Non-Destructive Series Testing of Large Fiber-Reinforced Components

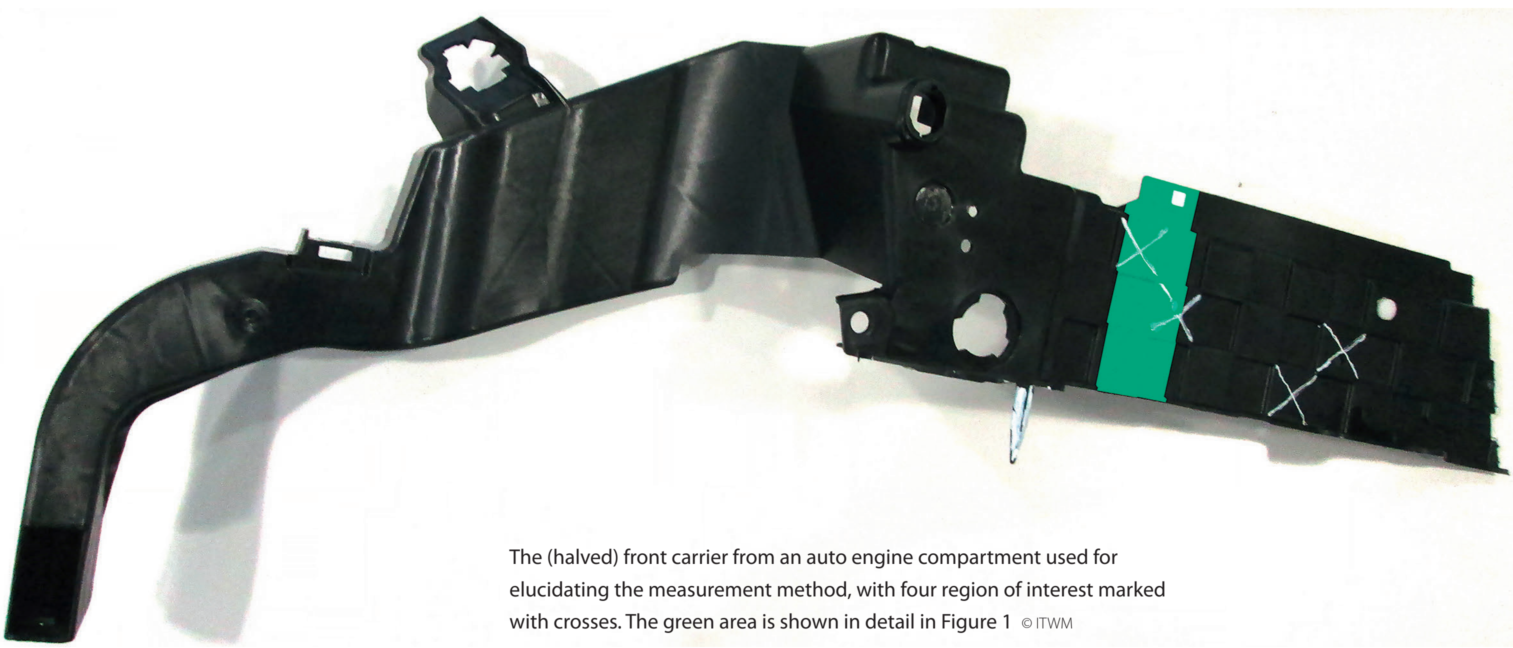
"Region of Interest" (ROI) Computed Tomography for Local Analysis of the Fiber Orientation without Sampling

The local fiber orientation in composite materials can be analyzed non-destructively using microcomputed tomography. In practice, however, usually small samples are taken from larger components in order to avoid imaging errors. However, the ROI method allows parts of a size relevant to practice to be analyzed directly.

The local fiber orientation influences the mechanical properties of fiber-reinforced plastic (FRP) parts. It can be analyzed with the aid of 3D image data provided by microcomputed tomography (µCT). Although this method is non-destructive, samples with a few millimeters edge length are usually cut from larger parts in order to avoid imaging artifacts. Here, it is shown that images of subregions from large glass fiber-reinforced carriers, combined with orientation analysis of the 3D texture permit the µCT method to be actually applied non-destructively to parts of a size relevant to practice.

