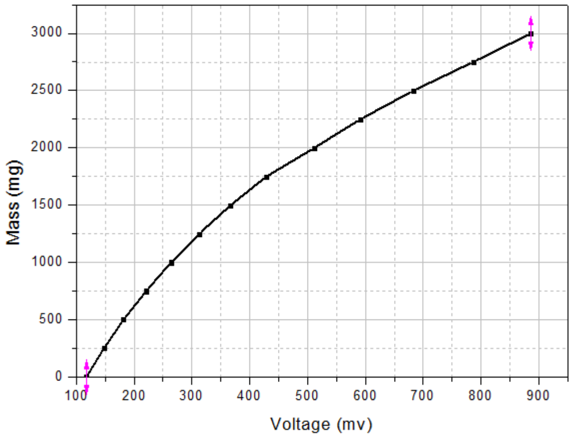

Fig. 5. Electromagnetic dilatometer calibration: m = f (V).

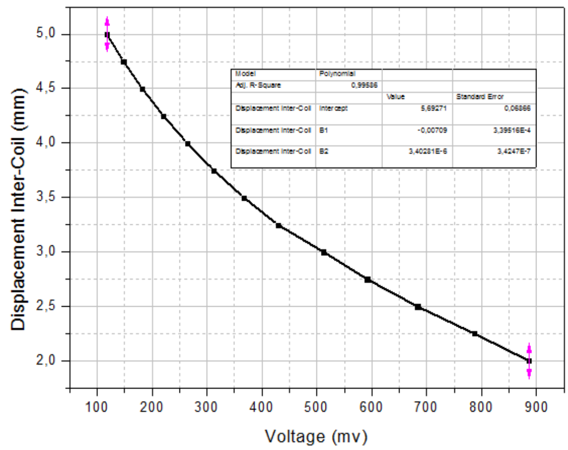

Fig. 6. Electromagnetic dilatometer calibration: d = f (V).

The fit polynomial of order 2, characterized by a standard deviation consistent with the experimental accuracy of the sensor (ΔV= ±0.1 mV), appears suitable:

$$d(mm)_i = \sum_{j=0}^{2} B_j \times v_i^j \tag{5}$$

The coefficients of the polynomial fit are: B_0=5.69237; B_1=-0.00709×E^{-5}; B_2=3.39671×E^{-6}.

The polynomial adjustment of the displacement as a function of the voltage corresponding to the experimental accuracy of our sensor is as follows:

$$d(mm) = 3.3910^{-6} \times V^2 - 0.007 \times V + 5.69 \tag{6}$$

6. Experimental Set-up

In the study we carried out, pieces of Iron and Copper with lengths of 9.5 cm for Iron. The thermal expansion factors of the subject materials are 11×10^{-6}/°C and 16.6×10^{-6}/°C, respectively. The linear expansion of the subject materials placed in the oven of the thermal expansion experiment is achieved by increasing the interior oven temperature.

When the linearly expanding subject material changes, and inter coil distance varies and transferred to the data acquisition card to be analyzed in LabVIEW 10. The amount of displacement is calculated as indicated in Equation (6) after the voltage detected by sensor is determined. The temperature values of the metals are transferred to the temperature–voltage converter circuit by the temperature sensor, through the data acquisition card and onto the LabVIEW 10 software. The displacement temperature graph can be monitored in real time via the interface (Fig. 7) created in LabVIEW 10, used in analyzing the data and calculating the linear expansion amount.

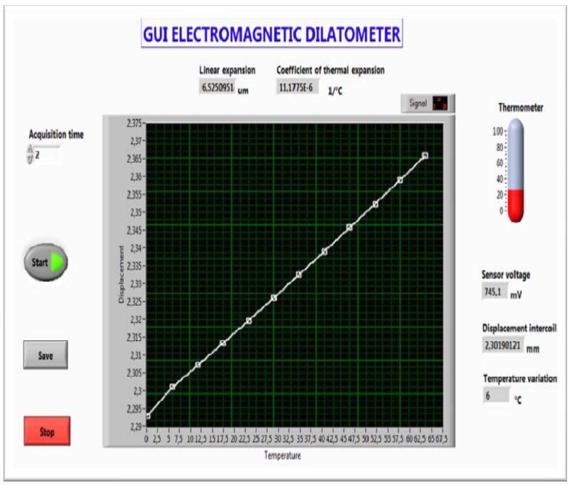

Fig. 7. The displacement – Temperature graph interface created in LabVIEW 10.

We connected a test piece to the sensor by a hook, we can deduce the displacement inter coil by the Equation (6) this displacement is used for determine the new original length of the test piece through the expression:

$$L = L_0 + d_{01}, \quad (7)$$

where L_0 is the original length of simple tests and d_{01} is the distance inter coil in the first measurement by the sensor.

