Use of infrared thermography to measure fiber orientation on carbon-fiber reinforced composites

Henrique Fernandes and Xavier Maldague

Abstract. Carbon-fiber reinforced composites are widely used in the industry. One of the key features regarding their quality and usefulness is related to the fiber orientation and content. One technique that is used to test this kind of material is Infrared Thermography (IT). In this paper it is presented a technique based on diode-laser spot heating to measure fiber orientation on the surface of a carbon-fiber reinforced composite manufactured by compression molding of Random-Oriented Strands (ROS) of carbon/PEEK (Polyether ether ketone).

Keywords: fiber orientation, infrared thermography, random-oriented strands, carbon-fiber reinforced composites

1. Introduction

The use of composite materials (CM) is growing more and more every day in several applications, especially in aeronautic structures. The arrangement or orientation of the fibers relative to one another, the fiber concentration, and the distribution all have a significant influence on the strength and other properties of fiber reinforced composites. Thus testing techniques must be developed 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 well-known and widely used NDT&E technique for composite material inspection. 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]. Qualitative and quantitative assessment of flaws is a very popular application of IT for CM. However there are others such as fiber orientation assessment. In this work we apply IT to assess fiber orientation on a plate's surface. More specifically a "laser spot" technique, that we call Pulsed Thermal Ellipsometry (PTE), is used to assess fiber orientation on the surface of a carbon/PEEK (Polyether ether ketone) plate. The inspected plate was molded with Random-Oriented Strands (ROS) of carbon/PEEK. Figure 1 shows the molded plate. Thus, fiber orientation on the surface is also random since each strand has its own fiber orientation. In this paper the measuring of fiber orientation of individual strands is presented. It shows the feasibility of the proposed NDT&E technique to measure fiber orientation of such material.

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2. 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 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 [5-8] 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 [3] and Cielo [4] showed that heat propagates faster in the longitudinal direction of fiber on the surface of fiber reinforced laminates. In [3], Aindow et al. detected local anisotropy in CFRP (nylon-66) injection moldings 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 seconds) 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 [4] 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. A typical configuration is shown in Figure 2. 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 seconds with a 0.5 W laser.

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 [5]. 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 [6], 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 [9], Karpen et al. used lock-in thermography (harmonic thermal waves) to probe orientation fields of carbon fibers both along the surface and in depth at low modulation frequencies and within a short time. Later, in [10] he developed a theoretical model in order to correctly interpret the measurements.

3. Experiments and Results

The PTE technique using diode-laser spot was applied on ROS plate. The plate was placed in front of the laser beam and a plano-convex lens was placed between the laser beam and the plate. It was used to focus the beam in a small spot. Laser beam formed a 90° angle with plate's surface while camera optical axis formed a 75° angle with plate's surface. A short pulse was shot heating a small circle area on the plate's surface. This small area was previously chosen so the heated area stayed restricted to a single strand. The goal with this configuration was to detect fiber orientation on a single strand since orientation changes according to the strand. Then, heating and cooling down process were recorded using middle

Table 1 - Parameters used in the experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode-laser frequency</td>
<td>805 nm</td>
</tr>
<tr>
<td>Beam power used</td>
<td>5W of 30W</td>
</tr>
<tr>
<td>Shooting duration</td>
<td>0.1 seconds</td>
</tr>
<tr>
<td>Spot size on plate's surface</td>
<td>3 mm</td>
</tr>
<tr>
<td>Recording time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Image used to extract fiber orientation</td>
<td>0.2 seconds after beam had stopped</td>
</tr>
</tbody>
</table>
wave infrared camera (MWIR). As mentioned before, the pattern formed on the plate's surface is elliptical in anisotropic materials, which is the case of carbon-fiber reinforced plates and the ellipse major axis is related with the fiber orientation. The setup configuration prepared in the laboratory is shown in Figure 3 and the parameters used in this experiment are in Table 1.

Two different strands were chosen to show the feasibility of the technique. First strand was spot heated while the plate was in vertical position (same position shown in Figure 1) and then to prove that

![Figure 3 - Diode-laser experimental setup](image)

![Figure 41 - Fiber orientation measurement of the first strand](image)

(a) Plate in vertical position, red dot show where beam heated the chip, (b) Ellipse formed after 0.2 seconds after beam has stopped, red line show major axis. Its orientation is 55.99°. (c) Plate in horizontal position, red dot show where beam heated the chip, (d) Ellipse formed after 0.2 seconds after beam has stopped, red line show major axis. Its orientation is -47.52°.

![Figure 5 – Fiber orientation measurement of the second strand](image)

(a) Plate in vertical position, red dot show where beam heated the chip, (b) Ellipse formed after 0.2 seconds after beam has stopped, red line show major axis. Its orientation is -85.19°. (c) Plate in horizontal position, red dot show where beam heated the chip, (d) Ellipse formed after 0.2 seconds after beam has stopped, red line show major axis. Its orientation is 6.37°.
the technique works the same strand was heated again however now while the plate was rotated 90° counter clockwise (in horizontal position). Thus the difference between in the two major axes of those two experiments should be around 90° (the difference in rotating the plate from vertical to horizontal position). After this procedure was done for the first strand the same procedure was done for the second chosen strand. Results show that the PTE works well for single strands case. Results can be seen in Figure 4 and Figure 5. Orientation angles are shown with respect to x-axis.

Figure 4 shows the first tested strand. Figure 5b shows the ellipse major axis while the plate was in vertical position. The ellipse major axis orientation is 55.99 degrees measured with Matlab®. Figure 5d shows the ellipse major axis while the plate was in horizontal position. The ellipse major axis orientation is -47.52 degrees measured by the same Matlab® script. When the plate was rotated (vertical to horizontal position) an error of 13 degrees was introduced between the measurements. Figure 5 shows the other tested strand. Figure 5b shows the ellipse major axis while the plate was in vertical position. The ellipse major axis orientation is -85.19 degrees measured with Matlab®. Figure 5b shows the ellipse major axis while the plate was in horizontal position. The ellipse major axis orientation is 6.37 degrees measured by the same Matlab® script. When the plate was rotated (vertical to horizontal position) again an error of 1.5 degrees was introduced between the two measurements.

4. Discussion

For both strands, the difference between the two major axis measurements (first when the plate was in vertical and then in horizontal position) should be 90°. However it was not. For the first strand, the difference between the orientation of the two ellipse’s major axis was 76.49° (an error of 13.5° approximately). This happened because the exactly position heated in each case was not the same and perhaps in the second case a place nearer the chip border was heated and it got more influence from a neighbor chip which could have different fiber orientations. Additionally, during the plate’s molding process heat and pressure are applied on the strands which leads to a high degree of deformation in the shape of consolidate strands in the final plate and it could give to strands a high level of "shape interaction". Thus in some cases neighbors strands can play a bigger role in the heating dissipation of a single strand which could affect the elliptical pattern. For the second inspected strand the difference between the two major axis was 88.44° (an error of 1.5° approximately). Here the error between measurements is smaller. This happened because the second chip is better placed and large enough so the heating spot could hit the same position (no edge or neighbor strands effects).

5. Conclusions and Future Work

In this work infrared thermography was used for non-destructive characterization of composite materials. The Pulsed Thermal Ellipsometry (PTE using a laser spot pulse as excitation source) was tested and showed effective to measure fiber orientation on the surface of a ROS carbon/PEEK specimen. However, the diode-laser laser spot technique (PTE) measures fiber orientation of a small region of plate's surface at a time and this is not good enough for real industrial applications. Thus, this research must continue in order to develop a faster approach which can measure fiber orientation of a bigger area at once.

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