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FAST CONTINUOUS IN-SITU XCT OF ADDITIVELY MANUFACTURED CARBON FIBER REINFORCED TENSILE TEST SPECIMENS

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Abstract. The reinforcement of fused filament fabricated (FFF) components with continuous fibers allows for high versatility in the design of mechanical properties for a specific applications needs. However, the bonding quality between continuous fibers and the FFF matrix material has high impact on the overall performance of the composite. To investigate the bonding quality within additively manufactured (AM) continuous fiber reinforced specimens, tensile tests have been performed which revealed a sudden reduction in tensile stress, that most likely was not related to actual rupture of continuous fibers. Consequently, within this work we will expand upon these findings and present results of fast on-the-fly in-situ investigations performed on continuous carbon fiber reinforced specimens of the same AM build. During these investigations, specimens are loaded under the same conditions while fast XCT scans, with a total scan time of 12 seconds each, were performed consecutively. The resulting three-dimensional image data reveals internal meso- and macro-structural changes over time/strain to find the cause of the aforementioned reduction in tensile stress.

Keywords: Additive manufacturing, composites, X-ray computed tomography, in-situ tensile testing.

1. Introduction

Fused filament fabrication (FFF) is a widely adopted technique used in additive manufacturing for the production of structural components from scratch. Recent advancements in AM devices have made it possible to reinforce components by incorporating continuous fibers, such as carbon or glass, into the polymer matrix [1]. This reinforcement significantly enhances the strength and stiffness of the manufactured parts. However, despite various studies demonstrating the successful production of composites with highly oriented carbon fibers using FFF, internal defects such as insufficient bonding quality between the embedded fibers and the matrix material remains a significant challenge in FFF-manufactured fiber-reinforced specimens and composite materials in general [2, 3]. Consequently, the behavior of additively manufactured components under load can deviate considerably from the expected values which necessitates the investigation and characterization of complex composite parts for quality assurance. For this purpose, X-ray computed tomography (XCT) serves as a powerful, non-destructive testing method to visualize the internal microstructure in specimens in a three-dimensional manner [4]. In a previous study [5], we examined additive manufacturing (AM) continuous fiber-reinforced tensile test specimens to investigate the influence of fiber quantity and material on tensile strength and AM build quality. During these tests, an unexpected decrease in tensile stress, most likely unrelated to the actual rupture of continuous fibers, was observed. Unfortunately, since XCT scans were conducted only before and after the tensile testing, a detailed analysis of the causes behind these drops in tensile stress was not feasible. Consequently, such studies are typically performed as interrupted in-situ experiments to acquire image data during the mechanical test while blurring of image data is avoided by pausing the tensile strain during the XCT measurements [6]. The interruption of the strain rate however can influence the mechanical behavior of the specimen under investigation and consequently lead to different results of the experiment. In this study, we employ on-the-fly [7] in-situ XCT tensile tests to investigate continuous carbon fiber-reinforced specimens manufactured via FFF. Because of the fast scan time of only 12 s for a single full 360° XCT scan, it was possible to perform a continuous tensile test and consequently, effects arising from specimen relaxation during XCT scanning could be avoided. Thereby we aim to provide valuable insights into the

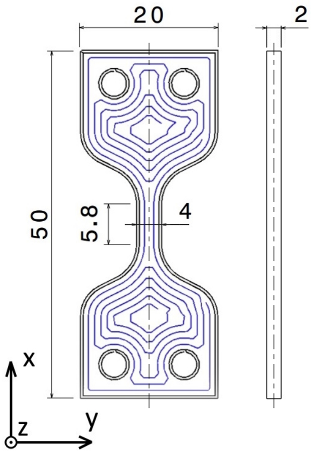

Figure 1. Schematic of a tensile test specimen with dimensions in mm. The print path of continuous fiber reinforcement is indicated in blue color.

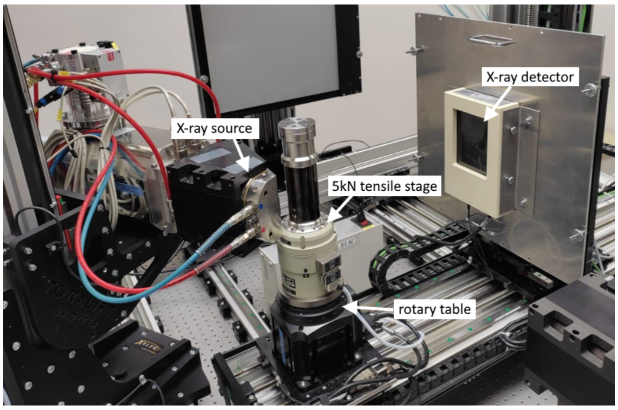

Figure 2. Photography of the measurement setup with the 5 kN tensile test stage mounted to a rotary table between X-ray source and detector.

mechanical behavior in terms of internal meso- and macro-structural changes throughout the course of the experiments.

