MICRO-COMPUTED TOMOGRAPHY MEASUREMENT OF THE FIBRE MISALIGNMENT IN THE IN- AND OUT-OF-AUTOCLAVE AFP/ATL COMPOSITES

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Abstract

A method for characterization of fibre misalignment in composite laminates manufactured by automated fibre placement/tape laying (AFP/ATL) is presented. It is applied to laminates produced with in-autoclave (prepreg technology) and out-of-autoclave (vacuum assisted resin infusion) processes. The measurement identifies three types of the fibre misorientation: deviation of the tapes from their nominal direction and inter-tape scatter of the fibre in-plane and out-of-plane orientation angles. For both materials the tape misorientation is about 1° or less (in different plies); the fibre out-of-plane misorientation (standard deviation of the angle) is 1…2°. The inter-tape fibre misorientation in-plane is 1…2° for in-autoclave and 2…4° for out-of-autoclave laminates. The results can be used for estimation of properties such as stiffness, strength, and permeability, as well as for evaluation of manufacturing allowances associated with the precision of the AFP/ATP process.

1. Introduction

Automated Fibre Placement (AFP), an automated process to lay thin tows of fibrous material on a flat or curved part surface, shows great potential for efficient manufacturing of large and complex composite structures [1]. AFP can be used with thermoset and thermoplastic prepregs. For dry tapes, it is also known as (Automated) Dry Fibre Placement or (Automated) Dry Tape Laying – ATL. Below the abbreviation AFP is used collectively to designate these processes.

Although AFP is a precise and automated process, materials produced with it have specific microstructural inhomogeneities and defects, such as gaps and overlaps of the tapes, voids, local delaminations and misalignment of fibres. Since carbon fibre is a highly anisotropic material, any deviation of the direction from the nominal or curvature of the fibre can lead to a significant reduction of material properties, especially the compressive strength [2, 3]. Characterisation of fibre (mis)alignment is therefore essential in the process design and the material characterisation.

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In the present paper this characterisation is carried out using X-ray micro-computed tomography (micro-CT). The micro-CT data set (3D image) is then used as input for VoxTex software (developed at KU Leuven) to define the orientation distribution of fibres. The algorithms employed in VoxTex are described in detail in [4]. This measurements are done for two types of carbon/epoxy laminates, produced with in- and out-of-autoclave processes.

2. Materials and micro-CT imaging

Two different types of carbon fibre reinforced plastics are characterized in the present study. Both laminates are created with AFP processes. The difference is in the impregnation techniques.

The first material ("material A" below) is made with Automated Dry Fibre Placement and resin infusion (out-of-autoclave) at NLR, the Netherlands. The composite material is reinforced with dry AS7 carbon fibre tows. The areal density of the tape is 126 g/m^2, and the tape width is 6.35 mm (1/4 inches). The stacking sequence of the laminate is $(-45/0/45/-20/0/20/90/0)_{so}$, the superscript "so" stands for "symmetric odd": the laminate is symmetric with an odd number of plies. HexFlow RTM6 resin was used for infusion. The fibre volume fraction of the composite is 50%.

The second material ("material B" below) is produced by Automated Tape Laying (ATL), and cured in autoclave at SABCA Limburg, Belgium. The tape prepreg is *Hexcel AS4/8552 RC34 AW194*, which is a toughened epoxy resin system reinforced with unidirectional carbon fibres. Tape thickness and width are 0.186 mm and 150.0 mm, respectively. The nominal fibre volume fraction is 57.4 %. By means of ATL, an 8-layer laminate is produced with a stacking sequence of $(67.5, 22.5)_{2S}$. After laying up, the laminate is cured in an autoclave according to the recommended cure cycle.

The samples were scanned with Skyscan 1172 X-ray computed tomography system. The cross section images and a 3D view of material A are shown in Figure 1.

