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Scan quality optimization for measuring Fiber-Metal-Laminates with X-Ray computed tomography

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Abstract

In this study, X-Ray computed tomography is used as an inspection method for Fiber-Metal-Laminates (FML) with an aluminum core and a carbon fiber reinforced thermoplastic matrix. As the mechanical characteristics of thermoplastic based FML strongly depend on the quality of the interface between metal and laminate, it is important to particularly investigate this region. However, the aluminum core may cause beam-hardening artifacts, which reduce the image quality especially in high-resolution scans. Therefore, a parameter study was carried out using different combinations of metal filters out of aluminum and copper to find an efficient balance between artifact reduction and scan duration. The investigated FML-specimens are used for short-beam shear tests (SBS). The optimized parameters lead to a scan quality, which allows for a more detailed description of both matrix cracking and delamination at the interface between the aluminum core and the fiber-reinforced-polymers (FRPs). As a reference measurement of the FML specimens, we used a computed tomography scan acquired at the Synchrotron radiation facility SOLEIL.

Keywords: cone-beam CT, beam-hardening, synchrotron CT, scan parameters, fiber-metal-laminate, CFRP

1 Introduction

Fiber-Metal-Laminates are hybrid composite materials, which contain thin layers of metal sheets between the FRPs. Combining both materials leads to advantages like superior strength, fatigue resistance, fracture toughness and impact resistance compared to conventional FRPs [1]. Due to these characteristics, FML are already used for different aircraft applications like large fuselage elements [2]. However, potential defects induced during production or further processing can lead to a significant deterioration of the overall performance. Thermoplastic matrix based FRPs, like the ones demonstrated in this study have several advantages when compared to conventional thermoset based FRPs, like better impact and chemical resistance as well as reparability and reprocessing possibilities [3]. Besides, fabrication time and costs can be reduced because of the simple manufacturing process where only melting and consolidation is required. Therefore, FMLs have become an important research subject [4, 5]

When manufacturing FMLs, the joint technologies for combining the material components have a huge impact on the durability. Therefore, it is crucial to inspect these materials by non-destructive methods. Conventional methods like 2D X-Ray radiography, thermography and ultrasonic methods are well suited for the detection of certain damage types but are often limited in terms of resolution. To detect smaller defects like fiber misorientation, fiber fracture, matrix cracking or delamination at the interfaces, a higher resolution is necessary which can be achieved with X-Ray computed tomography [6, 7]. However, when measuring multi-material components like FMLs, beam hardening and scattered radiation can lead to severe artefacts, which lower their image quality especially at the interface between metal sheet and FRPs. A well-established method to reduce the non-linear behavior of the multi-material specimens is the usage of filter materials within the beam path of the CT-scan. This paper presents a case study to optimize the scan procedure for aluminum based FMLs to assess the bonding quality volumetrically focusing on the interface between aluminum and FRPs.

2 Experimental methodology

2.1 Specimens

The specimens examined in this measurement series consist of an Al1050 aluminum core (0.3 mm thickness) and two outer layers of carbon fiber reinforced PA6 (containing 5 laminate layers each) in $[0^\circ]$ fiber orientation as shown in Figure 1. The fiber orientation was chosen according to the SBS (DIN EN 2563) testing standard. The beam hardening effect was compared between six different filter combinations as well as to a scan without any filters and a scan using synchrotron radiation. One specimen was scanned with the established parameters after short-beam shear testing to demonstrate the possibility of assessing the interlayer and possible failure modes.



CFRP $[0^\circ]_5$	1.25 mm
Aluminium	0.3 mm
CFRP $[0^\circ]_5$	1.25 mm

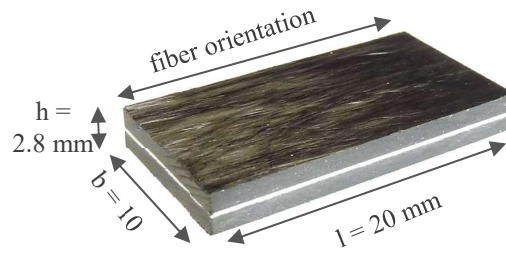


Figure 1: Stacking sequence of the FMLs (left) and specimen dimensions for SBS testing

The FML was manufactured with a heating press using pre-impregnated PA6-tapes. The samples were then cut with a water-cooled diamond blade.

2.2 Evaluation Method

As a typical effect of beam hardening, the contrast at the edge of the aluminum sheet is significantly different from the bulk region. Therefore, the imaging quality for the different settings is compared by plotting the gray value profiles along the dashed lines seen in Figure 2. As quality indicator, the slope of the edges at the aluminum-CFRP transition can be evaluated by a linear regression as shown in Figure 3. Each volume scan was investigated within the same cross-section at the middle of the specimen.

