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An active infrared thermography method for fiber orientation assessment of fiber-reinforced composite materials

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ABSTRACT

Fiber orientation in composite materials is an important feature since the arrangement or orientation of the fibers relative to one another has a significant influence on the strength and other properties of fiber reinforced composites. In this paper we present a method to assess the fiber orientation on the surface of carbon fiber reinforced polymer (CFRP) laminates. More specifically, a diode-laser beam is used to locally heat a small spot on the surface of the sample. Observation of the heat pattern in the infrared spectrum enables the assessment of the fiber orientation. Different samples and different regions on the surface of the samples are tested in order to estimate the precision of the method.

1. Introduction

Composite materials are widely used in the aeronautic industry. One of the reasons is because of they have strength and stiffness comparable to metals with the added advantage of significant weight reduction. Fiber orientation, concentration and distribution have a significant influence on the strength and stiffness of fiber reinforced composites and consequently must follow some quality standards in order to ensure that they will not fail during their lifetime. Thus, it is important to develop inspection techniques to assess fiber content. Destructive methods can be employed to evaluate the fiber on a composite, e.g. cutting a section of the material, polishing the area and evaluating it with microscopy. However, the destructive approach is not always an option since the sample will be damaged after inspection and probably unfit for use. Thus, Non-Destructive Testing and Evaluation (NDT&E) techniques must be employed in some cases to assess the material's fiber content.

Infrared Thermography (IT) is a NDT&E technique which is widely used for diagnostics and motoring in several areas including composite materials. Some of the reasons for its popularity are that it is a safe technique, usually contactless and has a fast inspection rate. In active IT an external heat source is used to stimulate the material being inspected in order to generate a thermal contrast between the feature of interest and the background. The active approach is adopted in many cases given that the inspected parts are usually in equilibrium with the surroundings [1].

In this paper, IT is used in order to assess fiber orientation on the surface of carbon fiber reinforced polymer (CFRP) laminates. More specifically, a pulse laser heating technique known as Pulsed Thermal Ellipsometry is used to locally spot heat a region on the surface of the sample. If the material has an oriented structure (i.e. fibers orientated in one direction) with anisotropic thermal properties, an elliptical pattern will be observed. The fiber orientation in this case is the same direction of the ellipse's major axis. The heating and cooling down profiles are recorded using an infrared camera. The steps required to extract the local fiber orientation from the infrared sequence are presented in this paper. Additionally, tests of several points on different CFRP laminate samples were performed in order to estimate the precision of the method.

This paper is organized as follows: the next section presents the material and methods including a brief literature review on PTE and the proposed method to extract the fiber orientation from a PTE inspection; in Section 3 results obtained are presented and in Section 4 they are discussed; finally our conclusions are presented in Section 5.

2. Material and methods

2.1. Pulsed Thermal Ellipsometry – PTE

More than one century ago, De Senarmont [2] applied a thermal approach to determine the principal orientations in crystal plates: he covered them with a thin layer of wax, heated them over a small spot and monitored the isotherm shape revealed by the solid/liquid transition contour appearing in the wax layer. The isotherm

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proved to be elliptical and its aspect ratio is related to the square root of the principal conductivities in the surface plane.

This method, referred to later by Krapez et al. [3–6] as "Thermal Ellipsometry", was later used for various applications (with, of course, up-to-date experimental equipment) by means of thermography. It was applied on polymer materials to establish a correlation between their draw ratio and the induced thermal anisotropy. It was also used to evaluate the fiber orientation in the case of composite materials using short or long carbon fibers. For the latter problem, authors like Aindow et al. [7] and Cielo et al. [8] showed that heat propagates faster in the longitudinal direction of fiber on the surface of fiber reinforced laminates. In [7], Aindow et al. detected local anisotropy in CFRP (nylon-66) injection mouldings by two methods: thermography using infrared scanning, which reveals anisotropy of thermal conductivity, and polarized shear-wave ultrasonic showing elastic anisotropy. For the thermographic method, they recorded isotherms formed around a point source of heat on a plane surface (heat was applied for a period of 15 s) using an infrared imaging camera. The isotherms that they observed were ellipses of which the ratio of lengths of the principal axes (b/a) are proportional to the square root of the ratio of thermal conductivities. They assumed that the longest dimension of the counter in each picture indicated the major axis of thermal conductivity in the surface, which in turn is related to the direction of fiber orientation.