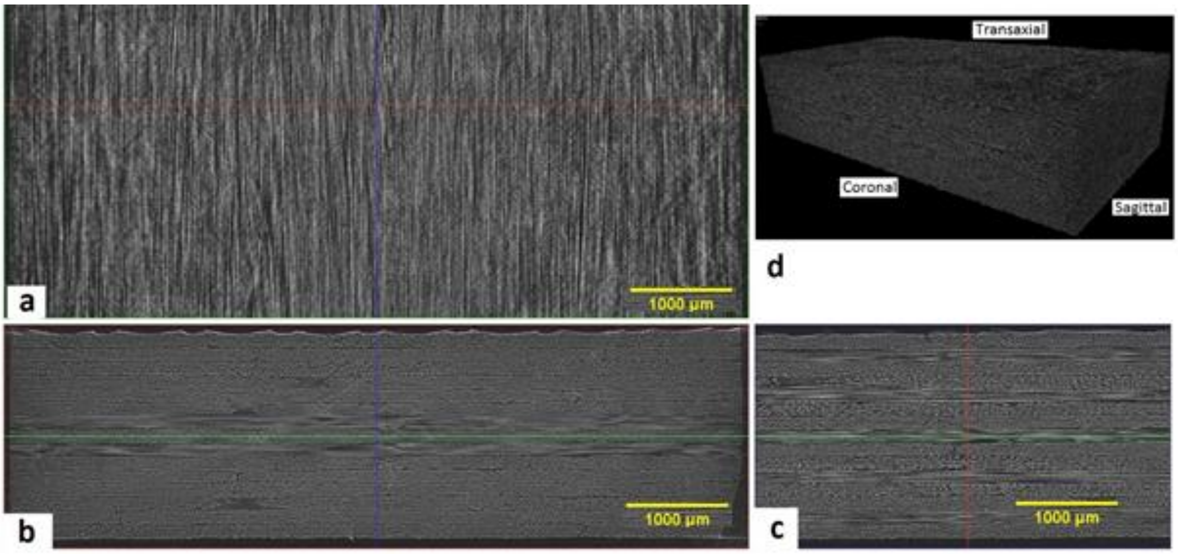

Figure 1. Cross section images of material A scanned in the 0 degree direction
(a) Transaxial cross-section, (b) Coronal cross-section, (c) Sagittal Cross-section, and (d) a 3D view.

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3. Orientation analysis

VoxTex software was used to compute the orientation vectors at a set of equidistant points ("voxels") in the micro-CT images and to transform them into a spherical coordinate system. The orientation is represented by a pair of angles of a spherical coordinate system (φ,θ), where φ characterises the in-plane, and θ – out-of-plane orientation. Besides orientation, VoxTex also computed the degree of anisotropy and the grey scale value for each voxel, which were used for the image segmentation into volumes of individual plies, matrix pockets and voids.

The orientation vector ν for all the voxels was calculated in VoxTex as an eigenvector of the three-dimensional structure tensor [4], integrated over a "region of interest", surrounding the voxel. The orientations were first assigned to individual voxels and then accumulated to the level of plies in the laminate. The local orientation (φ,θ) of tows in the ply in the composite was calculated as the average value of the fibre orientations in that ply.

$$\varphi_{ti}^{\alpha} = \langle \varphi_{fi_j}^{\alpha} \rangle; \; \theta_{ti}^{\alpha} = \langle \theta_{fi_j}^{\alpha} \rangle;$$

where: φ_{ti}^{α}: in-plane orientation of tow in ply i with nominal orientation α
φ_{fi}^{α}: in-plane orientation of fibre in ply i with nominal orientation α
θ_{ti}^{α}: out-of-plane orientation of tow in ply i with nominal orientation α
θ_{fi}^{α}: out-of-plane orientation of tow in ply with nominal orientation α
j: the index of a voxel (free index)

Here the operator $\langle \circ \rangle$ denotes averaging over free indices. The mean in-plane orientation angle of the tows with nominal orientation α φ_t^{α} in the composite is the average of the angles measured in different plies with the same nominal orientation α:

$$\varphi_t^{\alpha} = \langle \varphi_{ti}^{\alpha} \rangle$$

Misalignment of the fibres of each ply orientation was calculated as the square root of the variance of local fibres orientation angles, averaged over the number of plies with the same orientation in the sample:

in-plane misalignment:

$$m_{\varphi}^{\alpha} = \sqrt{\langle \tilde{\varphi}_i^{\alpha} \rangle}$$

out-of-plane misalignment:

$$\mathrm{m}_{\theta}^{\alpha} = \sqrt{\langle \tilde{\theta}_{\mathrm{i}}^{\alpha} \rangle}$$

where:
$\tilde{\varphi}$: the variances of the in-plane fibres orientation in the ply with nominal orientation α
$\tilde{\theta}$: the variances of the out-of-plane fibres orientation in the ply with nominal orientation α
i: the voxel index

4. Results

Figure 2a and Figure 2b show a histogram of the in-plane fibre orientation in different plies of materials A and B. The data for all the plies with the same nominal orientation are mixed together, as the analysis of separate plies has shown that there is no statistically significant difference between fibre orientation in different plies with the same nominal direction.

