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Characterizing Fiber Orientations and Layer Stacking Sequences in CFRP Laminates through Induction Heating Patterns: A Nondestructive Approach

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Abstract

The induction heating using a circular coil in Carbon Fiber Reinforced Polymer (CFRP) laminates produces unique heating patterns, significantly influenced by the fiber orientations in each layer and electrical contacts between layers. This study investigates these patterns using thermography and reveals a transition from circular to rectangular heating patterns under the influence of a circular induction coil. This shift is driven by changes in interlaminar microstructure, particularly increasing fiber separation at interfaces, interpreted as fewer electrical contacts. The research also presents a novel nondestructive, non-contact method for identifying fiber orientations within CFRP laminates. The method employs a 2D Fast Fourier Transform (2D-FFT) to extract fiber orientations from the spatial characteristics of the heating patterns. The study demonstrates the effectiveness of this method for accurately determining fiber orientations in quasi-isotropic CFRP laminates. This methodology opens potential applications for large-area inspection and quality control in fiber-reinforced composite manufacturing.

1. Introduction

Carbon Fiber Reinforced Plastics (CFRP) are advantageous for their high strength-to-weight ratios and customizable properties. However, due to their inherent non-uniformity, correct fiber orientation is critical to prevent potential structural failure. Various techniques exist to measure fiber orientation [1, 2], but comprehensive and non-destructive measurement of depth-resolved fiber layup remains a challenge. This paper explores the use of Active Infrared Thermography (IRT), a rapid non-contact method [3], combined with induction heating for thermal stimulation of CFRP laminates. The distinctive heating patterns observed are processed using a two-dimensional Fast Fourier transform (2D-FFT) to identify fiber orientations and characterize the stacking order within the material. This efficient approach offers a non-destructive means to assess layer orientation, accurately predicting stacking sequences for up to 12 layers in quasi-isotropic CFRP laminates. [4]

2. Materials and Methods

Carbon Fiber Reinforced Polymer (CFRP) composites exhibit a distinctive heating response during induction heating, contingent on the orientation of the conductive carbon fibers. In a unidirectional carbon fiber layer, there are two possible current flow patterns, but unidirectional laminates don't heat via induction due to lack of closed current paths, even at frequencies over 15 MHz. A two-dimensional Fourier transformation is used to extract geometric features from thermal images, which helps determine the fiber orientations in the CFRP sample. The samples used for the study are given in Table 1 For induction heating observation, a minimum of two layers of unidirectional fabric-based laminate, aligned differently, are

Table 1. *Details of the CFRP laminates used for the study*

Sl. No.	No. of Layers	Layup Sequence	No.Active pairs	Active pairs (AP)	Sample Label
1	4	$[0/90/90/0]$	1	$[0/90]$	CFRP-4L-1P
2	4	$[0/30/30/90]$	2	$[0/30], [30/90]$	CFRP-4L-2P
3	4	$[90/\pm 45/0]$	3	$[90/45], [\pm 45], [-45/0]$	CFRP-4L-3P
4	6	$[-60/90/\pm 45/90/0]$	5	$[-60/90], [90/45], [\pm 45], [-45/90], [90/0]$	CFRP-6L-5P

necessary. The heating can occur due to Joule loss in fiber, polymer dielectric loss between fibers, and contact resistance at overlapping fiber junctions. The dominant heating mechanism depends on factors like fiber volume fraction, layer thickness, fabric type, and consolidation processes, shaping surface temperature distribution. Low junction resistance leads to a circular temperature pattern, whereas high resistance causes a non-circular pattern. The study examines the influence of consolidation processes and fabric types on induction heating patterns, using four CFRP laminates of varied fiber orientations, prepared through compression molding.

3. Preliminary Results

The orientations of the fibers in the samples configuration were identified from the frequency domain analysis and are presented in figure 1. However, as the number of different active pairs increases, identifying fiber orientations from thermal images becomes difficult. The complexity of geometrical features present in thermal images of CFRP-4L-2P, CFRP-4L-3P, and CFRP-4L-4P is shown in the top row of figure 1. The frequency domain images and the polar plots showing the fiber orientations are shown in the second and the third rows of figure 1, with the identified fiber orientations.

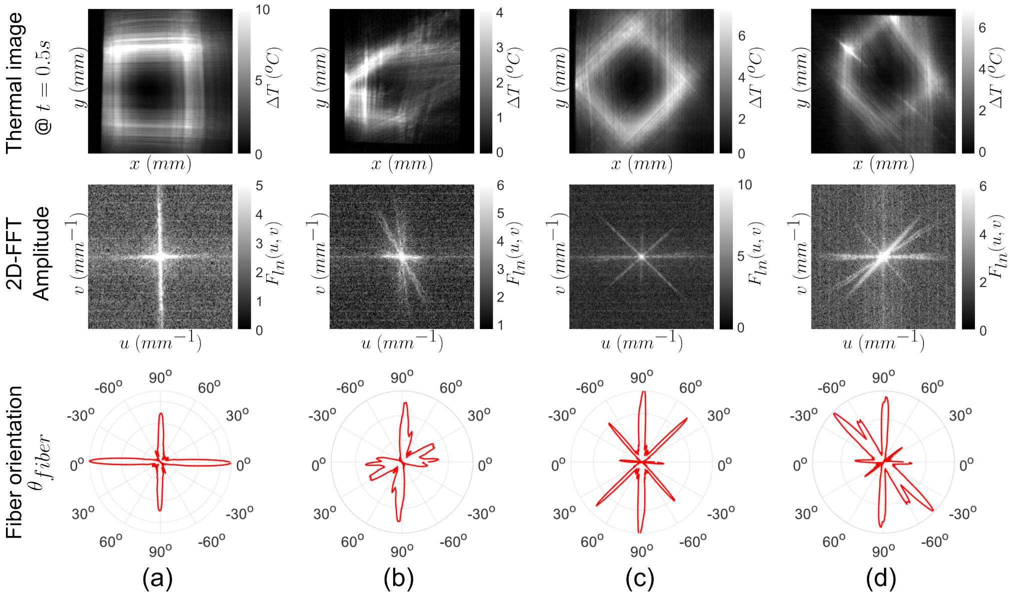

Fig. 1. *Thermograms at $t = 0.5s$ (top row), 2D FFT amplitude spectrum: $F_{ln}(u, v)$ (middle row) and fiber orientation: θ_{fiber} plots (bottom row) for (a) CFRP-4L-1P, (b) CFRP-4L-2P, (c) CFRP-4L-3P, and (d) CFRP-4L-5P*

4. Conclusion

This study has demonstrated that the surface heating patterns of CFRP laminates, obtained through induction heating, reveal essential information about the orientations of the fibers in the material. As the number of active pairs of fiber layers increases, identifying fiber orientations becomes challenging. Therefore, a two-dimensional Fast Fourier Transform-based image processing tool was proposed to extract spatial features of heating patterns and consequently, the fiber orientations. The proposed method was successfully demonstrated to identify fiber orientations with a maximum error of 6^o compared to design orientations. It can also be applied to quasi-isotropic laminates with orientations $k <= 6$ (12 layers). This approach could be extended to detect internal defects such as fiber misalignment, breakages, or waviness.

References

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