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Measurement of a Thermal Expansion Coefficient for a Metal by Diffraction Patterns from a Narrow Slit

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ABSTRACT

In this work, we made an effort to determine linear coefficient of thermal expansion of metal using single-slit diffraction. An aluminium strip was used as sample. The design of the apparatus for this method allows for the width of a single slit to increase by the same amount as the thermal expansion of a length of a strip or a rod of a material. The increase in the slit width, hence the linear expansion, can be determined by measuring the fringe width. A He-Ne laser with a wavelength of 632.8 nm was used to obtain a diffraction pattern for the single slit. The value of the linear coefficient of thermal expansion of the material can then be calculated using the principle knowledge of diffraction equation and thermal expansion. The experimental result was found that the linear coefficient of thermal expansion of aluminium is 22.512×10^{-6} $(C°)^{-1}$, giving a 2.545 % error.

Key words: thermal expansion coefficient, single-slit diffraction, aluminium

INTRODUCTION

Thermal expansion is a consequence of the change in the average separation between the atoms in an object. At ordinary temperatures, the atoms in a solid oscillate about their equilibrium positions with amplitude of approximately 10^{-11} m and a frequency of approximately 10^{13} Hz. The average spacing between the atoms is about 10^{-10} m (Serway and Jewett, 2004). As the temperature of the solid increases, the atoms oscillate with greater amplitudes; as a result, the average separation between them increases. Consequently, solids typically expand in response to heating and contract on cooling; this response to temperature change is expressed as its coefficient of thermal expansion (CTE). Thermal expansion is an intrinsic property as it depends on lattice and associated forces. It reflects nature of binding forces responsible for the close interplanar spacing between stacked molecules. The lattice and electronic vibrations contribute to the thermal expansion and it is controlled by the motion of vibrating atoms, which deviate from the simple harmonic motion (Kanagaraj and Pattanayak, 2003). Thermal expansion is used to characterize the different binding forces in solids and also for the thermodynamic model. Moreover, it is also used in mechanical applications to fit parts over one another.

The primary knowledge of thermal expansion of the metals/ alloys/ composite materials is very essential where these materials are used as a structural material for cryogenic use. Accurate data of the thermal expansion of the constituent materials and the theories, which

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predict these values as a function of temperature and percentage of the constituents, are very important in this area. There are different techniques available to study the thermal expansion of metals and composites materials at low and high temperature such as capacitance method (Bijl and Pullan, 1955; Tong *et al.*, 1991), variable transformer technique (Evans and Morgan, 1991), Fabry-Perot laser interferometer (Foster and Finnie, 1968) and Michelson laser interferometer (Wolff and Eselun, 1979; Wolff and Savedra, 1985). All these techniques used for the measurements of thermal expansion can be divided into two categories namely absolute method, the linear changes of dimension of the sample are directly measured at various temperature, and relative method where thermal expansion coefficients are determined through comparison with a reference materials with a known thermal expansion. However, some technique is extremely limited and needed of precision measurement in mechanical and electronics equipments. Therefore, we made an effort to determine linear coefficient of thermal expansion of metal using single-slit diffraction. In this work, aluminium was chosen to study the CTE. Aluminium is a good thermal and electrical conductor. It is most widely used non-ferrous metal. Some of the many uses for aluminium metal are in transportation (automobiles, aircraft, railway cars, etc.), electrical transmission lines for power distribution, heat sinks for electronic appliances such as transistors and CPUs.

MATERIALS AND METHODS

A method to determine linear CTE using single-slit diffraction is presented. The design of the apparatus for this method allows for the width of a single slit to increase by the same amount as the thermal expansion of a length of a strip or a rod of a material. An aluminium strip, approximately 39 cm × 2.3 cm × 3 mm thick, was used as sample. Figure 1 shows a strip-slit assembly for this work. An aluminium strip was bent symmetrically at right angles. The middle section of strip has length L_0 (8.20 cm). It can be immersed in a water bath for heating. Two pieces of square dowel rods were screwed to the two ends of the strip, so they could support two razor blades to create a thin slit of small width w_0 at initial temperature T_0. The expansion of the horizontal portion of the strip affects the slit width.

Figure 2 shows the schematic of the usual single-slit experimental set up. A He-Ne laser beam of wavelength λ (632.8 nm) passes through single slit and produces a diffraction pattern of fringe width Z_0 on a screen a distance D (1.703 m) away. The beaker may be appropriately covered to prevent slight warming of the blades due to the rising warm air and moisture from the water bath. The water bath is slowly heated to a temperature T. The expansion of the vertical portions of the bent strip does not affect the fringe width. As the temperature increases from T_0 to T, the length of the horizontal section of the strip increases from L_0 to L, the slit width increases from w_0 to w and the fringe width decreases from z_0 to z. The increase in length ΔL and the linear CTE α can be determined as following.

