MEASUREMENT AND PREDICTION OF SHORT GLASS FIBRE ORIENTATION IN INJECTION MOULDING COMPOSITES

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Abstract

Within this paper we compare predictions of short glass fibre orientation developed during injection moulding based on the reduced strain closure (RSC), Folgar-Tucker (FT) and Moldflow Adjusted Folgar-Tucker models within Autodesk Moldflow Insights software. Accuracy of fibre orientation predictions from analyses has been evaluated by comparing with experimental data at specific locations within the test mouldings. The traditional Folgar-Tucker model was shown to over predict fibre orientation in both 2D and 3D analyses. The modified version of the Folgar-Tucker model showed significant improvement on the original theory in the 2D case but was not available for the 3D analysis. The RSC model showed the closest orientation compared to the measured values in both 2 and 3D models, although determination of the scalar factor k required experimental determination.

1 Introduction

For many years thermoplastics have been extensively used in a wide variety of applications due to their relatively cheap cost and high processability, particularly by injection moulding. However, commodity polymers such as polypropylene and nylon have relatively poor mechanical properties, which limits their use to non-structural applications. The use of short glass fibre reinforcement is a well established means of significantly improving mechanical performance without compromising processability. Apart from the fibre and matrix properties, the mechanical properties of the final components are crucially dependent on the fibre orientation distribution developed during the process, which depends on a number of factors such as cavity shape. Consequently, accurate predictions of fibre orientation are essential for the design process of commercial components [1-5, 10].

Here we present a review of the current available fibre orientation prediction models available in the commercial software Autodesk Moldflow. Test geometries and have been used to provide experimental values for fibre orientation at specified locations along a flow path. Analyses have been optimized so that fibre orientation predictions closely approximate the experimental data at these locations.

2 Sample preparation and testing

2.1 Injection moulding

A series of geometries were moulded at the University of Bradford to provide samples for fibre orientation measurements at the University of Leeds. Two flat plates 40 mm wide and 120 mm long were selected with thicknesses of 2 and 4 mm. Both plates were gated at one end using a fan and well configuration, the 2 mm plate having an inlet gate thickness of 0.5 mm and the 4 mm plate having a gate inlet thickness of 2 mm, Figure 1. All samples were moulded from Rhodia 216 v40 40% wt short glass fibre reinforced nylon 6.

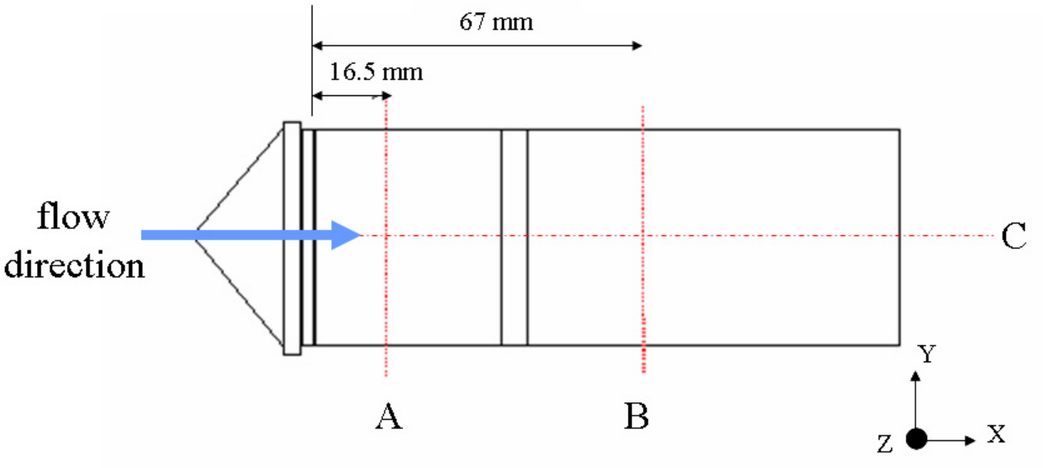

Figure 1. Flat plate geometries with fibre orientation measurement locations A and B

2.2 Fibre orientation measurement

Fibre orientation measurements were conducted at the University of Leeds using an optical microscopy technique [3]. Sections were taken in the YZ plane at two locations along the flow path (A and B, Figure 1) and prepared as per published protocols [3,4,6]. Orientation angles θ and ϕ were averaged over the sample thickness to produce orientation distribution plots across the plate width, as shown in Figure 2.