Fiber-composite components that are subject to high mechanical loads or safety-relevant must be reliably non-destructively tested, since their mechanical properties critically depend on their anisotropic microstructure, which varies within a part due to the production process. In general, glass and carbon fibers are stiffer than the surrounding plastic matrix and therefore have a strengthening effect in the fiber direction. The part behavior of fiber-reinforced plastic parts therefore depends crucially on the local volume density and the local orientation of the reinforcing fibers.

Spatial imaging with µCT provides this valuable microstructure information: the method generates three-dimensional volume images, whose intensities (grayscales) essentially reflect the X-ray absorption of the respective material component. Glass fibers consequently appear light-colored in a polymer matrix. For carbon fibers, the imaging contrast is low. If denser matrix polymers are used, the grayscale contrast is inverted, i.e. the ma-



The (halved) front carrier from an auto engine compartment used for elucidating the measurement method, with four region of interest marked with crosses. The green area is shown in detail in Figure 1 © ITWM

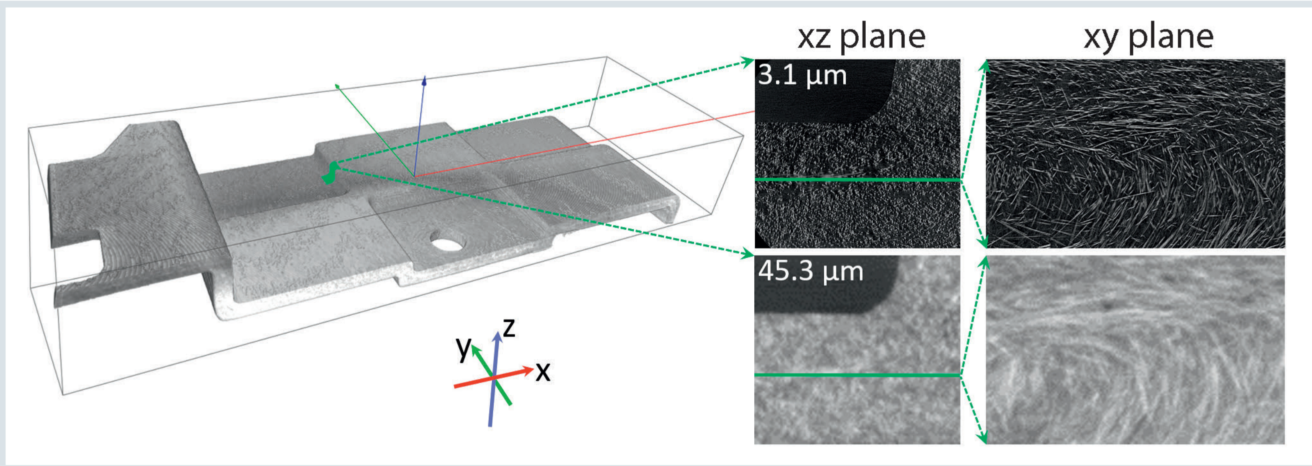


Fig. 1. Volume rendering of the region marked green in the Title figure and cross-sections from the 3D images of region of interest A3 with highest and lowest resolution © ITWM

trix appears light colored compared to dark carbon fibers.

For analysis of the fiber orientation with voxel precision, 3D scans with voxel edge length Δx of 1/3 of the fiber thickness or finer have been used until now, i.e. for 10µm fiber thickness, that is Δx ≤ 3.5 µm. Larger parts were cut up into small samples with edge lengths of a few millimeters in order to image them in high resolution in the cone-beam of the tomograph. These problems are overcome with region-of-interest CT (ROI-CT) combined with 3D texture-orientation analysis. Quantitative fiber-orientation analysis based on ROI-CT images is a non-destructive quality assurance method suitable for series testing.

