Polymer Testing 40 (2014) 39–45

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Test method

Determination of the Paris' law constants by means of infrared thermographic techniques

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ARTICLE INFO

Article history:
Received 20 June 2014
Accepted 14 August 2014
Available online 23 August 2014

Keywords:
Infrared
Thermography
Paris' law
Crack growth rate
Polyamide

ABSTRACT

Determination of the Paris' law constants requires the continuous measure of the crack length. This measure has usually been performed using methods based on electric potential differences or by means of correlations between crack length and the compliance of the specimen.

Bearing in mind that the crack tip undergoes a temperature rise due to the corresponding stress concentration and the generation and growth of a plastic zone, it is possible, using infrared thermographic techniques, to quantify the crack growth. Thus, in this paper, the fatigue crack propagation behaviour of a polyamide has been characterised by determining the Paris' law constants with the aid of thermographic tools. The values obtained by means of this methodology have been compared with those resulting from the use of conventional measurement techniques.

1. Introduction

In order to follow and measure the crack growth in a fatigue process, the usual practice is to use indirect methods based on study of the variation of the mechanical compliance, or the electric potential or the use of high-speed CCD (Charge-coupled device) cameras [1,2]. Direct measurement by optical means has the difficulty of establishing where the actual position of the crack tip is [3].

In this paper, the possibility of directly measuring the crack length is suggested, not by means of visible radiation, detected by the human eye, but through the infrared radiations emitted by the crack tip during its heating due to the fatigue process.

The main source of infrared radiation is heat or thermal radiation. Any object with a temperature above absolute zero, 0 K or −273.15 °C, emits radiation in the infrared zone of the electromagnetic spectrum. The hotter the body is, the greater the amount of infrared radiation emitted [4].

This radiation from a body can be focused by a set of lens over an infrared detector that sends the information to an electronic sensor. The sensor converts the received data into an image which can be seen on a standard monitor. This technique is called infrared thermography and it is defined as the art of transforming an infrared image into a radiometric image, which also allows the values of temperatures to be defined.

Thermography is a tool which has been used in the detection of defects generated in fatigue processes, as well as in the determination of the level of accumulated damage in the same processes [5–10].

In this work, a methodology that allows the evolution of crack length to be followed has been developed from infrared thermography. The measurement of the variation of temperatures at the crack tip boundary is a non-destructive technique without any contact with the tested specimen. Taking advantage of the developed methodology, the fatigue crack propagation behaviour of a

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http://dx.doi.org/10.1016/j.polymertesting.2014.08.005
0142-9418/

Abbreviations

$\dot{Q}$	hysteresis energy disipation rate
J^*	complex compliance
J' and J''	real and imaginary part of complex compliance, J^*
G^*	complex modulus
G' and G''	real and imaginary part of complex modulus, G^*
H	heat transfer coefficient to the environment from the sample surface
ν	test frecuency
T	instantaneous temperature of specimen
T_0	instantaneous temperature of environment
VS_i	virtual temperature sensor
Δ_{VS}	distance between virtual temperatura sensors
a	crack length measured from the line connecting the bearing points of force application
a(C)	crack length measured by means compliance
a(T)	crack length measured by means Infrared Thermography
a_f	final crack length, measured on broken specimen.
C	Compliance, $C = \nu/P$
δ	displacement between measurement points
P	load
C_i	rotation coefficients
ΔK	stress-intensity factor range
da/dN	fatigue crack growth rate
K_{max}	maximum stress-intensity factor

polyamide has been characterised by determining the Paris' law constants using thermographic tools. Then, the obtained values have been compared to those resulting from the use of conventional measurement techniques [11–16].

2. Thermal evolution associated to dynamic behaviour of a polymer

The thermal increase undergone by a polymer as a consequence of a fatigue crack propagation can be analysed from a thermodynamic point of view. To do this, several models of thermal heating based on the balance between the generation of hysteresis energy during the dynamic process and the heat dissipated to the surroundings when a polymer has been subjected to fatigue, have been established [17]. The general equation which presents the temperature difference between the environment and the sample is expressed as:

$$\Delta T = f\left(\dot{Q}, \frac{V}{S}\right) \tag{1}$$

This equation shows that this difference increases with sample volume, V, and is reduced, mainly, with the surface of the specimen, S. The factor $\dot{Q}$ represents the hysteresis energy dissipation rate in the form of heat per cycle and per volume unit during the fatigue process, and can be expressed according to [18]:

$$\dot{Q} = \pi \cdot \nu \cdot J'' \cdot \sigma_0^2 \tag{2}$$

where ν is the test frequency, σ_0 is the applied stress and J'' is the imaginary part of the complex compliance, J^*, which can be expressed as a function of G' and G'':

$$J^* = J' - iJ'' = \frac{1}{G^*} = \frac{G' - iG''}{E^2} \tag{3}$$

where G^* is the complex modulus (G' and G'' being the real and the imaginary part, respectively) and E is the Young's modulus of the material [19]. Observing this last expression, it can be verified that J'', and then $\dot{Q}$, are proportional to G'', which, at the same time is proportional to the dissipated energy in the form of heat.

Experimental studies [20] are in very good agreement with the heating model established above, and corroborate the high sensitivity to temperature increase in the material with the frequency and the maximum applied stresses.

If adiabatic conditions prevail, that is, all the heat generated by the polymer is displayed as a temperature increase in the sample, and no heat is transferred to the surroundings, then the variation temperature rate in the material is given by expression (4) [18]:

$$\frac{dT}{dt} = \frac{\dot{Q}}{\rho \cdot C_p} = \frac{\pi \cdot \nu \cdot J'' \cdot \sigma_0^2}{\rho \cdot C_p} \tag{4}$$

where ρ and C_p are the density and the specific heat per mass material unit, respectively.

In the most general case, some heat is transferred to the environment. Thus, if T and T_0 are the instantaneous temperatures of specimen and environment respectively, the above equation can be modified in order to consider the loss of heat through the surface, obtaining the following expression:

$$\frac{dT}{dt} = \frac{\pi \cdot \nu \cdot J'' \cdot \sigma_0^2}{\rho \cdot C_p} - \frac{H \cdot S}{\rho \cdot C_p \cdot V} \cdot (T - T_0) \tag{5}$$

where S represents the surface area, V the tested specimen volume and H the heat transfer coefficient between the environment and the sample surface.

As can be seen in equation (5), the temperature to which a polymer is subjected in a fatigue crack propagation process depends on the squared stress level. Thus, in the presence of a defect such as a crack, where concentrated stresses exist on the crack tip, the corresponding temperature increment can be identified by a thermographic camera.

3. Tested material

The material selected for this work is a polyamide 6, PA 6, which has an elastic modulus of 2,7 GPa and an ultimate strength of 78 MPa. A compact test specimen, CT, of 11,2 mm thickness (B) was machined. The dimensions and