Cielo et al. presented in [8] a comparative review of a number of optical techniques for the characterization of non-metallic materials. One possibility reported by them is the evaluation of phase (or fiber) orientation in stretched polymer films or in composites by an analysis of the thermal propagation pattern. They spot-heated the inspected part by a narrow laser beam and the resulting heat-propagation pattern was analyzed by an IR camera. If the material is oriented, such as the unidirectional graphite-epoxy sheet they inspected, an elliptical thermal pattern is observed, with the ratio between the two principal axes (b/a) being related to the square root of the thermal conductivities in the longitudinal and transverse directions. A test on an isotropic material would give a circle instead of an ellipse. They illustrated this approach showing results from two 8-ply unidirectional NARMGO 5217 sheets spot heated for a period of 20 s with a 0.5 W laser. A typical set-up used in PTE inspection is showed in Fig. 1.

A more detailed theoretical analysis was later undertaken through an analytical treatment of thermal diffusion in laminates made of orthotropic layers assuming the surface is submitted to concentrated heating by Krapez in [3]. Three temporal regimes were considered in that study: steady-state regime, transient regime (as obtained during step heating), and modulated regime (in order to analyze how the so-called thermal waves "propagate" in orthotropic laminates). Experiments were performed on carbon-epoxy laminates for all three regimes. In [4], Krapez used the same theory (thermal anisotropy measurements method which consists in analyzing the shape of the isotherms which develop around a heated spot) to develop a thermal inversion method to infer thickness of skin and core layers of a 3-layer carbon/epoxy laminate.

In our previous work [9], as in Karpen et al. [10], lock-in thermography (harmonic thermal waves) is used to probe orientation fields of carbon fibers both along the surface and in depth at low modulation frequencies and within a short time. Later Karpen et al. [11] developed a theoretical model in order to correctly interpret their measurements.

2.2. Image processing technique

After the sample is spot-heated and the temperature profile of heating and cooling down process is recorded, the infrared sequence is stored in a 3D matrix M for post-processing. The matrix M is composed of k images of the size $m \times n$. The number of images depends on the acquisition rate of the infrared camera used in the acquisition and on the duration of the acquisition. The processing steps in order to obtain the fiber orientation from the acquisition sequence can be divided in three: selection of the optimal diffusion time, binary shape segmentation and extraction of the ellipse's orientation. Fig. 2 shows a summary of these steps which are described next.

2.2.1. Optimal diffusion time selection

The result of a PTE inspection is a sequence of infrared images which contains: the plate before heating, the moment when the beam heated the plate, the rise of the temperature profile and finally the temperature profile decrease. In the case of CFRP which are thermally anisotropic, the heat pulse will produce an elliptical pattern on the surface of the sample. The ellipse major axis orientation indicates which direction has the larger thermal conductivity and since the thermal conductivity along the fibers is always larger than the one perpendicular to it, the orientation of the major axis of the ellipse will be the same as that of the fibers.

The thermal pattern is closer to a circle in the images just after the pulse. Shortly after it becomes an ellipse and as time elapses the ellipse become closer to a circle again due to the influence of deeper layers and heat diffusion through thickness and not only on the surface. Thus, in order to assess the fiber orientation on the surface, an image from an early time when the conductivities of the surface are playing a stronger role must be selected. However, this time must not be too early. If a very early image is selected the heat would not have diffused enough on the surface of the plate and consequently the influence of the larger thermal

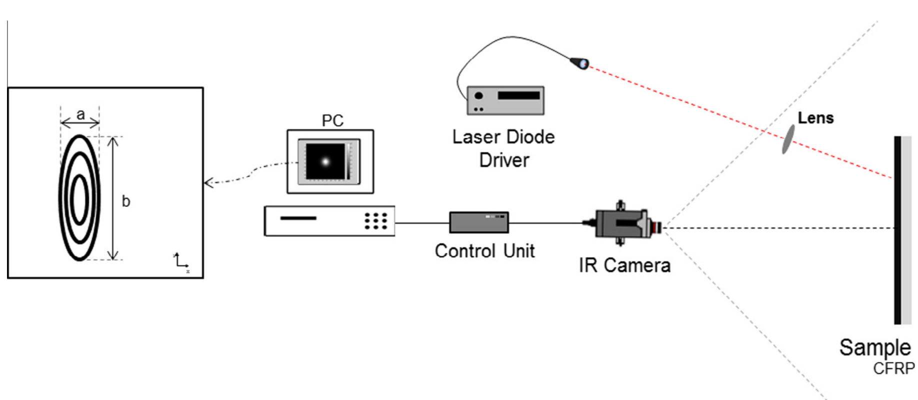

Fig. 1. PTE experimental se-tup.