Analysis of short glass fibre orientation in samples from a PA6.6 GF35 car clutch pedal

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ABSTRACT. Composite materials like short fibre reinforced polymers (SFRP) are widely employed for the production of load bearing parts in many industrial sectors as they offer numerous advantages from both the economic and mechanical point of view.
One of the most commonly employed methods for the production of these parts is injection moulding.
Mechanical properties of injection moulded SFRP components depend upon fibre orientation with reference to the acting stresses, and for the analysis of fibre distribution experimental methods are required.
Using phase contrast imaging techniques available at SYRMEP beamline of the Trieste synchrotron, we obtained 3D micro-tomographic reconstructions of relatively large samples. Fibre orientation and anisotropy properties were characterized by means of a global parameter, the Mean Intercept Length (MIL) and the consequent Fabric tensor. In order to test if this methodology for fibre orientation assessment can be used for industrial purposes, it was applied to a real part and the results are presented in this paper.

INTRODUCTION

Polymeric materials reinforced by short fibre of glass are very interesting because fibre improves the mechanical properties like stiffness, static strength, fatigue resistance, etc. and in some cases, these materials can be considered excellent substitutes for metallic materials.
These improvements are conditioned by the aspect ratio (i.e. the ratio between the diameter and the length of fibre) and by the fibre orientation relative to the direction of the stresses acting in the component ([1], [2]). The first of these factors can be easily verified because it depends on the material, while fibre orientation is strongly influenced by the production process and it is difficult to predict.
The experimental method used for this test is based on micro computed tomographies (micro-CT) of material samples, obtained at the SYRMEP beamline of the Trieste synchrotron ([3]). It is a non-destructive method which allows to achieve 3D images of considerable accuracy, in our case 9 μm resolution.
The reconstructed 3D image of the internal structure is analyzed in terms of the component of the Mean Intercept Length fabric tensor ([4], [5]) and in this way it is possible to obtain a characterization of the material anisotropy and to estimate the direction of the fibre.

The samples analyzed were extracted from a PA6.6 GF35 (i.e. short glass fibre - 35% by weight - reinforced Polyamide 6.6) car clutch pedal manufactured by injection molding. Fig. 1 and 2 show the different areas from which the two specimens (B and E) were obtained, and the injection point.

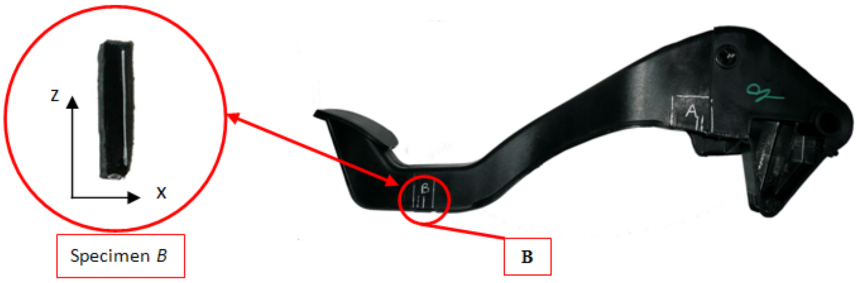

Figure 1: the clutch pedal - SIDE VIEW: position of the specimen *b*.

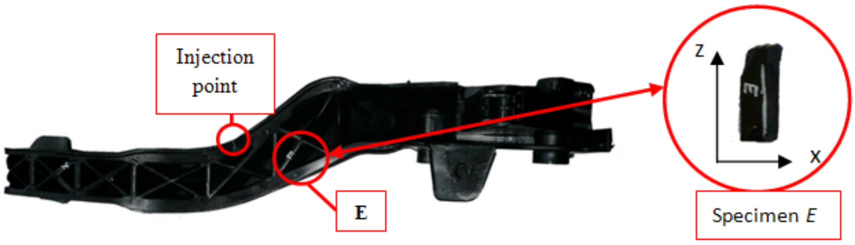

Figure 2: The clutch pedal – BOTTOM VIEW: position of the specimen E and of the injection point

DATA ACQUISITION

Micro-CT consists essentially in acquiring a large number of radiographic projections, obtained at different angular positions, of the specimen placed on a rotating table. In our case 1440 projections were used, covering a rotation of 180 degrees. The projections were then processed in order to obtain the reconstructed cross-sections (slices) by using well-known algorithms based on the filtered back-projection method. By stacking the slices along the *z* direction, the 3D volume reconstructions of the samples could then be reconstructed.
The acquisitions were conducted at the SYRMEP beamline of Elettra, the synchrotron radiation facility in Trieste. Its set-up is shown in Figure 3. The use of a synchrotron light source and of phase-contrast radiographic techniques, improves image quality and allows for highlighting the internal structure of the specimen and the fibre arrangement which was the subject of this study.