FRP Part from a Car Engine Compartment

The methodology is explained with the aid of a front carrier from a car engine compartment. The carrier of injection molded glass fiber-reinforced polypropylene (PP-LGF30) is approx. 90 cm long and 35 cm wide and serves to receive the hood lock, the hood buffer, the radiator and the front headlamp, and also contributes to impact protection. 30 % of the weight is accounted for by long glass fibers with 10 to 20 µm thickness and 10 to 15 mm length (before processing). The wall thickness of the structure is approx. 2 mm. Flow simulations of the manufacturing process formed the basis for choosing regions for 3D imaging with ROI-CT and fiber orientation analysis (**Fig. 1**).

If the µCT scanner has a suitable configuration (long source-detector distance), small sample sections from large parts can also be measured with fine three-dimensional scanning without the need to cut regions out of the part. The MetRIC µCT scanner from Fraunhofer EZRT is designed especially for such ROI-CT. It has a microfocus transmission tube and an X-ray flat-panel detector. The construction of the scanner allows high-precision positioning of the sample and measurement regions (regions of interest) within the sample. The extremely large focus-detector distance (up to 3.3 m) as well as 10 motorized degrees of freedom permit voxel edge lengths up to 3 µm, also in parts several centimeters thick. Artifacts that may occur in the volume-image reconstruction due to the ROI geometry are avoided by continuous sample rotation and by window functions during filtering of the projection images.

Local Fiber-Orientation Analysis

The computed CT- image represents the entire measurement region as a set of voxels. Each voxel corresponds to a cubic volume element in the region of interest. Correspondingly, individual fibers in the reconstructed CT-image can only be identified as individual image objects in the case of low fiber-volume contents and with very high local resolution. In the case of glass fibers, the fiber component can be easily distinguished from the matrix. For this material, image pro- »

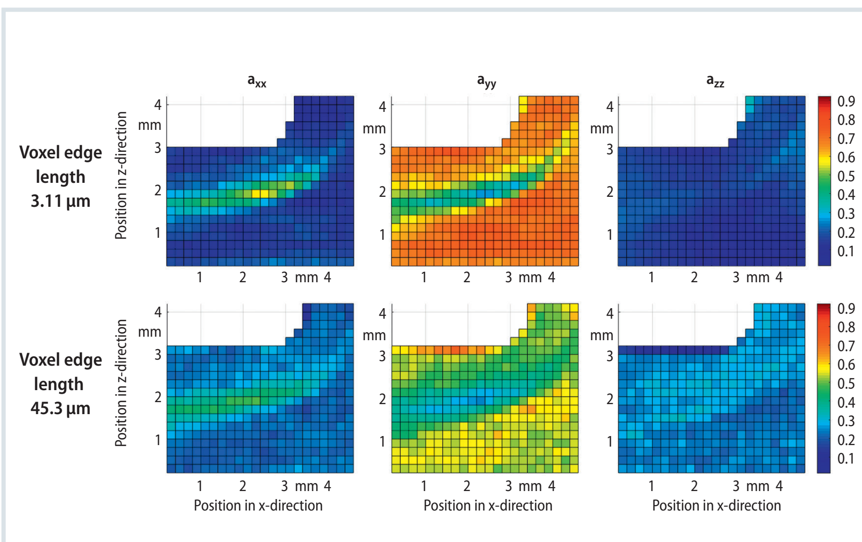


Fig. 2. Diagonal components of the 2nd order orientation tensor measured from the CT images. Sections through the 3D images in the xz-direction in the coordinate system from Figure 2 are shown (y: injection direction, z: thickness direction) source: ITWM, graphic: © Hanser

