MODELLING THE MECHANICAL AND THERMAL PROPERTIES OF SHORT FIBRE COMPOSITES

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SUMMARY: The main difficulty in modelling the properties of short fibre composites is the complexity and wide range of the orientation states of the fibres. Furthermore, in short fibre composites, fibre length distributions exist as a result of processing, which obviously affects the composite's properties. To deal with this situation, models must be able to predict the properties for any kind of fibre orientation and length distribution, in any direction. In the present work, existing models for the prediction of stiffness and coefficient of thermal expansion (CTE), a recently developed model for the prediction of strength and a new model for the prediction of thermal conductivity are evaluated. Predictions of stiffness and strength are typically within 10% of the experimental values. The accuracy of CTE and thermal conductivity predictions is smaller, although in both cases a good description of the variation of the properties with fibre volume fraction can be obtained.

KEYWORDS: short fibre, thermomechanical, properties, micromechanics, prediction, thermoplastics.

INTRODUCTION

Short fibre polymer composites are increasingly used, as they have better thermomechanical properties than unfilled polymers and comparable processability. Besides, the use of conductive fibres, like carbon fibres, can make the composites thermally or electrically conductive, which is impossible for most unfilled polymers. Furthermore, by controlling fibre content and orientation, the composite properties can be tailored to meet required values. The combination of the above makes short fibre composites specifically suitable for products with complex geometries that require specified material properties. However, the complexity and wide range of the orientation states of the fibres in short fibre composites complicates the control and prediction of the final composite properties. Various models for predicting these orientation states are available and are already implemented in commercial software packages for flow simulation, such as C-Mold. Furthermore, in short fibre composites fibre length distributions exist as a result of processing, which obviously affects the composite's properties. To predict reliably the final composite properties, models must therefore be able to calculate these properties for any kind of fibre orientation and length distribution, in any direction.

THEORY

Micromechanical models to predict properties of short fibre composites have been developed and successfully applied [1,2,3], all following the same general method. First, the models derive expressions for the properties of a unidirectionally aligned short fibre composite as a function of fibre length. By integrating these expressions over the whole range of fibre lengths measured, or alternatively substituting the average fibre length in the expressions, the unidirectional composite properties are obtained. These properties can then be used to construct the different property tensors. The tensors are averaged over all directions and weighted by the fibre orientation distribution function. From these 'averaged' property tensors, the final composite properties can be obtained.

Differences between methodologies to predict the properties of short fibre composites can be sought in the way the unidirectional properties are derived and the property tensors are averaged. For the unidirectional stiffnesses, the well-known Halpin-Tsai equations [4] have proven to give good estimates. Although alternative models have been proposed, some with increased accuracy [5], the Halpin-Tsai equations are still widely used due to their relative simplicity. Expressions for the CTE of short fibre composites are less commonly found, and most are based on Schapery's equations, as adapted by Halpin [6]. Although different expressions for the strength of unidirectional short fibre composites exist, the relations based on the Kelly-Tyson theory [7] are the most widely used. In our recent work [3], they gave useful estimates for short fibre composites in combination with the Tsai-Wu failure criterion [8]. In this work we will therefore use the equations proposed by Halpin-Tsai, Schapery and Kelly-Tyson to derive the unidirectional stiffness, CTE and strength, respectively. Additionally, we will use the relations proposed by Nielsen [9] to derive the unidirectional thermal conductivities. The property tensors will be orientation averaged, following the widely used method introduced by Advani and Tucker [10].

RESULTS AND DISCUSSION

To obtain the composite material, Montell's Moplen F30G polypropylene (PP) and TENAX' PAN-based HTA 5131 carbon fibres were processed in a twin-screw extruder. Tensile bars, with fibre volume fractions of 0, 5, 10 and 15% were subsequently injection moulded and their tensile strength and modulus obtained. Tensile properties of the carbon fibres were obtained by testing single filaments. Fibre length distributions were determined experimentally by burning of the composites in an oven and subsequent measurement of the fibre lengths by microscopy, as described in our previous work [3]. Fibre volume fractions were obtained by density measurements. Fibre orientation distributions for the different samples were obtained by microscopy observations on polished cross-sections, following the method developed by Bay and Tucker [11]. The CTE of the specimens were measured by TMA, as described elsewhere [12]. The thermal conductivity of the specimens was measured using the optical beam deflection technique [13]. The material data obtained on the matrix and fibres are given in Table 1. These data were then used in the different models to predict the properties of the composites. Although in Table 1, for ease of comparison, only the average fibre lengths are given, the full fibre length distributions were used to average the unidirectional properties. The predictions, together with the experimental results, are depicted in Figs. 1 and 2 for the tensile modulus and strength and the thermal conductivity and CTE, respectively.

