Multi-modal characterization of CFRP samples produced by resin infusion using phase contrast and dark-field imaging

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Summary: In this work we present a multi-modal approach to characterize macro- and microstructural features in carbon fiber reinforced polymer samples produced by resin infusion. Imaging of fiber lay-up and defects is carried out using grating-based X-ray imaging, simultaneously providing attenuation contrast, differential phase contrast, and dark-field contrast during image acquisition.

1. INTRODUCTION

Vacuum resin infusion is an advanced approach for the manufacturing of void free composite components showing high performance. During the resin infusion process a mixed resin system is forced into a dry, preformed reinforcing material (e.g. carbon fiber fabric) under vacuum pressure. The main objective during resin infusion is to reach a full impregnation as the resin propagates between the fiber rovings and fibers. The resin infusion process, when carried out correctly, prevents some of the difficulties that can be observed in blight wet-lay composites, such as air voids due to air bubbles trapped in the laminate. Also resin-rich areas or variations in performance characteristic in traditional wet-lay manufacture can be avoided. Hence, this method is suitable for large part production and sandwich structures. However, defects like pores and resin rich zones cannot be completely eliminated, e.g. in carbon fiber reinforced polymer (CFRP) components with complex geometries [1]. Defects can for example be caused by gaps between the fiber preform and the internal mold surface due to mold closure. Those zones are difficult to control and are causing part-to-part variations [2]. Experimental studies showed that the presence of resin-rich areas and resin pockets has a significant effect on the materials´ performance under static, fatigue, and impact loading [3].

In this contribution we show that Talbot-Lau grating-based X-ray micro-CT (TLGI-XCT) is suitable to quantify porosity and resin-rich zones in CFRP parts produced via resin infusion. This method provides three complementary characteristics in a single scan: 1) attenuation contrast (AC), 2) differential phase contrast (DPC), and 3) dark-field contrast (DFC). AC provides information on the attenuation of the X-ray beam intensity. DPC is related to the index of refraction and image contrast is achieved through the local deflection of the X-ray beam. DFC reflects the total amount of radiation scattered at small angles, e.g. caused by microscopic particles, pores, and cracks [4]. Depending on the micro-structure, the scattering has a preferred direction perpendicular to the local orientation, which is reflected by the measured dark-field signal. This immanent physical property of grating-based dark-field imaging can be used to extract directional information about the angular variation of e.g. differently oriented carbon fiber bundles or layers [5]. Hence, the combined application of AC, DFC, and DPC provides information on both the fiber lay-up and defects during image acquisition and post-processing. Results clearly show that TLGI-XCT delivers advantageous image contrast in relation to refraction (DPC) and scattering (DFC).

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2. EXPERIMENTAL METHOD

In total, 6 CFRP samples with a maximum diameter of 14 mm and a thickness of 3 mm were investigated. Samples were manufactured by vacuum resin infusion. Each sample was scanned with an isometric voxel size of (22.8 µm)³ in four different orientations using a desktop TLGI-XCT system (Skyscan 1294, Bruker microCT). Acceleration voltage was 40 KV using 4 phase steps with an exposure time of 600 ms at each phase step. Scan parameters were optimized in relation to fringe visibility. Volume data was reconstructed using filtered back projection using NRecon 1.6.10.0. Each sample was additionally scanned with a voxel size of (5.7 µm)³ using a Nanotom 180NF (GE phoenix | X-ray) system. Acceleration voltage was set to 50 KV with an exposure time of 900 ms. Volume data was reconstructed using filtered back projection using Datos | x.

3. RESULTS

In general, only the component of the scattering perpendicular to the vertically oriented grating of the TLGI system will cause a DFC visibility decrease. Hence, to obtain information about the main orientation of the scattering structures, i.e. fiber rovings, it is possible to measure the angular dependence of this signal by rotating the specimen. Figure 1 shows DFC images of sample 1 obtained from four different orientations. Sample orientation was governed by the general fiber lay-up of this sample batch, namely 0°, 90°, 45°, and -45°. Consequently, in addition to improving the visualization of pores and resin-rich areas in CFRP samples, e.g. using differential phase contrast, TLGI-XCT also provides information concerning the fiber lay-up in the form of dark-field contrast.

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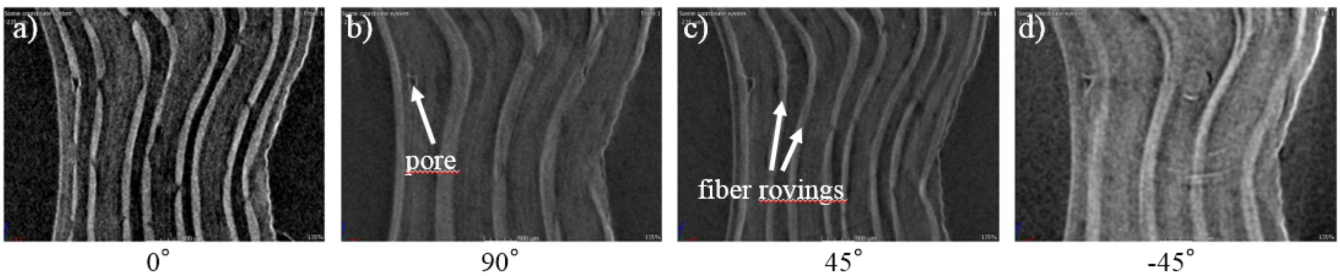

Figure 1: Visualization of the fiber layup in a CFRP specimen produced by resin infusion using dark-field imaging (DFC). The sample was scanned four times in different orientations (a-d). Scan orientation was selected according to the fiber lay-up to extract directional information concerning the fiber rovings.