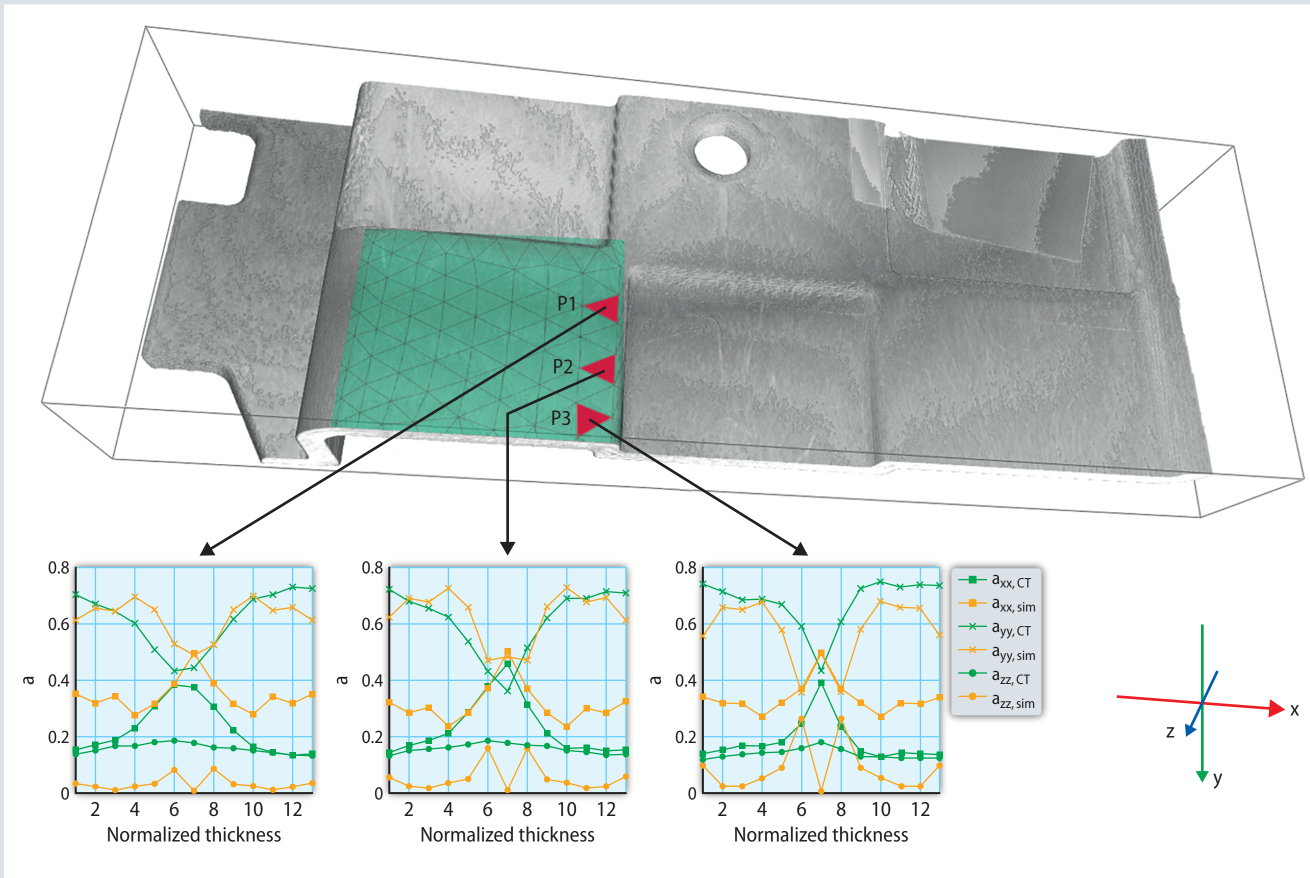


Fig. 3. Diagonal components of the 2nd order orientation tensor, comparison of the orientation predicted by injection molding simulation (orange) and the orientation measured in the 3D images with highest resolution (green). The position of the regions used in the simulation is marked red in the volume rendering source: ITWM, graphic: © Hanser

cessing algorithms have been developed over the last decade that compute a preferred spatial direction (the direction of the fiber axis) from the grayscales of the individual voxels of the fiber component. For a detailed description of the voxel-precise methods and a comparison see [1]; for an overview of the different algorithm classes for global, locally averaged or voxel-precise fiber orientation analysis, see [2].