Table 1: Material parameters used for the evaluation of the models

Material parameters	PP-matrix	PP-PAN 5%	PP-PAN 10%	PP-PAN 15%	PAN-fibres
Matrix modulus (GPa)	1.343				
Matrix Poisson ratio	0.40				
Matrix yield stress (MPa)	30.4				
Matrix stress at fibre failure strain[1] (MPa)	20.8				
Matrix CTE (10^{-6}/°C)	114.0				
Matrix thermal conductivity (W/mK)	0.2				
Fibre modulus (GPa)					218
Fibre diameter (μm)					7.2
Fibre Poisson ratio					0.26
Fibre tensile strength[2] (MPa)					$\frac{4940.1}{l^{0.1554}}$
Fibre CTE (10^{-6}/°C)					-0.1
Fibre thermal conductivity (W/mK)					17
Critical fibre length (μm)					1012
Fibre volume fraction (%)		4.5	9.6	14.7	
Average fibre length (μm)		161.7	148.3	161.3	

[1] calculated from fibre failure strain and matrix modulus

[2] fibre length l in mm

As can be seen from Fig.1, the predictions of composite strength and stiffness are in good agreement with the experiments, typically within 10%. From Fig.2 it can be observed that the predictions of both thermal conductivity and CTE are less accurate - as was also observed in [2] for CTE - but describe the variation with fibre volume fraction quite well. Considering the accuracy of the stiffness and strength-predictions, which use the same orientation averaging methodology, improvement of the thermal conductivity and CTE-predictions should result from a deeper knowledge of the underlying expressions for the unidirectional properties.

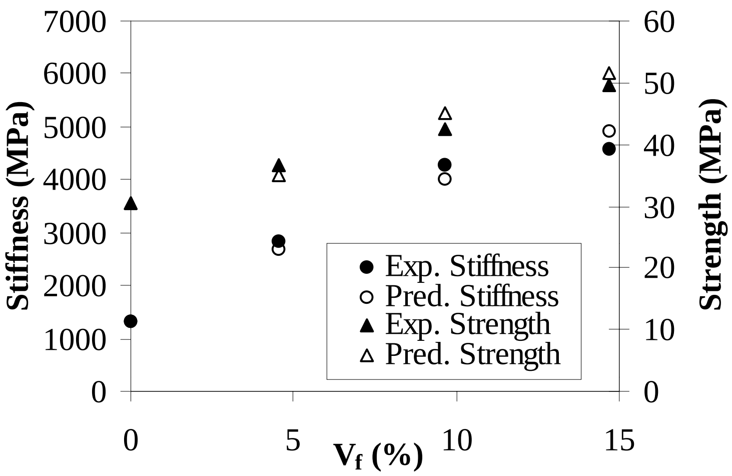

Fig. 1: Experimental and predicted stiffness and strength

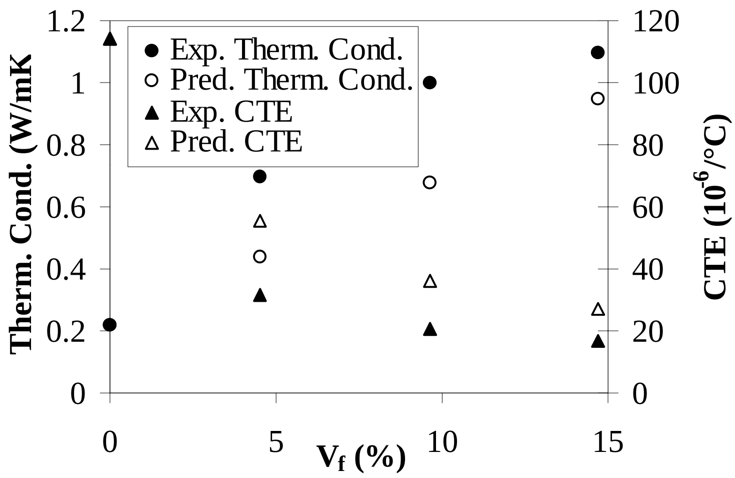

Fig. 2: Experimental and predicted thermal conductivity and CTE

CONCLUSION

From this work it can be concluded that models to predict stiffness and strength of short fibre composites are able to predict the experimental data within 10%. The accuracy is smaller in the case of the coefficient of thermal expansion. The same happens with a newly developed model used in this work to predict thermal conductivity, although in both cases a good description of the variation of the properties with fibre volume fraction can be obtained.

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