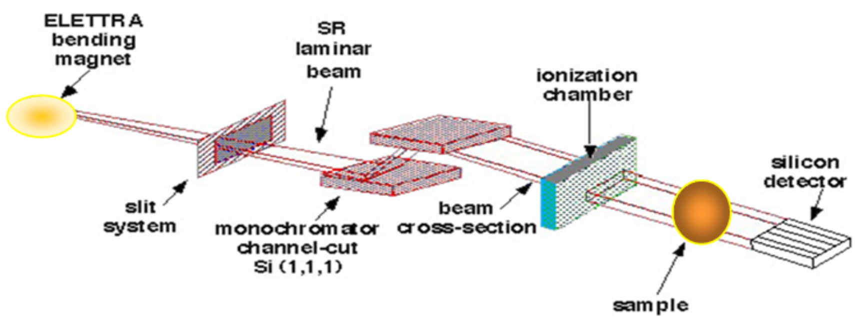

Figure 3: Set-up of SYRMEP line of Synchrotron in Trieste

The reconstructed volume is composed of several stacked 8-bit greyscale images, and in order to identify phase transitions (matrix-fibre), which is required for MIL computations, the images necessitate segmentation. Different segmentation methods exist. In our case, the threshold was set so that the *fibre volume/total volume* (FV/TV) value, evaluated over the

entire reconstructed volume of the micro-tomographed sample was 18.8%, corresponding to the volumetric fibre fraction of the composite analyzed, as in [3].
As the beam height is of about 3.5 mm, in order to analyze an entire specimen it was necessary to perform multiple tomographies by changing the vertical position of the specimen. For this reason, during the specimen volume reconstruction the various micro-CT had to be superimposed by performing a manual positioning using the presence of structures (i.e. aggregation of groups of fibre) that were particularly evident and recognizable, as described in [6].
The analyzed Volumes Of Interest (VOIs), 80x80x80 voxel^3, were extracted from the central area of the micro-CT reconstruction (30 VOIs from the sample *B* and 18 VOIs from the sample *E*) and were then reconstructed in three dimensions to highlight the orientation of the fibre (3D-Doctor software), as shown in Fig. 4.

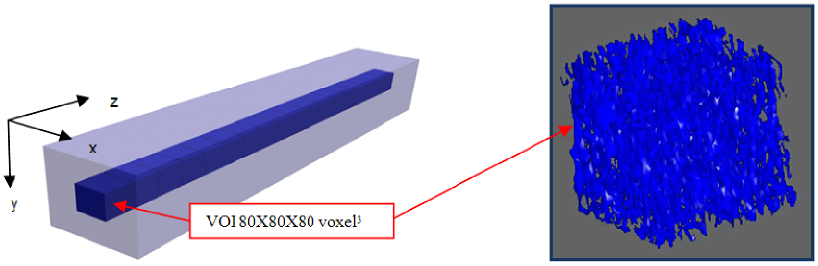

Figure 4: Representation of a sample with the VOIs highlighted and the 3D reconstruction of one of them

MORPHOLOGICAL ANALYSIS

Mechanical properties of this type of composite material depend on fibre orientation in relation to stress directions. This dependence can be expressed by appropriate relations ([6]). In case of components made by injection molding, as in this case, the resistance is influenced by the shape of the molded part (notch effect) but also by the distribution of the fibre, which is in turn influenced by the position of injection points ([7]).
Fibre orientation within the matrix can be described by Mean Intercept Lenght, MIL, which is the average distance between the two phases along a certain direction, computed as the ratio of the length (L) of a hypothetical grid of lines crossing the sample and the number (n) of phase transitions fibre - matrix in a number of directions (θ) ([8]):

$$MIL(\theta) = \frac{L}{n(\theta)} \tag{1}$$

The arrangement of the fibre can, in this way, be represented by an ellipsoid, which is equivalent to a positive-definite second order tensor, called MIL fabric tensor, whose eigenvectors represent the principal directions (i.e. the axes of the ellipsoid) and the eigenvalues quantify the tendency of the fibre to be oriented along the respective principal directions.
Eigenvalues $\boldsymbol{H_1}$, $\boldsymbol{H_2}$ and $\boldsymbol{H_3}$ (from the largest to the smallest) are usually normalized by imposing:

$$\boldsymbol{H_2 + H_3 = 1} \tag{2}$$

An Index of Anisotropy (IA) can also be defined by the relation:

$$\boldsymbol{IA = 1 - (H_3/H_1)} \tag{3}$$

0 in case of perfect isotropy and tending to 1 in case of increasing anisotropy. MIL computations were performed using Quant 3D software [(9)].

