Characterization of Random Long Fiber Composites and Prediction of the Local Stiffness Properties

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SUMMARY: Long glass fiber polypropylene (LGFPP) composites become more and more attractive because they enable easy, low cost part production and good mechanical properties for stiffness, durability and impact. Fiber breakage and local change in orientation occur during the processing of those composites, especially in injection-molding. Fiber length and fiber orientation distributions were measured experimentally and were then used as one of the inputs in the elastic model to get the stiffness properties of the composite, taking into account the local microstructure of the material. The model is based on the inclusion model approach, namely Mori and Tanaka model, and can predict all the engineering constants. A comparison of the results of this model with other models from literature shows good agreement for elastic moduli. In this work the effects of fiber length distribution and fiber orientation distribution on final elastic properties of LGFPP composites were investigated. The length and orientation of the fibers play an important role in the determination of final mechanical properties of LGFPP composites.

KEYWORDS: random, discontinuous long-fiber composites, fiber-length distribution, fiber-orientation distribution, stiffness properties, Mori and Tanaka method.

INTRODUCTION

The use of glass fiber reinforced polypropylene composites in engineering applications increases more and more these last years. Especially, long glass fiber polypropylene (LGFPP) composites offer specific advantages over classical laminates such as higher production rates at lower costs, improved thermal and mechanical properties. However during injection molding of the part fiber breakage occurs, leading to a distribution of fiber lengths inside the material. Moreover a change in orientation of the fibers also takes place during injection process, leading to micro-structural variations that affect the overall mechanical properties of the composite. Hence, the final properties of LGFPP composite are highly dependent on the processing conditions of the part. Therefore the effect of fiber length on the mechanical properties of injection molded LGFPP composites must be combined with the effect of fiber orientation changes because the two effects would determine the final mechanical properties of these composite materials [1].

First, microstructural characterization of LGFPP was performed, using the resin burnout technique to get the fiber length distribution and optical microscopy method (applied to a polished cross-section) to obtain the fiber orientation distribution. Fiber and matrix properties and experimental data on fiber length and orientation distributions were used as input in a software based on Mori and Tanaka method. This was coupled with a Monte-Carlo simulation, which was developed to predict local mechanical properties of LGFPP composites, taking into account the real microstructure in the part.

EXPERIMENTAL

Materials

This work was conducted in collaboration with DOW Automotive, which provides all the materials employed in this investigation in addition to material, CAE, process, testing and application knowledge. The composite material for the study, produced by injection molding, is made of polypropylene reinforced with long glass fibers. The initial length of the fibers was 11 mm and the fiber content was 20% fibers by weight.

Fiber length measurement

To measure the fiber length distribution first the composite material is burnt out in a classical oven. After burning, entangled fibers remain, and some fibers are extracted from the sample and dispersed in a glass dish filled with liquid and stirred carefully to detach the fibers. The liquid is removed and the dish is heated in an oven until vaporised. The dish is then placed under the microscope. Magnified images of fibers are digitised by image analysis software and fiber length distribution is thus determined.

Fiber orientation measurement

Optical microscopy on polished cross-sections was used to measure orientation. This method is based on the fact that individual fibers are assumed to have a circular cross-section, which is the case for the glass fibers [2]. As the intersection of a straight circular cylinder and a plane gives an ellipse, by determining the principal axes of the ellipse, (Fig. 1), the out of plane orientation (θ) is computed from Eqn. 1 [3], exactly valid for an infinite fiber but the difference counts only for an out of plane angle bigger than 89.95°, which is assumed equal to 90°. The in-plane orientation of the fiber (φ) is given directly by the image analysis software.

$$\theta = \cos^{-1}\left(b/a\right) \qquad (1)$$

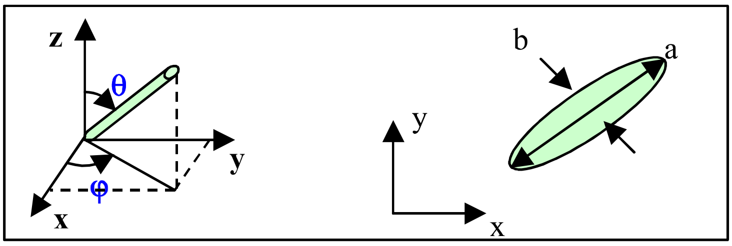

Fig. 1 Elliptical cross-section of a cylindrical fiber cut by a plane

RESULTS AND DISCUSSION

Fiber length

The fiber length distribution obtained for a LGFPP composite is shown Fig. 2. The maximum fiber length is 10.75 mm and the minimum fiber length: 0.5 mm. The mean value, calculated from those experimental data, is: 5.3 mm and the standard deviation is: 2.4.