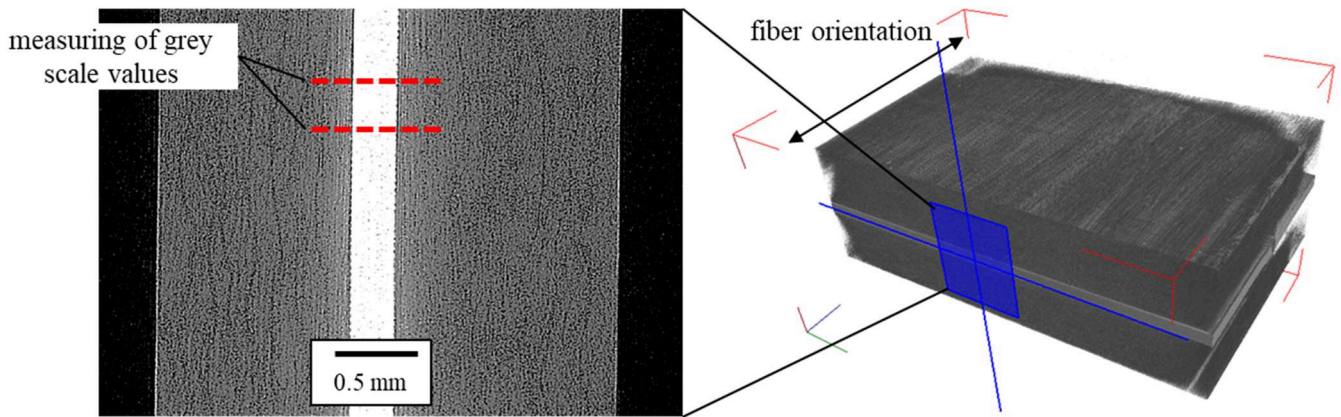


Figure 2: Cross section of specimen showing contrast between aluminum and CFRP (left) and position of selected region of interest (ROI) in the volume rendering of the specimen

2.3 Computed tomography

The specimens were scanned on a phoenix nanotom m system (General Electric). X-Rays were generated by a diamond target using a voltage of 120 kV and a current of 100 μ A. The effective voxel size was 3.18 μ m with an exposure time of 2000 ms averaging three pictures and skipping one. 1000 images were taken in each case, the reconstructed volumes were analyzed with VGStudio 2.1. For this study, we applied copper and aluminum filters in front of the X-Ray window in a thickness range between 0.1 mm and 0.3 mm as well as combinations thereof. To generate images with similar intensity for the different filter approaches used in this comparison, more images were averaged accordingly. For comparison, the same sample was investigated at the Synchrotron SOLEIL at the beamline PSYCHE with a voxel size of 0.86 μ m. The segmentation shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** was done using a region grower for grey values within a selected range. The segmentation was performed with AVIZO 2019.3.

In each filter setting, a representative cross section of the inner part of the volume (as seen in Figure 2) was used to extract the grey value profiles at the interface of the FML. Three profiles in each volume were used to generate the slope values shown on the right side of Figure 3. Visually, a higher slope corresponds to a noticeable improvement of the interface sharpness. This is highly desired to reveal details of defects occurring in this interface region. The absolute grey value difference corresponds to image contrast.

Table 1: Scanning parameters and filters used for each X-Ray scan (XCT) and the Synchrotron scan (SCT)

No.	condition	Radiation	Integration time/ #Image stacking	Voxel size [μm]	Filter Combinations/thickness [mm]
1	Before SBS	XCT	2,000 ms/3	3.18	none
2	Before SBS	XCT	2,000 ms/3	3.18	Aluminum 0.1
3	Before SBS	XCT	2,000 ms/3	3.18	Aluminum/0.1 + Copper/0.1
4	Before SBS	XCT	2,000 ms/3	3.18	Copper 0.2
5	Before SBS	XCT	2,000 ms/4	3.18	Copper 0.3
6	Before SBS	XCT	2,000 ms/4	3.18	Aluminum/0.1 + Copper/0.3
7	Before SBS	XCT	2,000 ms/4	3.18	Aluminum/0.3 + Copper/0.3
8	Before SBS	SCT	(pink beam)	0.86	none
9	After SBS	XCT	2,000 ms/3	2.70	Copper 0.2

3 Results

Overall, the evaluation displays a clear trend to improved interface imaging (edge sharpness) with thicker filters. The slope of the regression line of the synchrotron measurement is 1.08×10^9 despite the smaller voxel size, which clearly shows the quality of a wider radiation spectrum. For scaling reasons, it was left out of the diagram in Figure 3. The other samples are listed with ascending filter thickness and measuring time.