2. Materials and methods

Although in a previous study only specimens with six continuous fiber reinforced layers have shown the characteristic drop in force under load, for comparison, a total of three different specimens with six (CF6), four (CF4) and two layers (CF2) of continuous carbon fiber reinforcement are produced and tested for this work. The tensile test specimens were produced from short carbon fiber reinforced PA6 (OnyxTM) with additional continuous carbon fiber reinforcement via FFF on a Mark Two device (Markforged, US). Specimens were designed dimensionally proportional to the Type 5A/B samples described by the EN ISO 527-2 standard but reduced in size in order to fit the in-situ tensile test device used for the experiment. The specimen geometrical characteristics and the corresponding dimensions are presented in Figure 1. The Eiger^{TM} software interface, which is integrated with Markforged 3D printers and allows control over the placement of prepreg fibers and matrix polymer beads in each layer, was utilized to define the printing parameters like slicing and deposition strategy. The software automatically imposed a continuous fiber reinforcement printing pattern that followed the contours of the component, as depicted in Figure 1. Thereby, for each reinforced layer, two parallel and symmetrical continuous fiber filaments were placed through the gage region of the specimens. For the deposition of the Onyx matrix material, a solid fill pattern at an infill density of 100 % was chosen, finished by two wall layers in order to ensure a solid and enclosed surface. Apart from the customized settings, standard printing parameters provided by Markforged were applied for nozzle temperature, deposition rate, and print head speed.

The specimens were loaded in a Deben CT5000 tensile/compression stage (Deben UK Ltd.) at a clamp distance of 28 mm and 0.2 mm min^{-1} test speed to achieve a strain rate closest to EN ISO 527-2: 1996 (0.87 % min^{-1}). The tensile force was applied in x-direction (see Figure 1) in displacement-controlled mode to achieve a constant strain rate. During the tensile testing, XCT measurements were performed using a XWT 240 SE X-ray tube (X-Ray WorX, DE) in combination with a Dexela 1512NDT flat panel detector (Varex Imaging, US). The X-ray tube was operated at 60 kV acceleration voltage and 50 W target power. The detector was grabbing images at 15 ms exposure time in 2×2 binning mode at a voxel size of 18 μm. At 800 projection images recorded per specimen revolution, a total scan time of roughly 12 s could be achieved. Subsequently, a backwards rotation of the tensile stage was necessary to avoid winding of its connected wires. Consequently, a new XCT scan could be started every 24 s (see Figure 3). With a scan duration of 12 s and a test speed of 0.2 mm min^{-1} a displacement of 40 μm was applied during each scan equaling a strain of 0.14 % over the entire clamp distance. Consequently, at a voxel size of 18 μm^3 the investigated region of interest in the center of the tensile specimens experiences a displacement of less than about two times the voxel size of the image data. However, at the target power of 50 W a focal spot size of approximately 50 μm is achieved and given the associated image blurring the displacement during scanning was considered negligible for the investigations planned. The full measurement setup can be seen in Figure 2.

3. Results and discussion

The start and end of each XCT scan was labeled as Fn,0 and Fn,1 respectively, where n is the number of each consecutive scan. As expected from preliminary investigations, the mentioned drop in force in the CF6 specimen is noticeable in the force over strain diagram in Figure 3 roughly around 520 N, shortly after F3,1.