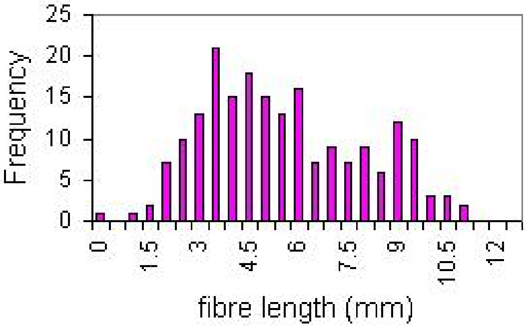

Fig. 2 Fiber length distribution

Fiber orientation

In-plane orientation

Fig. 3 presents the result of the in-plane orientation distribution obtained for the upper surface of the material. We notice that most of the fibers are oriented between 80 and 100°, which corresponds to the flow direction of the injection molding process.

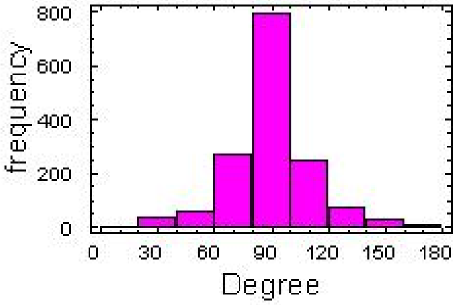

Fig. 3 In-plane orientation distribution

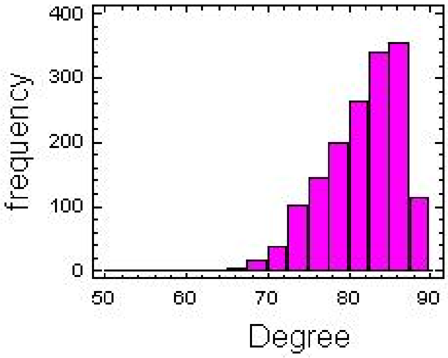

Fig. 4 Out of plane orientation distribution

Out of plane orientation

The distribution of the out of plane orientation (Fig. 4) shows that majority of fibers are oriented between 80 and 90°, which means that the fibers are mainly in plane. The histogram bin closest to 90° is determined with large inaccuracy. Fibers oriented at out of plane angle close to 90° have less probability to be cut by a cross-section at a fixed depth than the fibers with lower out of plane angles.

Mechanical properties

A software programme based on the Mori and Tanaka model was developed to predict local mechanical properties of LGFPP [4]. The fibers in the unit cell are modeled by inclusions of an ellipsoid shape. The length and orientation of each inclusion is determined individually by sampling the experimental distribution for length, in-plane and out of plane orientations respectively, using a Monte Carlo simulation. In this way, each inclusion is assigned a unique, independent value for length, in plane orientation and out of plane orientation. Knowing the materials properties, listed in Table 1, the elastic micro-mechanical calculation can then be performed giving the total stiffness tensor of the composite material.

	Matrix	Fibers
Density : ro (g/cm^3)	0.9	2.54
Young's moduli: E = Et (MPa)	1000	70 000
Poisson's ratios: Po = Pot	0.33	0.23
Shear moduli: G = Gt (MPa)	588	29 268
Fiber diameter : d (mm)		0.017

Table 1 Materials properties used in the micro-macro calculation

Fiber length effect

Elastic properties of unidirectional (UD) LGFPP composites were calculated for different constant fiber length values with 10% fibers in volume (24.6% by weight).