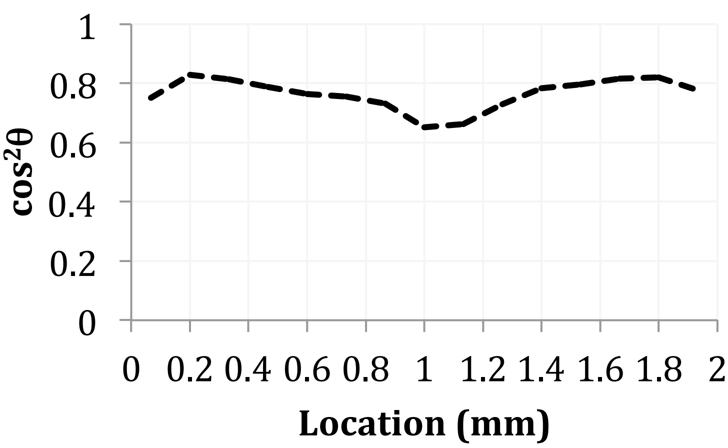

Figure 2. Typical fibre orientation data across plate width

3 Injection Moulding Analyses

3.1 Fibre orientation prediction models

Autodesk Moldflow fibre orientation predictions for short glass fibre reinforced materials can be implemented using one of three models; Folgar-Tucker [1], modified Folgar-Tucker or

Reduced Strain Closure. A review of each of these models was presented by Wang et al (2010) [8] where each model was related to the second order orientation tensor [1] , defined as

$$A = \langle pp \rangle \qquad (1)$$

were p is the unit vector along the fibre length and "<>" denotes a volumetric average domain.

The Folgar-Tucker model defines the orientation tensor in terms of vorticity (W), rate of deformation tensor (D), a particle shape parameter ζ and the fibre interaction coefficient c_i.

$$\frac{DA}{Dt} = (W \bullet A - A \bullet W) + \xi(D \bullet A + A \bullet D - 2\Lambda : D) + 2C_i\dot{\gamma}(I - 3A) \qquad (2)$$

Λ is the forth order orientation tensor and is commonly approximated by a closure function.

The modified version of the Folgar-Tucker model, developed by Moldflow, includes an additional parameter D_z, ranging between 0 and 1, and seeks to reduce the effect of the fibre interaction term. A D_z value of 1 returns the modified equation to the original Folgar-Tucker model.

$$\frac{DA}{Dt} = (W \bullet A - A \bullet W) + \xi(D \bullet A + A \bullet D - 2\Lambda : D) + 2C_i\dot{\gamma}(I - (2 + D_z)A) \qquad (3)$$

The Reduced Strain Closure model modifies the Folgar-Tucker equation (2) [8,9] by introducing an additional scalar factor k to slow the fibre orientation kinetics. Currently k can only be assigned from experimental data.

$$\frac{D\mathbf{A}}{Dt} = (\mathbf{W} \cdot \mathbf{A} - \mathbf{A} \cdot \mathbf{W}) + \xi(\mathbf{D} \cdot \mathbf{A} + \mathbf{A} \cdot \mathbf{D} - 2[\mathbb{A} + (1-\kappa)(\mathbb{L} - \mathbb{M}:\mathbb{A})]:\mathbf{D}) + 2\kappa C_I\dot{\gamma}(\mathbf{I} - 3\mathbf{A}). \qquad (4)$$

Table 1 summarises the feasible applications of the three fibre orientation models in terms of Autodesk Moldflow analyses along side the associated limits of their respective parameters.

Midplane / Dual Domain	**3D**
Folgar-Tucker Fibre interaction coefficient c_i (<0.1) Larger c_i implies more fibre-fibre interaction	Folgar-Tucker (Default) Fibre interaction coefficient c_i (<0.1) Larger c_i implies more fibre-fibre interaction
Modified Folgar-Tucker (Default) Thickness moment of interaction D_z ($0<D_z<1$) Fibre interaction coefficient c_i (<0.1)	-
Reduced Strain Closure (RSC) Scalar factor k (<1) k determined by fitting experimental data Fibre interaction coefficient ci (<0.1)	Reduced Strain Closure (RSC) Scalar factor k (<1) k determined by fitting experimental data Fibre interaction coefficient ci (<0.1)

Table 1. Fibre orientation models within Autodesk Moldflow including limits of their respective parameters

3.2 Moldflow models

Only midplane and 3D analyses are shown here, although it should be noted that the dual domain analysis uses the same internal flow algorithms as the midplane version so would be expected to produce identical results.