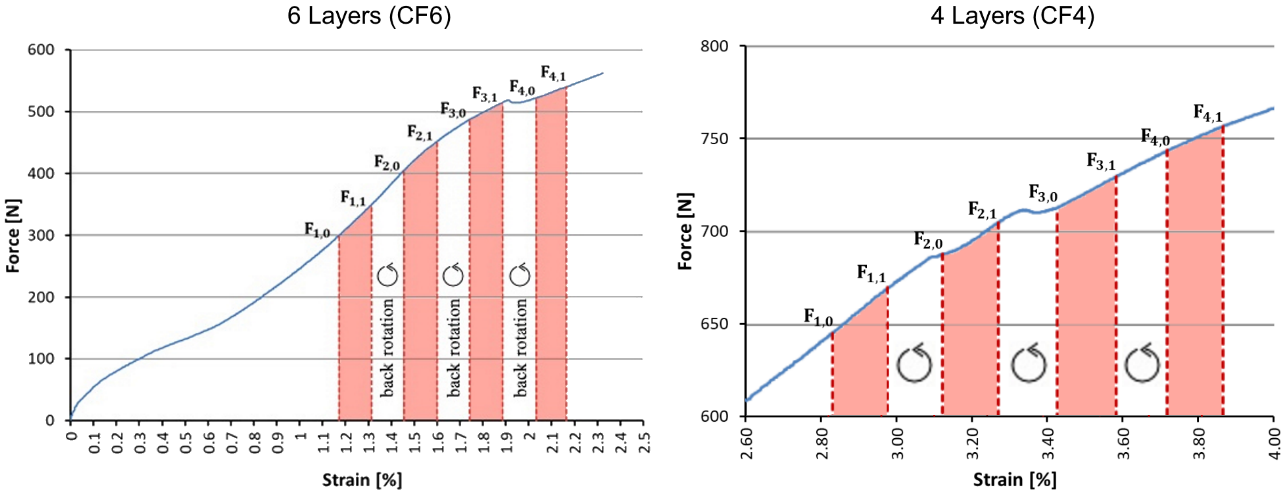

FIGURE 3. Force over strain diagram during continuous in-situ test for a specimen with six and with four continuous fiber reinforced layers, respectively. The diagram for the CF4 specimen is a zoomed section to enhance visualization of the comparably small bumps in force. On-the-fly XCT scans were performed during Fn,0 to Fn,1.

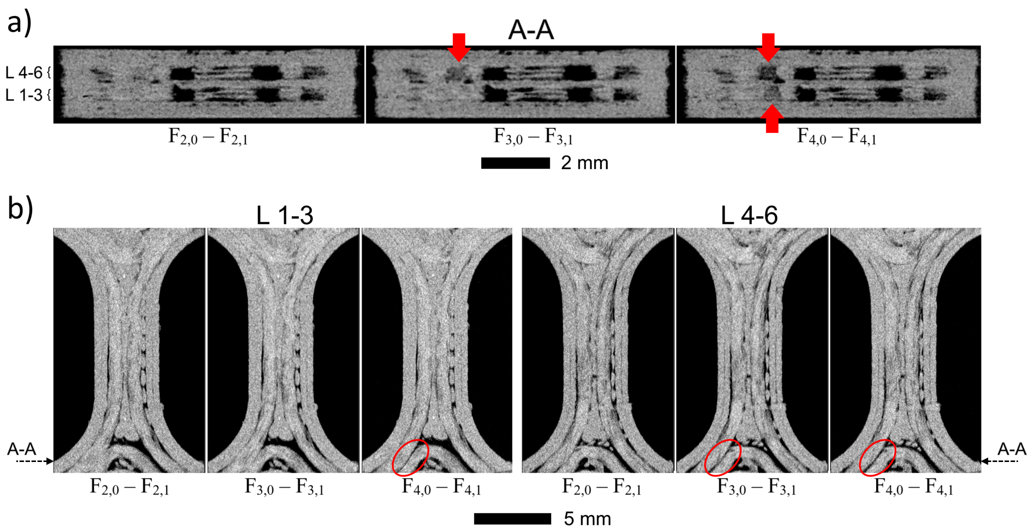

FIGURE 4. a) Minimum intensity projections over a 0.5 mm thick cross-section in the y-z-plane at the region where delamination has been observed. Red arrows indicate the delamination of layers L 4-6 in scan F3 while in scan F4 remaining layers were affected as well. b) Cross-sections in the x-y-plane visualizing the delamination at different layers and tensile strain.

Consequently, the structural changes causing the drop should be visible latest in Scan F4. In the CF4 specimen a similar behavior is noticeable in the force over strain diagram but divided into two separate, less distinct drops happening over a wider period of time. In the CF2 specimen no significant delamination could be observed until fiber failure.

In Figure 4 and Figure 5 we find that due to the automatically generated print path of continuous fibers along the specimen contour not all continuous fibers are aligned in direction of the applied tensile strain. Besides the generally poor bonding quality, which leaves gaps between continuous fibers and matrix material over wide regions, it becomes obvious from XCT image data that the deposition of continuous fibers diagonally to the applied strain can lead to additional debonding between continuous fiber bundles and surrounding matrix material. In the CF6 specimen this detachment was noticeable within the third and fourth scan iteration (F3-F4) which coincides with the drop in force that happens between these two scans as well. Consequently, it is reasonable to assume this effect is related to the delamination of fiber bundles from the matrix material. In the CF4 specimen delaminations appear in similar regions as in the CF6 specimen but less distinctly (see Figure 5). However, first signs of detachment were noticeable already in the second scan iteration explaining the separate bumps at roughly 3.1 % and 3.3 % strain in the force over strain curve.