According to the results, longitudinal Young's modulus increases with fiber length until a limit length value of 4 mm where the modulus approaches an asymptote equal to the modulus of UD glass polypropylene composite laminate. To validate the modeling results, a comparison was done with UD models such as empirical models (Cox and Tsai-Halpin) and three Finite Element models performed by DOW Automotive (Fig. 5). Different geometries of the composite cell were simulated in FEA models: a single cylindrical fiber embedded in a square matrix cell (FEA1), a single fiber embedded in a circular matrix cell (FEA2), and a cylindrical cell containing more fibers (FEA3).

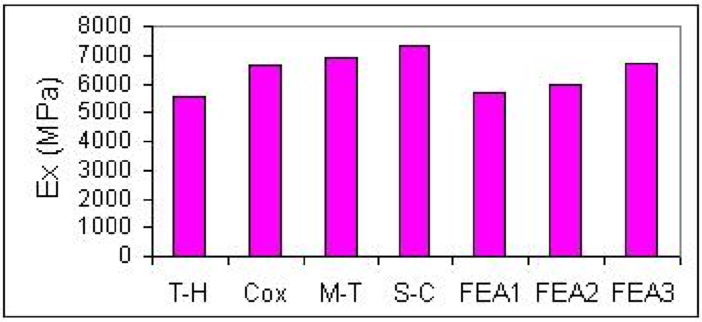

Fig. 5 Longitudinal modulus obtained from different models: Mori and Tanaka (M-T), self-consistent (S-C), Tsai-Halpin (T-H), Cox, Finite Element Analysis (FEA) with l = 3 mm

The Tsai-Halpin model gives the lowest modulus whereas the Cox model and FEA3 give equivalent result. The reason is that in a Cox model, other fibers surround the fiber so the effect of those fibers is taken into account, as is the case in the finite element model with multiple fibers. As the Mori and Tanaka model also takes into account the other fibers, its predicted modulus value is close to the one of Cox. FEA1 and FEA2 have different composite moduli, which means that the geometry of the composite cell can affect the stiffness of the composite material. Finally as usual, the self-consistent model predicts a higher modulus compared to the Mori and Tanaka model because in the first model the fiber is embedded in a matrix with properties of the composite material and not the properties of the matrix like in the second one.

Fiber orientation effect

To understand the effect of the fiber orientations on the final mechanical properties of LGFPP composites, calculations were done for composite material with all fibers aligned in y direction (UD: Table 2, column 2), composite material with in-plane experimental orientation distribution and an out of plane angle equal to 90° for all the fibers (Table 2, column 3). Finally, experimental distribution of in-plane orientation was combined with out of plane orientation distribution to take into account the effect of out of plane orientation (Table 2, column 4). In the three cases, a fiber content of 20% by weight was considered and the experimental fiber length distribution (Fig. 2) was used.

	UD ($\varphi = 90, \theta = 90°$)	$\{\varphi_i\}$ and $\theta = 90°$	$\{\varphi_i\}$ and $\{\theta_i\}$
E_x (MPa)	1246 (± 5)	1670 (± 92)	1629 (± 78)
E_y (MPa)	6564 (± 179)	5027 (± 185)	4614 (± 164)
E_z (MPa)	1246 (± 5)	1341 (± 12)	1309 (± 11)

ν_{yz}	0.32	0.25	0.33
ν_{zx}	0.46	0.33	0.33
ν_{xy}	0.06	0.15	0.15
G_{yz} (MPa)	441 (± 2)	438 (± 2)	533 (± 11)
G_{zx} (MPa)	428 (± 2)	430 (± 2)	451 (± 5)
G_{xy} (MPa)	441 (± 2)	863 (± 43)	835 (± 44)

Table 2 Comparison of mechanical properties for a composite material with 20% fibers by weight, with experimental fiber length distribution for different orientations

By taking into account the experimental distribution of out of plane orientation Ey decreases by 8%; the transversal shear moduli increase whereas G_{xy} decreases, which is normal since the fibers are not totally in-plane like when $\theta = 90°$.

CONCLUSION

The length and orientation of the fibers play an important role on the final elastic properties of LGFPP composites, so their local distributions must be known. Elastic modeling results are satisfactory and showed the anisotropy of LGFPP composites. In the future, the model will be extended to include damage development in the fibers and the fiber/matrix interface.

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