Considering the measuring time, the use of a copper filter with 0.2 mm delivers a reasonably good image quality close to the ones with noticeably thicker filters.

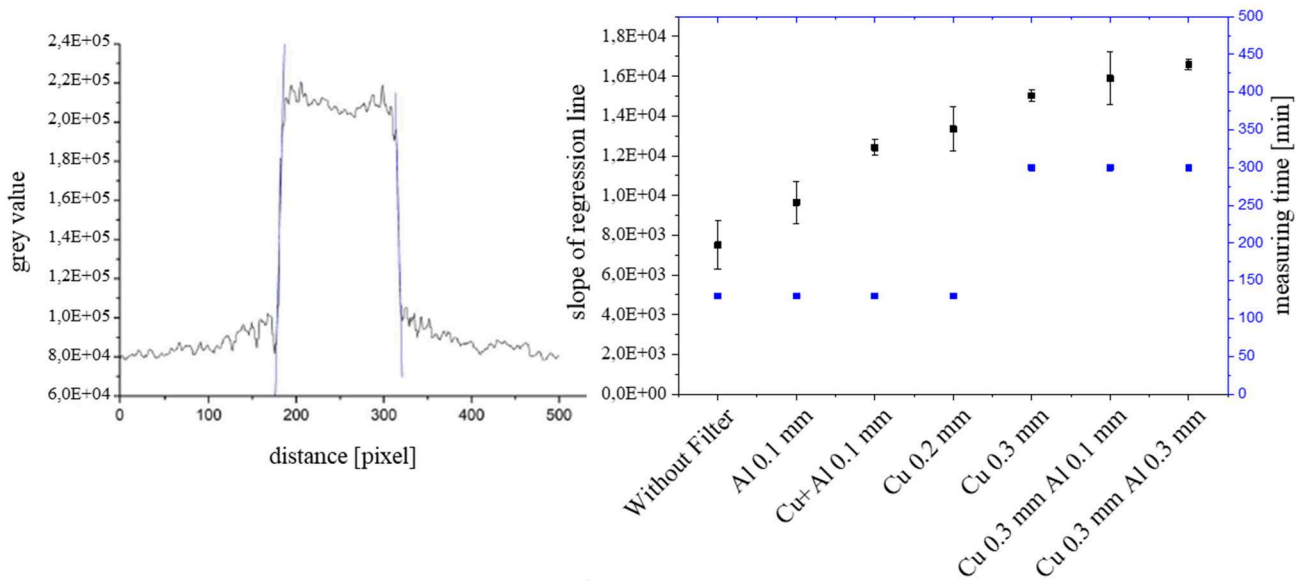


Figure 3: Profile plot of cross section and regression line (blue) at the edges between aluminum and FRP (left), comparison of the influence of different filter combinations (right)

Fehler! Verweisquelle konnte nicht gefunden werden. shows a 2D cross-section of a SBS-tested sample as well as a combination of an ortho slice and the segmented aluminum core. Although there are noticeable beam-hardening artefacts at the short edges of the aluminum layer, the direct interface to the CFRP layer has a sharp edge. However, the scan shows that depending on the specimen's geometry, beam-hardening is influencing the image quality significantly. The aluminum layer can still be segmented without the artifacts at the short edges using a manual seeding based segmentation process.