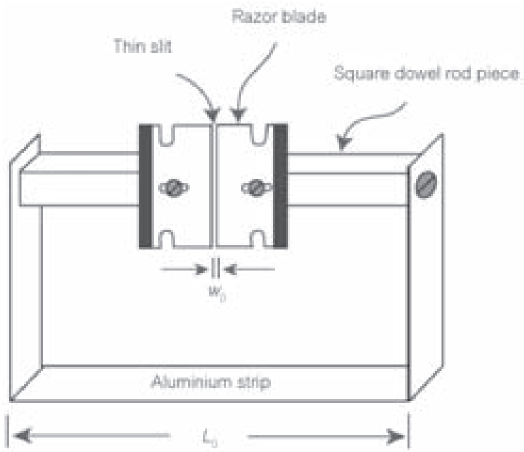

Figure 1 A strip-slit assembly.

From Figure 2, laser beam passing through the thin slit produces a diffraction pattern on a screen, as shown in Figure 3. The aluminium strip expands as it is heated and increases the slit width, thereby changing the diffraction pattern. Using the usual equation for single-slit diffraction (see Figure 3), we get

$$w_0 = \frac{\lambda D}{z_0},$$

$$w = \frac{\lambda D}{z},$$

$$\Delta L = w - w_0 = \frac{\lambda D}{z} - \frac{\lambda D}{z_0},$$

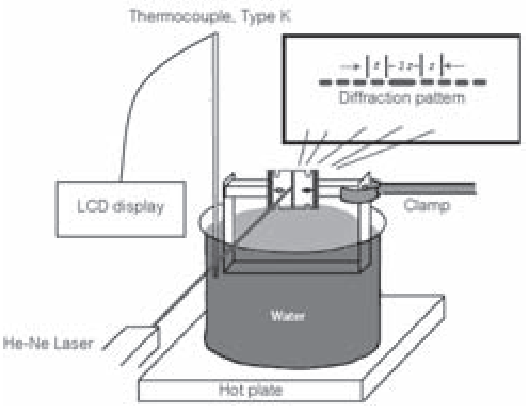

Figure 2 Experimental setup.

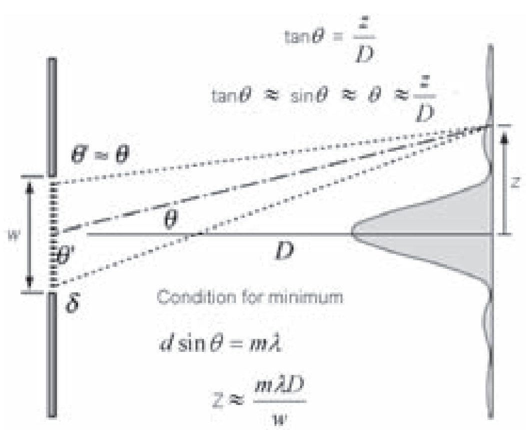

Figure 3 Diffraction pattern for a single slit.

So, $$\Delta L = \lambda D \left[\frac{1}{z} - \frac{1}{z_0}\right]. \quad (1)$$

Furthermore, this change in length ΔL is found to be proportional to the original length of the strip L_0 and to the change in the temperature ΔT, where $\Delta T = T - T_0$. In equation form, the result is

$$\Delta L = \alpha L_0 \Delta T. \quad (2)$$

where α is a constant called the linear CTE. Solving Eq. (2) for the constant α gives

$$\alpha = \frac{\Delta L}{L_0 \Delta T}. \quad (3)$$

From the form of Eq. (3), it is clear that α is the fractional change in length per unit change in the temperature. Since the fractional change in length $\Delta L/L_0$ has no dimensions, the units of α are $(C°)^{-1}$.

Substitution of Eq. (1) into (3), the above equation becomes

$$\alpha = \frac{\lambda D\left[\frac{1}{z} - \frac{1}{z_0}\right]}{L_0(T - T_0)}. \quad (4)$$

RESULTS AND DISCUSSION

In this experiment, the temperature was gradually increased from 29.60 °C to 90.00 °C. The value of z was considered when the water temperature was enlarged every 5 °C. The results shown in this work were taken from the average of observation in three repetitions. Statistical analysis was performed using the software program Sigma Stat by SPSS Inc. The results are shown in Table 1. These obtained results can be analyzed graphically as described below:

Solving Eq. (4) for $1/z$, we achieve

$$\frac{1}{z} = \frac{\alpha L_0}{\lambda D} T + \left[\frac{1}{z_0} - \frac{\alpha L_0 T_0}{\lambda D}\right].$$

Thus, a graph of $1/z$ versus T will be a straight line with

$$\text{slope} = \frac{\alpha L_0}{\lambda D}. \quad (5)$$

From the graph in Figure 4, slope is 1.713 m^{-1} $(C°)^{-1}$. Replacement this value, L_0, λ and D into Eq. (5), α is 22.512 × 10^{-6} $(C°)^{-1}$. The theoretical value of α for aluminium is 23.100 × 10^{-6} $(C°)^{-1}$ (Serway and Jewett, 2004). Therefore, the percentage error of linear CTE of aluminium from this experimental is 2.545 %. 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.

