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Determination of linear thermal expansion coefficient of polymeric materials by infrared thermography

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ABSTRACT

In this paper, we present a new method for determination of the linear thermal expansion coefficient (LTEC) of polymeric materials by infrared thermography. The method is based on the thermo-elastic effect, which is closely related to the LTEC. The advantage of this method is that it is not only suitable for any size and shape of polymeric material, but also for both amorphous and crystalline polymers.

1. Introduction

The linear thermal expansion coefficient (LTEC or α) is a basic parameter which is of considerable importance in mechanical and structural design of materials [1–3]. It is defined as the change in length with temperature for a solid material and is expressed as:

$$(L_f - L_0)/L_0 = \alpha(T_f - T_0) \quad or \quad \alpha = 1/L_0(dL/dT) \qquad (1)$$

where l_0 and l_f represent, respectively, the original and final lengths with the temperature change from T_0 to T_f. Obviously, to determine the LTEC, two physical quantities (displacement and temperature) must be measured on a sample during a thermal cycle. Based on this principle, several measuring techniques including dilatometry, thermomechanical analysis (TMA), and interferometry have been applied to measure LTEC of materials [3–6]. However, as described in Ref. [4], it is difficult to use these techniques to measure the LTEC of film materials, especially for thin polymeric film materials. Although the X-ray diffraction method can be used to measure the LTEC of thin film materials, it can only be applied in materials with crystalline structure [6].

Infrared thermography provides an alternate method for easily and quite accurately measuring the LTEC of polymeric materials based on thermo-elastic effect. According to the Ref. [7,8], the thermo-elastic effect of polymeric materials in the initial deformation phase is closely related to the LTEC value, and the resulting temperature change can be determined accurately by an infrared camera. The method is not only suitable for any size and shape of material, but also for materials with amorphous or crystalline structure. In this paper, the first section will present the basic principle underlying the method. The following section describes the method to determine the LTEC through the measurement of the temperature field of materials under stress. In the last section, the LTEC of a typical polymeric specimen (Ultra high molecular weight polyethylene, UHMWPE) was determined by infrared thermography.

2. Technology principle

When drawing polymeric materials, deformation is performed in two stages: the initial elastic deformation and

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the following plastic deformation. In the initial elastic phase, deformation is reversible. The second law of thermodynamics can be written as

$$dQ = TdS \qquad (2)$$

where T is the initial temperature. The total differential of the entropy $S = S(T,L)$ is [9]:

$$dS = \left(\frac{\partial S}{\partial T}\right)_L dT + \left(\frac{\partial S}{\partial L}\right)_T dL \qquad (3)$$

where,

$$\left(\frac{\partial S}{\partial T}\right)_L = \frac{C_L}{T} \qquad (4)$$

$$\left(\frac{\partial S}{\partial L}\right)_T = -\left(\frac{\partial f}{\partial T}\right)_L = -\left(\frac{\partial f}{\partial L}\right)_T \left(\frac{\partial L}{\partial T}\right)_f = -E\alpha \qquad (5)$$

it follows that

$$dS = \frac{C_L}{T}dT - E\alpha \cdot dL \qquad (6)$$

where C_L is the heat capacity at constant length, f is the force, and E and α are the tensile modulus and the LTEC respectively.

For reversible isothermal deformation ($dT = 0$), Equation (2) is integrated to give

$$dQ = -TE\alpha \cdot dL = -TL\alpha \cdot df \qquad (7)$$

The temperature change of the deformation process can be expressed from Equation (7) [7,8,10]

$$dT = -\frac{\alpha}{\rho C_p} \cdot T_0 \cdot d\sigma \qquad (8)$$

Equation (8) is a quantitative expression of the variations in temperature caused by the variations in applied stress. If adiabatic conditions are satisfied, the variation in temperature will be proportional to change of stress. Obviously, values of linear expansion coefficient can be calculated from

$$\alpha = -\frac{\rho \cdot C_p}{T_0} \cdot \frac{dT}{d\sigma} \qquad (9)$$

where, temperature variation (dT) during the loading process can be determined by infrared thermography. In the following section the experimental technology will be introduced.

3. Experimental method

As an application example, the method was used to determine the LTEC of UHMWPE. The specimens are about 4 mm × 8 mm in sectional area and 100 mm in length. The dumbbell specimens were prepared by ram extrusion using UHMWPE with an average molecular weight of 3.1 million g/mol, where the sintering pressure and temperature are 5 MPa and 220 °C respectively. Tensile
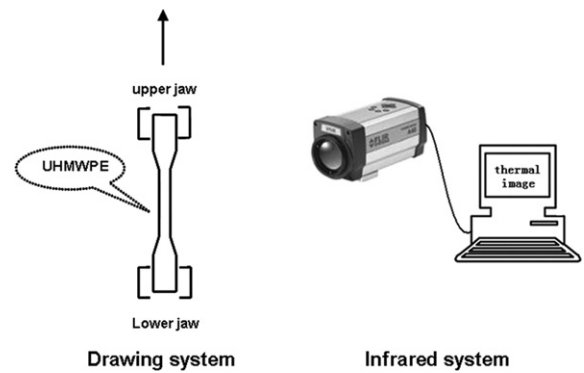

Fig. 1. Experimental equipments of tensile and temperature measurement.

testing and thermographic measurements were performed simultaneously (Fig. 1). The specimen deformation process was done at a constant extension rate, using a tensile testing apparatus with a fixed lower jaw and a moveable upper jaw. The infrared camera used to monitor the drawing process was a ThermaCAM A40M manufactured by FLIR Systems, which was placed in front of the test machine, the axis of the lens being perpendicular to the sample surface. The spectral range of this camera is 7.5-13 μm and the thermal sensitivity is 0.08 °C at 25 °C. The detailed process of measurement has been reported in our earlier paper [11]. All experiments were performed at room temperature and air humidity of 60%.

4. Results and discussion

As mentioned above, the temperature of the specimens can be determined by infrared thermography. Fig. 2 shows the load-elongation curves and some thermograms of UHMWPE at 50 mm/min drawing rate, and the temperature scale is also displayed on the right-hand side of the figure. A nearly even temperature distribution throughout the specimen is observed during the entire drawing period. Two characteristic phases of load-elongation are illustrated with corresponding thermograms: the beginning of elastic deformation and the following homogeneous plastic deformation to the final fracture of the specimen. At the
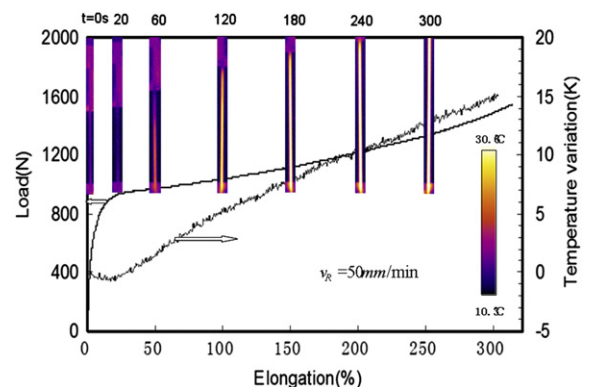

Fig. 2. Curve of load-elongation and some selected temperature distribution images from the drawing of UHMWPE at 50 mm/min.