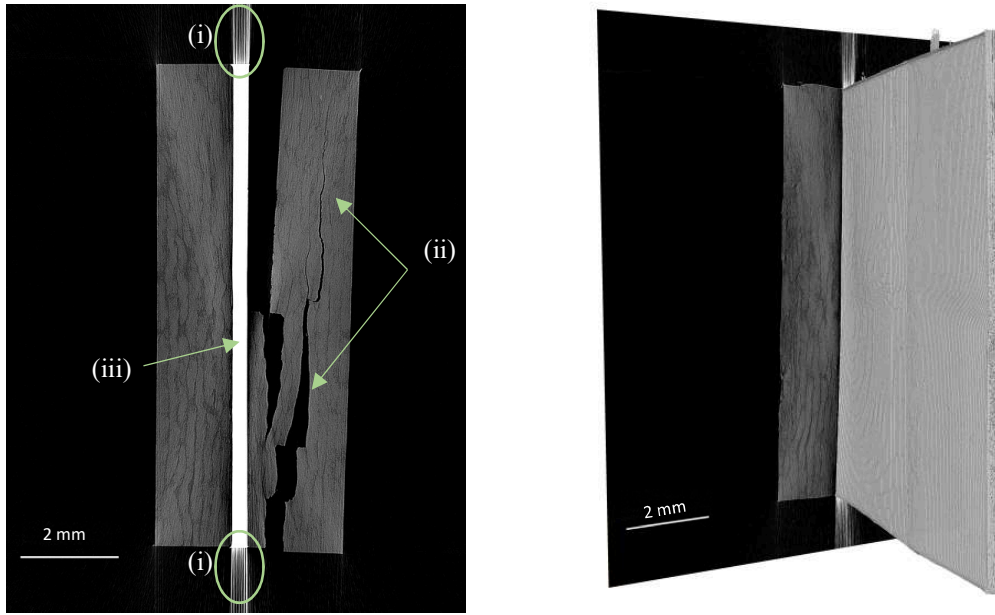


Figure 4: Specimen No. 9 after SBS testing. Beam hardening is clearly visible at the long edges (i) of the aluminium foil, however there is clear edge at the interface to the CFRP layers. Matrix failure (ii) and delamination at the interface (iii) can be identified.

The quality of the scan using a 0.3 mm Copper filter allows for segmentation close to the aluminum layer and thus for dimensional and geometric measurements of defects within this area. The segmented region is shown in **Fehler! Verweisquelle konnte nicht gefunden werden..** Segmented defects can be quantified in terms of volume and surface. As a result, the cohesive and adhesive failure share at the aluminum interface can be evaluated with this image quality.

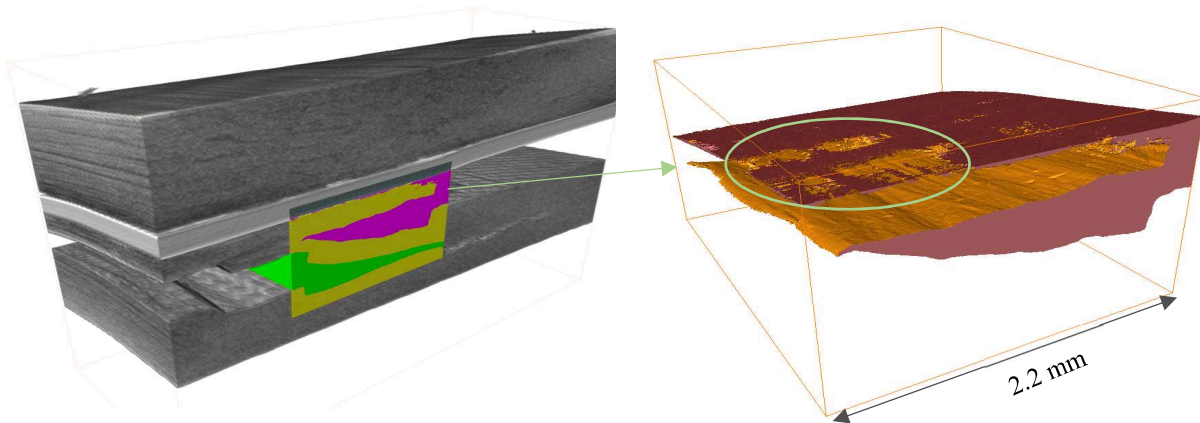


Figure 5: Region of Interest after SBS testing, segmentation of damage close to the aluminum surface. The segmented defect on the right shows parts of the delamination as well as cohesive and adhesive failure.

4 Conclusion

X-Ray computed tomography has been used as a non-destructive testing method to gain insight into FMLs, focusing on the interface between aluminum and the FRP layer. The study shows that the use of different metal filters causes significant differences regarding beam hardening artefacts and thus resulting in sharper edges. With suitable filters, the quality of the interface edges allows for segmentation of delamination within this region.

In the best constellation with the filter setting Cu 0.3 mm + Al 0.3 mm and a measuring time of 300 minutes however, the resulting gradient is still smaller than the reference measurement of the Synchrotron computed tomography by a factor of 7×10^4 . Regarding the measuring time, the usage of a Copper filter with 0.2 mm allows for a reasonable image quality, which is sufficient for segmentation of delamination up to a thickness of 10 μm with the given resolution of 3.18 μm voxel size.

Overall, the hardware filtering technique improves the measurement capabilities to a degree where defects like delamination close to the aluminum layer can be detected up to a very high resolution.

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