CONCLUSION

The use of a single-slit diffraction pattern allows the thermal expansion coefficient of metal to be measured. The width of a single slit increases by the same amount as the thermal expansion of a length of a strip or a rod of a material. This set-up supplies a simple, accurate, compact, multiplexible and numerically stable method for measuring the thermal expansion coefficient. Also, it can be

Table 1 The measured values of the fringe width *z* and its reciprocal as a function of temperature *T*.

T (°C)	*Z* (m)	1/*Z* (m^{-1})
29.60	0.014 ± 0.002	70.423 ± 9.217
35.00	0.013 ± 0.002	78.125 ± 11.396
40.00	0.012 ± 0.002	83.333 ± 13.333
45.00	0.011 ± 0.002	92.593 ± 17.595
50.00	0.010 ± 0.001	102.041 ± 11.000
55.00	0.009 ± 0.001	108.696 ± 8.889
60.00	0.009 ± 0.001	117.647 ± 9.111
65.00	0.008 ± 0.001	121.951 ± 9.375
70.00	0.008 ± 0.001	133.333 ± 7.500
75.00	0.007 ± 0.001	142.857 ± 15.429
80.00	0.007 ± 0.001	153.846 ± 13.714
85.00	0.006 ± 0.001	166.667 ± 13.500
90.00	0.006 ± 0.001	172.414 ± 15.333

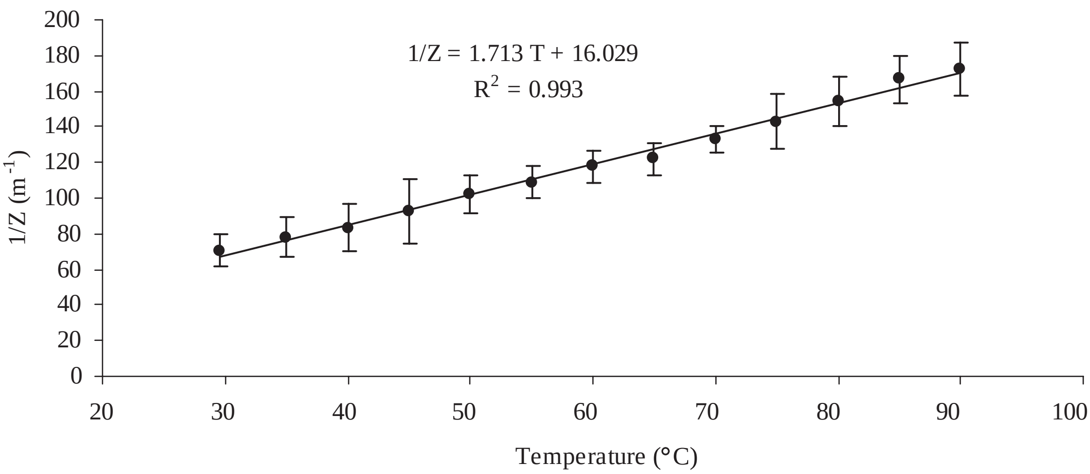

Figure 4 Plot of the reciprocal of fringe width as a function of the temperature of the aluminium strip.

designed to measure multidirectional thermal expansion coefficients in composite materials simultaneously. Furthermore, this technique can be used to show in an elementary optical course. It is considerably suitable for undergraduated student as of its facilitation on material and method setup.

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LITERATURE CITED

Bijl, D. and H. Pullan. 1955. A new method for measuring the thermal expansion of solids at low temperatures; the thermal expansion of copper and aluminium and the gruneisen rule. **Physica** 21: 285-298.

Evans, D. and J.T. Morgan. 1991. Low temperature mechanical and thermal properties of liquid crystal polymers. **Cryogenics** 31: 220-222.

Foster, J.D. and I. Finnie. 1968. Method of measuring small thermal expansion with a single frequency Helium-Neon laser. **Rev. Sci. Instrum**. 39: 654-657.

Kanagaraj, K. and S. Pattanayak. 2003. Measurement of the thermal expansion of metal and FRPs. **Cryogenics** 43: 399-424.

Serway, R.A. and J.W. Jewett. 2004. **Physics for Scientists and Engineers with Modern Physics**. Thomson-Brooks/Cole, Belmont. 588 p.

Tong, H.M., H.K.D. Hsuen, K.L. Seanger and G.W. Su. 1991. Thickness direction coefficient of thermal expansion of thin polymer films. **Rev. Sci. Instrum**. 62: 422-430.

Wolff, E.G. and S.A. Eselun. 1979. Thermal expansion of a fused quartz tube in a dimensional test facility. **Rev. Sci. Instrum**. 50: 502-506.

Wolff, E.G. and R.C. Savedra. 1985. Precision interferometric dilatometer. **Rev. Sci. Instrum**. 56: 1313-1319.