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Fiber orientation assessment on randomly-oriented strand composites by means of infrared thermography

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ABSTRACT

In this paper, an infrared thermography technique is used to assess the fiber orientation on the surface of carbon fiber reinforced polymer (CFRP) moulded with randomly-oriented strands (ROS). Due to the randomness of the material, a point by point inspection would be very time consuming. In this paper it is proposed to use a flying laser spot technique to heat a line-region on the surface of the sample instead of a spot. During our experiments, a flying laser spot inspection was performed in 30 s while a point by point inspection of the same area would require about 25 min. An artificial neural network (ANN) was then used to estimate the fiber orientation over the heated line. The classification rate obtained with the network was 91.2% for the training stage and 71.6% for the testing stage.

1. Introduction

In the last decades composite materials (CM) have become very important in the aeronautic industry. The *C Series* aircraft from Bombardier contains 70% advanced materials comprising 46% composite materials and 24% aluminium–lithium which allows for a 15% lower seat-mile cost and a significant reduction in maintenance costs [1]. One of the factors that motivates the use of CM is the fact that they are typically lighter and more resistant to corrosion than the metallic materials that have been used traditionally. Fiber orientation and distribution is an important feature of carbon fiber reinforced polymer (CFRP) materials since the material's strength and stiffness are greater along the direction of the fibers. Thus it is important to assess the fiber orientation in such materials for quality control purposes. Infrared thermography enables such an assessment.

Infrared thermography (IT) is a safe non-destructive testing (NDT) technique that has a fast inspection rate and is generally contactless. It is used for diagnostics and monitoring in several fields such as electrical components [2], thermal comfort [3], buildings [4], artworks [5], medical [6], security [7] and composite materials [8]. IT popularity has grown in the recent years due to spatial resolution and acquisition rate improvements of infrared cameras which have become more affordable. Another factor is the development of advanced image processing techniques focused on this kind of image. 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 [9].

A pulse laser heating spot technique known as Pulsed Thermal Ellipsometry (PTE) [10,11] enables the assessment of the fiber orientation of a region around a single spot. In the case of laminates which usually have a uniform fiber orientation on each ply, the inspection of two or three points with PTE would give a good indication of the fiber orientation on the surface for example. However, in the case of randomly-oriented strand (ROS) plates it is more complicated. Due to the randomness of the structure of the plate, the fiber orientation on the surface would also be random and to have a good assessment of the fiber orientation distribution, several points covering the entire surface should be inspected. This would prove to be very time consuming using the single spot-heating technique such as PTE. Thus, it is proposed herein a faster technique to assess the fiber orientation on the surface of a ROS plate: a flying-spot technique in combination with an artificial neural network (ANN) to assess the fiber orientation over a line on the surface of a ROS plate.

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This paper is organized as follows: the next section presents the material and methods including a brief literature review on PTE and ROS samples as well as a review on the flying spot technique used and ANNs; in section 3 results obtained are presented and in section 4 these results are discussed; finally, our conclusions are presented in section 5.

2. Material and methods

2.1. Randomly-oriented strand (ROS) material

Introduced in the late 2000s, a novel composite material called randomly-oriented unidirectional strand (ROS) composites allows the manufacturing of high performance complex parts. ROS utilizes the performance benefits of continuous fibers while sharing the advantages of processability common to short discontinuous fibers. This is illustrated schematically in Fig. 1a.

Conventional continuous fibers offer the mechanical performance although complex shape parts are more difficult to produce. On the other hand, parts with complex features can be injection moulded using lower volume content of short fibers, but they will lack mechanical properties. ROS composites lie in between these two material configurations. ROS composites are obtained from a bulk moulding compound comprised of strands of high fiber volume content unidirectional thermoplastic/thermoset pre-impregnated tape that are compression moulded with heat and pressure. Fig. 1b depicts the manufacturing cycle of ROS composite parts by compression moulding.

CFRP panels inspected in this paper were moulded using carbon/PEEK (*Polyether ether ketone*) unidirectional slit tape, which was cut into strands of 25 $\times$ 8 [mm] using an automated tape cutter. Strands were placed into the mould in small batches and shuffled each time to better control their distribution and to minimize their out-of-plane orientation. The mould was closed, placed into a pre-heated press and a pressure of 34 bars was applied. The mould temperature was increased up to 380° C and was maintained for 15 min. It was then cooled down at an approximate rate of 10° C/min and removed from the press. Panels were then cut in 100 $\times$ 100 [mm] samples for inspection. Fig. 2 shows the three inspected samples in the scope of this research. In each sample, 4 different lines were inspected with the approach described in sub-section 2.3. Thus, a total of 12 different lines (regions) were inspected.

2.2. Pulsed Thermal Ellipsometry – PTE

"Thermal Ellipsometry" is a method available for decades 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, Cielo et al. presented in Ref. [12] a comparative review of a number of optical techniques for the characterization of non-metallic materials. One possibility reported by the authors 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, in that case 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 produce a circle instead of an ellipse. A typical set-up used in PTE inspection is shown in Fig. 3.

Krapez conducted a detailed theoretical analysis [10] through an analytical treatment of thermal diffusion in laminates made of orthotropic layers assuming the surface is submitted to concentrated heating. Three temporal regimes were considered in that study: steady-state regime, transient regime 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 Ref [11], Krapez used the same theory, i.e., a thermal anisotropy measurements method that consists in analyzing the shape of the isotherms which form around a heated spot, to develop a thermal inversion method in order to infer thickness of skin and core layers of a 3-layer carbon/epoxy laminate.

Furthermore, Karpen et al. [13] developed a theoretical model in order to apply 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. In our previous work [14], lock-in thermography was also applied in order to assess fiber orientation on a CFRP sample sub-layer.

2.3. Flying laser spot

Flying laser spot is a dynamic active thermography technique, which can be employed for the inspection of materials by heating a component, point-by-point, while acquiring a series of thermograms with an infrared camera. This can be done in two ways, either the thermographic head, consisting of an infrared camera and an energy source, i.e., a CW laser source, moves along the surface while the sample to be inspected is motionless, or it may be

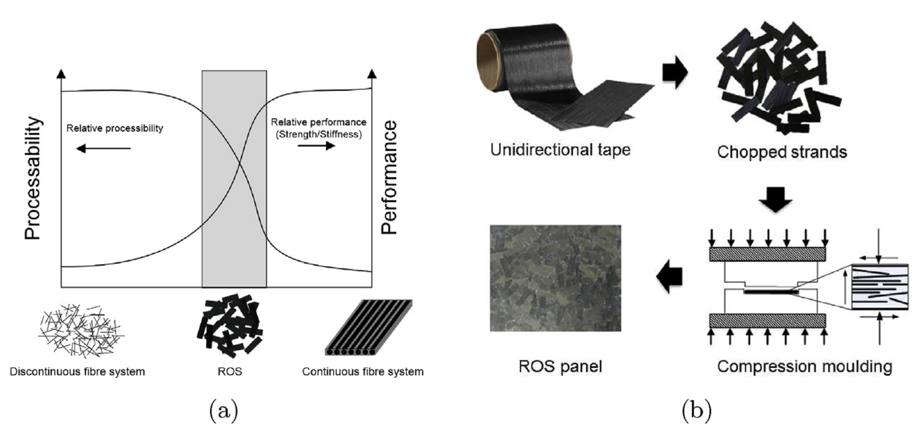

Fig. 1. (a) Processing and performance of various composite material systems, and (b)ROS manufacturing cycle.
Adapted from Ref. [28].