RESULTS AND DISCUSSION

The visual representation of the MIL values in a polar diagram (the so-called rose diagram) was compared to the images of the fibre architecture reconstructed by tomography in the same VOIs. Fig. 5 shows the polar diagrams in the xz plane and the corresponding orientation of the fibre obtained for each VOI. This operation was performed for both specimen B and E.

From top to bottom, in the specimen B fibre is initially oriented along the x axis but for increasing values of z (i.e. from the edge of the pedal to the inside) orientation changes towards the z axis, i.e. perpendicular to the injection flow direction.
The specimen E was extracted in a geometrically complex area, where the injection flow is more unstable. For this reason, fibre does not have a preferred orientation in the corresponding volumes.
Both visual inspection of the 3D reconstructions and the MIL computations confirm these results. The correspondence between fibre orientation and the first eigenvector of the ellipsoid, which represents the principal direction of the fibre, confirms that MIL description can be successfully used for fibre orientation description in real parts of injection moulded short fibre reinforced composite.
The next step of this research will be the comparison of these data with the results obtained from numerical analyses in order to validate the predictions of injection moulding process simulation by commercial software (e.g. Autodesk Moldflow).

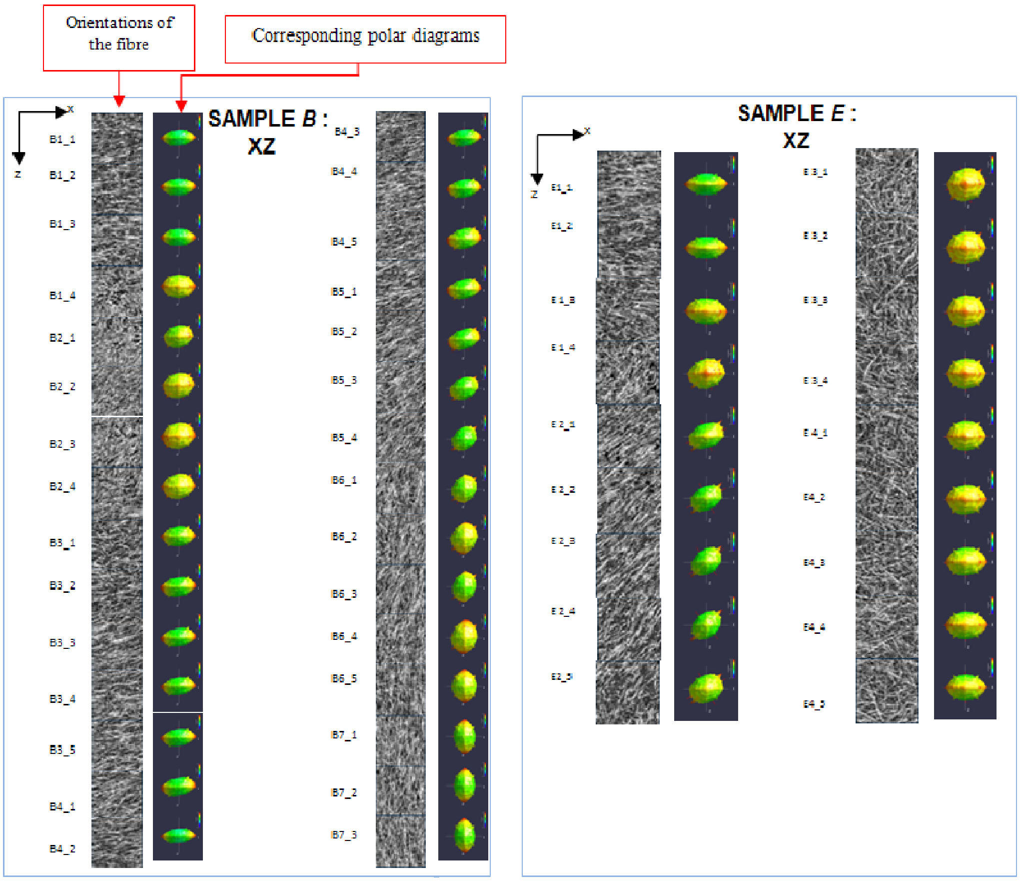

Figure 5: Sample B and Sample E - comparison of slices and polar diagrams in xz plane.

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