For determining the expansion caused by the temperature, we report the different voltages corresponding at different temperatures. By finding the displacement inter coil for every voltage with the characteristic equation, total displacement is determined using the below expression:

$$\Delta L = d_{02} - d_{01}, \quad (8)$$

where ΔL is the amount of displacement, d_{01} is the first distance inter coil and d_{02} is the next distance detected over the sensor.

We have measured the CTE of copper, Iron and Aluminum at ten different temperatures (a=36°C, b=42°C, C=48°C, d=54°C, e=60°C, f=66°C, g=72°C, h=78°C, I= 90°C, j=96°C) by using the Equation (1).

7. Results and Discussion

In this experiment, the temperature was gradually increased from 30 °C to 96 °C. The heating rate was 0.3 °C/min. The results shown in this work were taken from the average of observation in three repetitions. The results for Iron are shown in Table 1.

Table 1. Experimental data of displacement versus temperature for Iron.

No.	Temperature (°C)	Voltage (mV)	Displacement (mm)
1.	30	745.10	2.29537611
2.	36	741.90	2.30190121
3.	42	738.70	2.30849587
4.	48	735.55	2.31505543
5.	54	732.40	2.32168240
6.	60	729.20	2.32848358
7.	66	726.00	2.33535432
8.	72	722.80	2.34229463
9.	78	719.60	2.34930450
10.	84	716.40	2.35638394
11.	90	713.20	2.36353294
13.	96	710.00	2.37075151

The curve fitting method was applied to the measurement results to determine the characteristic of the measurement system. The linear thermal expansion ΔL (μm) – temperature (°C) graph for Iron is shown in (Fig. 8.)

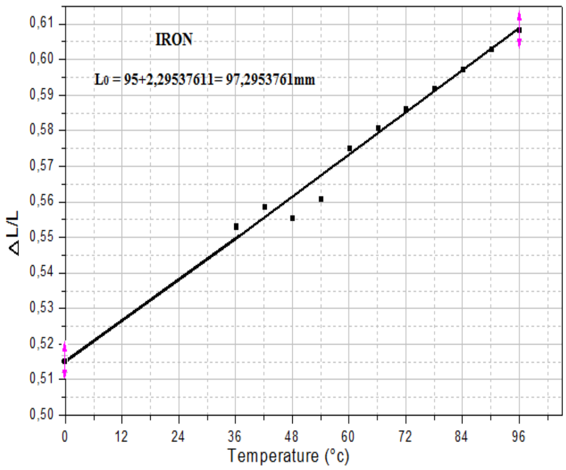

Fig. 8. Linear thermal dilatation – temperature graph for Iron.

Whereas the theoretical linear expansion for Iron is calculated as: 11×E^{-06}(°C^{-1}) [19], the average coefficient of thermal expansion amount determined by Equation (1) or from the graph in (Fig. 8.) Was 11.73×E^{-06}(°C^{-1}) as a result of the measurement, the results obtained for the temperature dependence of the voltage of sensor and displacement inter coil, are summarized in Table 2.

Table 2. Experimental data of displacement versus temperature for Copper.

No.	Temperature (°C)	Voltage (mV)	Displacement (mm)
1.	30	625	2,58795984
2.	36	621,7	2,59738241
3.	42	618,4	2,60687895
4.	48	615,1	2,61644947
5.	54	611,8	2,62609397
6.	60	608,5	2,63581245
7.	66	605,2	2,64560492
8.	72	601,9	2,65547136
9.	78	598,6	2,66541178
10.	84	595,3	2,67542619
11.	90	592	2,68551457
12.	96	588,7	2,69567694

The Linear thermal dilatation (μm) – temperature (°C) graph for Copper is seen in (Fig. 9.).

Whereas the theoretical coefficient of thermal expansion for copper is calculated as 16.6×10^{-6}(°C^{-1}), the CTE amount determined by Equation (1) or from the graph was 16.715×10^{-06}(°C^{-1}) as a result of the measurement.

Therefore, the percentage error of linear CTE from this experimental is 6.63 % of Iron and 0,69 % of Copper. It has a pretty good precision. From the results, they indicate that this technique is simple for measuring the linear coefficient of thermal expansion of metal using readily available materials.