As previously has been shown for specimens manufactured under equal conditions [8], porosity tends to increase in printing direction, indicating reduced

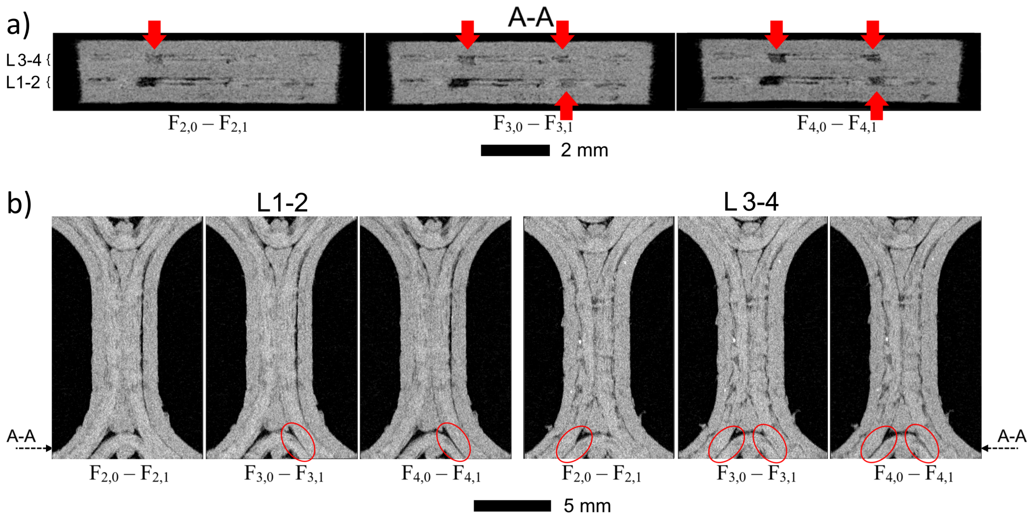

Figure 5. a) Minimum intensity projections over a 0.5 mm thick cross-section in the y-z-plane at the region where delamination has been observed. Red arrows indicate the delamination of fiber reinforcement and matrix material. b) Cross-sections in the x-y-plane visualizing the delamination at different layers and tensile strain.

build quality towards the top of the specimens (in z-direction). This effect is most likely coupled to the non-isothermal temperature distribution in z-direction during the printing process [9]. Results of the fast continuous XCT scans have shown that continuous fiber bundles located further to the top of the specimens (in z-direction) also tend to detach from the surrounding matrix material first. Hence, within the top layers L4-6 in the CF6 specimen and L3-4 in the CF4 specimen respectively, first signs of debonding was visible one scan iteration, and consequently roughly 0.3 % in strain, earlier than in other layers (see Figure 4 and Figure 5). This indicates that the increased porosity in higher layers, or generally poorer print quality respectively, is affecting the bonding quality of continuous fibers as well. Additionally, in the current investigations it became obvious, that the bonding quality within individual layers can also vary considerably. Generally, these specimens are characterized by rather poor intralaminar bonding between continuous fibers and matrix material. However, in Figure 4b it is noticeable that the bonding within this specimen is worse on the lower side (in x-direction) of the specimen, partially with huge gaps between the materials. The delamination of continuous fibers was also primarily observed in this region, while the bonding on the opposite side was relatively good. As preliminary work [5] has revealed, specimens that were affected by this characteristic drop in force, supposedly caused by fiber delaminations, also had significantly reduced total tensile strength. Consequently, specimens with higher amount of continuous fiber reinforcement happened to show lower tensile strength compared to specimens with less reinforcement but better bonding quality.

4. Conclusions

Continuous on-the-fly XCT has proven to be an invaluable tool for the investigation of dynamic processes during mechanical testing of composite materials. With the fast acquisition the investigation of characteristic drops in force during tensile testing was possible without the need of interrupting the experiment for XCT scans which could possibly obscure such features during the relaxation of the specimens prior to each scan. As the delamination of continuous fibers predominantly starts in layers located further towards the top of the specimen in printing direction (z-direction), the results suggest the decrease in print quality in this direction affects the bonding quality of embedded continuous fiber reinforcement as well. This highlights the importance of bonding quality once more, as specimens that were affected by the characteristic drop in force, also showed significantly reduced total tensile strength in previous investigations [5].

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