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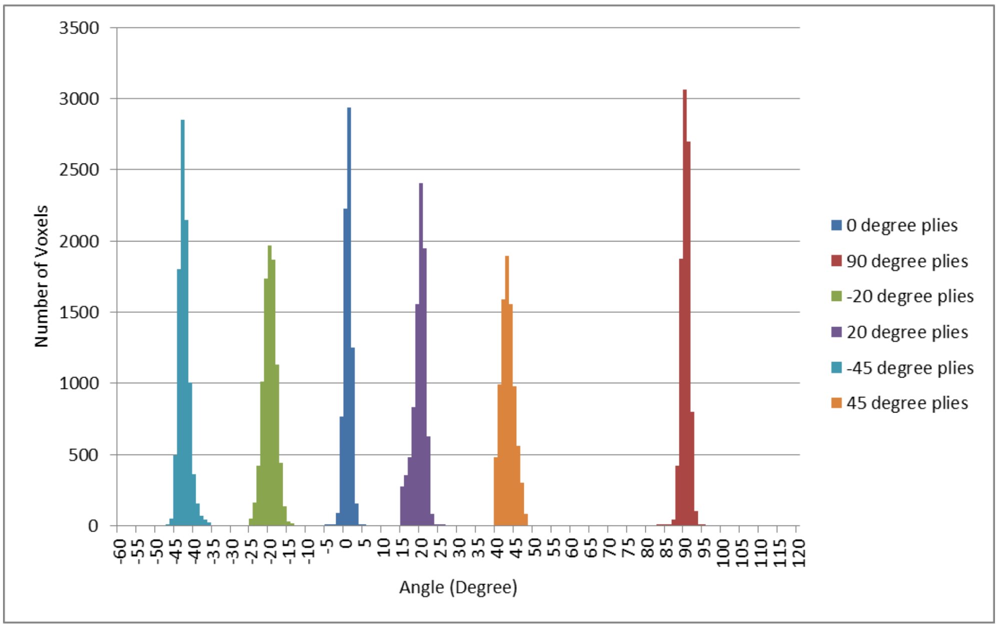
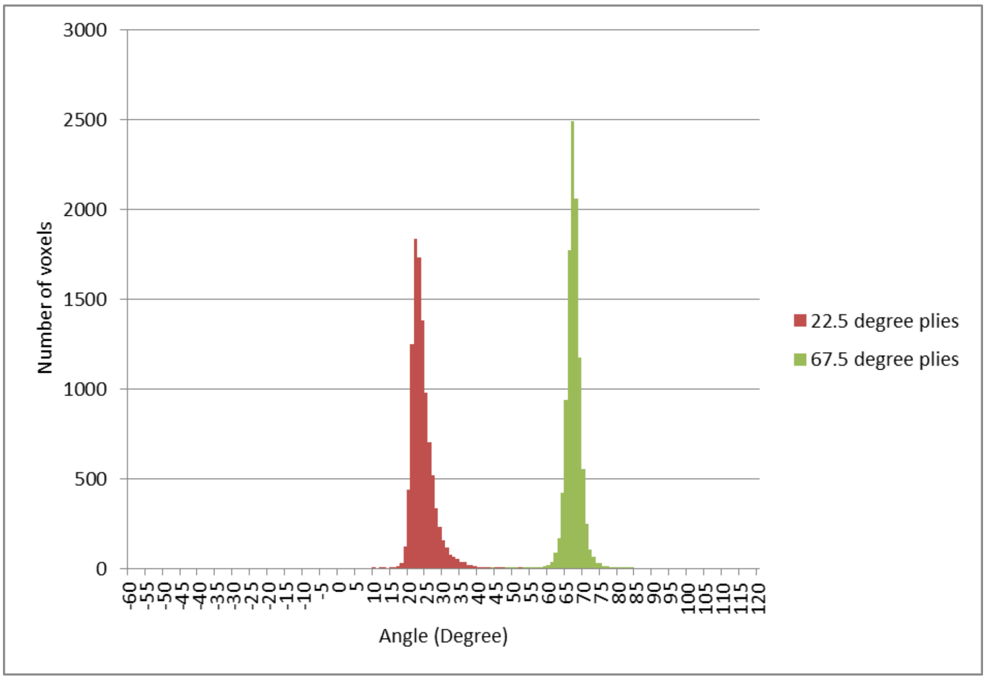


a/



b/

Figure 2. Histogram of in-plane fibre orientation a/ Material A and b/ Material B

The results of the local tow orientation and fibre misalignment are summarised in Table 1. For both materials the tape misorientation is about 1° or less (in different plies); the fibre out-of-plane misorientation (standard deviation of the angle) is 1…2°. The inter-tape fibre misorientation in-plane is 1…2° for in-autoclave and 2…4° for out-of-autoclave laminates.

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Table 1. Local tow orientation and fibre misalignment of Materials A and B.

Material Type	*In-plane*			*Out-of-plane*
	Nominal Ply Angle α *(Degree)*	*Ply Angle* φ_t^α *(Degree)*	*Fibres misalignment* m_φ^α *(Degree)*	*Fibres misalignment* m_θ^α *(Degree)*
A	0	0.2	1.01	0.79
	20	19.0	1.70	1.34
	-20	-20.5	1.72	1.05
	45	44.0	1.80	2.4
	-45	-43.1	1.42	1.6
	90	90.3	1.11	0.84
B	22.5	23.7	3.80	1.20
	67.5	66.7	2.16	1.25

5. Conclusions

Micro-CT images of a composite laminate can be used for assessment and qualitative characterisation of the precision of tow placements during the AFP/ATL process and inter-tow fibre misalignment in-plane and out-of-plane. VoxTex software of KU Leuven is a ready-to-use tool for such a measurement. Application of the method to two examples of in- and out-of-autoclave AFP/ATL laminates show that the precision of the tow placement is within 1° and the out-of-plane misorientation of fibres is below 2° for the both processes. The in-plane inter-tape misorientation of fibres in the prepreg laminate is 1…2°, which is twice lower than in the infusion-produced laminate (2…4°).

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