The algorithm applied here utilizes the Hessian matrix of the 2nd partial derivatives of the voxel grayscales in the immediate neighborhood of a pixel: as a local fiber-direction, the algorithm finds the one that is least curved in the grayscale histogram, i.e. the eigenvector of the smallest eigenvalue of the Hessian matrix. Uninformative values from matrix voxels are hidden. The 2nd order orientation tensor is subsequently derived. For this analysis, it was necessary to resolve the fiber diameter of 10 to 20 µm with at least three voxels. With a coarser resolution, the measurement results are actually shifted slightly toward isotropy; nevertheless, for the carrier investigated here, the orientation tensor could still be determined very accurately, even with voxel edge lengths of 45 µm, i.e. much coarser than the fiber thickness (**Table 1**). **Figures 1 and 2** show ROI scans and analysis results.

Comparison with Flow Simulation

With the aid of the 3D images (ROI-CT with high resolution was used here), the actual local microstructure can be compared with that predicted by simulation of the flow behavior in the part as a whole. For three partial regions, the 2nd order orientation tensors simulated with Moldflow were compared with the tensor components determined from the

Region of interest	Size in the sheet plane	Voxel edge length	Anisotropy index	Diagonal components of the 2nd order orientation tensor		
				xx	y	zz
A3c	4.9x2.5	45	0.61	0.23	0.54	0.21
A3m	2.0x1.4	21	0.60	0.22	0.54	0.22
A3h	1.0x0.7	10	0.65	0.21	0.58	0.21
A3uh	0.6x2.3	3	0.78	0.18	0.66	0.17
A3uh.1	0.6x0.4	3	0.75	0.18	0.63	0.18
A3uh.2	0.6x0.4	3	0.78	0.16	0.67	0.16
A3uh.3	0.6x0.4	3	0.76	0.18	0.64	0.16
A3uh.4	0.6x0.4	3	0.78	0.17	0.65	0.16
A3uh.5	0.6x0.4	3	0.77	0.18	0.63	0.17
A3uh.6	0.6x0.4	3	0.77	0.19	0.63	0.17

Table 1. Diagonal components of the 2nd order orientation tensor, measured in 3D images of the region of interest with different resolutions source: ITWM

ROI-CT. In the dual domain mesh, the entire carrier has 170,000 elements with an edge length of approx. 2 mm. This 2.5D mesh only has surface information, while a 3D mesh contains information, or data, for the entire part thickness. For the simulation, the rotational-diffusion model with default settings was used. The CT data were subdivided into regions of comparable size, but cubic.

Figure 3 shows the diagonal elements of the simulated orientation tensors determined by image analysis. The components in the sheet plane agree very well qualitatively; though quantitatively, the image analysis shows greater anisotropy than predicted by the simulation. The strongest deviation can be seen for the component perpendicular to the thickness direction, with conspicuous peaks in the simulated values for the central layer. These features do not occur in the ROI-CT measurement.

Conclusion

Using a standard component from automotive engineering, it has been demonstrated that ROI-CT can generate 3D image data for large FRP components with a quality adequate for a detailed local fiber-orientation analysis. The prerequisite for this is that the sample can be positioned in the tomograph with a sufficiently large number of degrees of freedom and extensive movement paths.

It was also shown that, even with voxel sizes well above the fiber diameter, local orientations can be (at least qualitatively) analyzed. The results for voxel edge lengths between 45 µm and 3 µm are consistent, the flow direction was always identified as the main fiber direction, but also the typical incorrect orientation of the central layer was found at each of the resolutions investigated. With coarser resolutions, however, the local structural information is smeared, which distorts the results of the orientation analysis toward isotropy. However, comparisons of the results for voxel edge lengths 45 µm, 21 µm and 10 µm also show that it is not the voxel edge length alone that decides how good the orientation can be measured using a 3D image. The signal-to-noise ratio (interpreted three dimensionally, see [3]) plays just as much a role as the nature of the material.

The comparison with the flow simulation shows qualitatively good agreement, especially for the dominant tensor component in the flow direction. Image analysis using CT images is consequently very highly suitable for validating spatio-temporal simulations of injection molding processes. ROI-CT thus has the potential to become the standard tool for local fiber-orientation analysis of GRP parts. Comparable investigations on CRP samples are also highly promising. ■

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