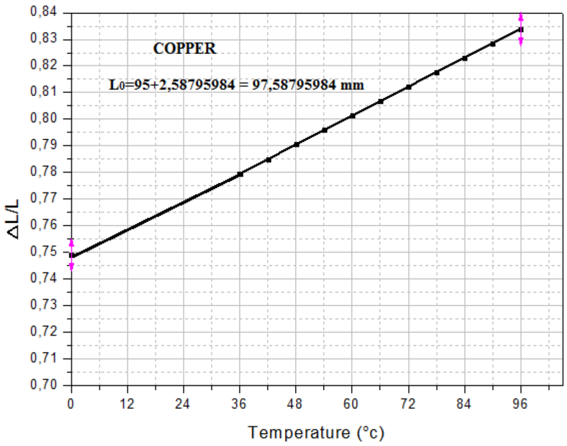

Fig. 9. The change in Linear expansion of Copper versus change in temperature.

8. Conclusions

In this work we have demonstrated an accurate experimental setup for measuring the coefficient of linear thermal expansion of solid materials over a temperature range from 30 ºC to 96 ºC. A computer-aided measurement system via which changes in displacement as temperature varies can be monitored in real time was realized in our study. Results with micrometer accuracy can be obtained with this measurement system, in which an Electromagnetic Dilatometer is used. As a result of the experiments carried out with Iron and copper it was confirmed that the measurement system is linear.

References

[1]. R. E. Taylor, CINDAS Data Series on Materials Properties, *Thermal Expansion of Solids, ASM International*, Vol. 1–4, 1998.

[2]. ASTM E 228-11 Standard, *American Society for Testing and Materials*, 2011.

[3]. T. Scientist, Standard Test Method for Linear Thermal Expansion of Solid Materials with a Vitreous Silica Dilatometer, E 228-95, Annual Book of ASTM Standards, *ASTM*, 1995.

[4]. N. Bobroff, Recent advances in displacement measuring interferometry, *Measurement Science and Technology*, 9, 1993, pp. 907-926.

[5]. S. Donati, L. Falzoni, S. Merlo, A PC-interfaced, compact laser-diode feedback interferometer for displacement measurements, *IEEE Transactions on Instrumentation and Measurement,* 45, 6, 1996, pp. 942-947.

[6]. ASTM E 289-04 Standard, *American Society for Testing and Materials*, 2010.

[7]. A. Standard Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry, E289-99, Annual Book of ASTM Standards, *ASTM*, 1999.

[8]. Fritschel Peter, Second generation instruments for the laser interferometer gravitational wave observatory (LIGO), *Astronomical Telescopes and Instrumentation, International Society for Optics and Photonics,* 2003.

[9]. James J. D., Spittle J. A., Brown S. G. R., Evans R.W., A review of measurement techniques for the thermal expansion coefficient of metals and alloys at elevated temperatures, *Measurement Science and Technology*, Vol. 12, 2001, pp. R1–R15.

[10]. Kim S., Kim J. H., Lee J. K., Jarng S. S., Measurement of thermal expansion coefficients by electronic speckle pattern interferometry at high temperature, *Journal of Materials Science Letters*, Vol. 16, 1997, pp. 1753-1756.

[11]. Dudescu C., Naumann J., Stockmann M., Nebel S., Characterization of thermal expansion coefficient of anisotropic materials by electronic speckle pattern interferometry, *Strain*, 42, 3, 2006, pp. 197–205.

[12]. Lee C. C., Tien C. L., Sheu W. S., Jaing C. C., An apparatus for the measurement of internal stress and thermal expansion coefficient of metal oxide films, *Review of Scientific Instruments*, 72, 4, 2001, pp. 2128–2133.

[13]. Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis, E 831, Annual Book of ASTM Standards, *ASTM*, 2000.

[14]. R. Schödel, Ultra high accuracy thermal expansion measurements with PTB's precision interferometer, *Measurement Science and Technology,* 19, 8, 2008, pp. 084003-1 - 084003-11.

[15]. R. A. Serway, Physics for Scientists and Engineers, *Saunders College Publishing*, 1990, pp. 513-515.

[16]. R. A. Serway, J. W. Jewett, Physics for Scientists and Engineers, 6th ed., *Brooks Cole Pub Co,* Thomson, Belmont, CA, 2004, pp. 949-951.

[17]. Z. Ezzouine, A. Nakheli, Z. Abbassi, A. Benabdellah, Conception and Realisation of a Sensor Electromagnetic Force-Displacement, *International Journal of Research in Engineering and Technology*, Vol. 03, Issue 10, October 2014, pp. 268-271.

[18]. Z. Abbassi, A. Benabdellah, A. Nakheli, New Electromagnetic Force Sensor: Measuring the Density of Liquids, *International Journal of Research in Engineering and Technology*, Vol. 03, Issue 09, September 2014, pp. 83-90.

[19]. John N. Fox, Measurement of thermal expansion coefficients using a strain gauge, *American Journal of Physics,* 58, 9, September 1990, pp. 875-877.