For the midplane analysis the 2 and 4 mm thick plates were defined by such that a line of coincident nodes were placed along the fibre orientation measurement locations A and B, Figure 1. The final midplane analysis incorporated 2000 elements each with 20 layers through the thickness. Alternate mesh densities were also studied and found to produce similar predictions of fibre orientation.

The three-dimensional analyses of the 2 and 4 mm plates had fibre orientation data extracted from relevant nodes along a transverse path relating to locations A and B on the original mouldings. As with the midplane case, alternate mesh densities were investigated and shown not to significantly affect fibre orientation predictions.

Fibre orientation model parameters were defined as shown within Table 2, with modified Folgar-Tucker D_z values decreasing from 0.8 to 0.2 in 0.2 steps.

Fibre Orientation Model	c_i	D_z	**k**
Folgar-Tucker	0.1	-	-
Folgar-Tucker	0.01	-	-
Folgar-Tucker	0.001	-	-
Folgar-Tucker	0.0001	-	-
Folgar-Tucker	0.00001	-	-
Modified Folgar-Tucker	0.1	0.8	-
Modified Folgar-Tucker	0.01	0.8	-
Modified Folgar-Tucker	0.001	0.8	-
Modified Folgar-Tucker	0.0001	0.8	-
Modified Folgar-Tucker	0.00001	0.8	-
Modified Folgar-Tucker	0.1	0.6	-
…	…	…	-
Modified Folgar-Tucker	0.00001	0.2	-
RSC	0.00001	-	0.8
RSC	0.00001	-	0.6
RSC	0.00001	-	0.4
RSC	0.00001	-	0.2
RSC	0.00001	-	0.1
RSC	0.00001	-	0.01
RSC	0.00001	-	0.001
RSC	0.00001	-	0.0001
RSC	0.00001	-	0.00001

Table 2. Fibre orientation model parameters

4 Results

Within this section we show results for the 2 mm flat plate sample only.

4.1 Folgar-Tucker

The Folgar-Tucker model was shown to over predict the fibre orientation at both locations A and B. Figure 3 shows a comparison for four Folgar-Tucker models at location B.

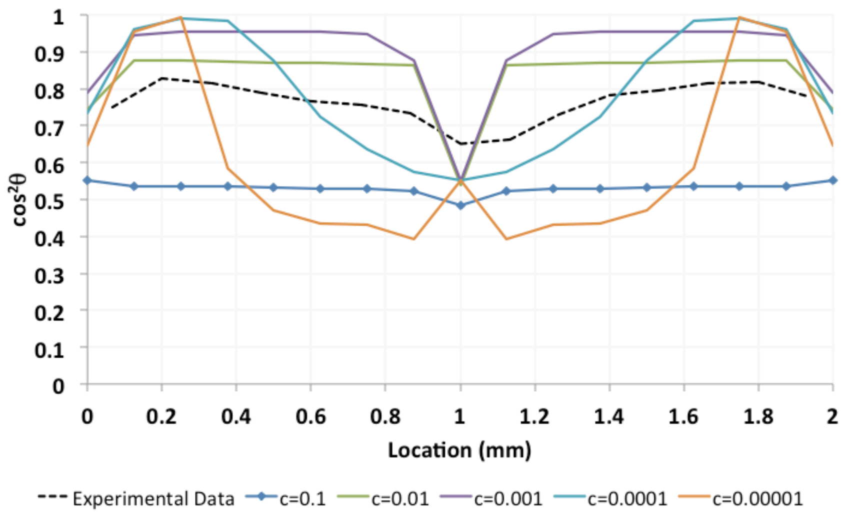

Figure 3. Midplane analysis fibre orientation predictions using the Folgar-Tucker fibre orientation model, at location B

Increasing the value of the fibre interaction coefficient c_i had the effect of increasing the shell orientation whilst maintaining identical levels of orientation within the centre of the sample.

4.2 Modified Folgar-Tucker

The modified version of the Folgar-Tucker model demonstrated a closer correlation to experimental values compared to the unmodified case. Figure 4 shows a reduced data set of the modified Folgar-Tucker fibre orientation predictions at location A, with fibre interaction coefficient c_i fixed at 0.001.

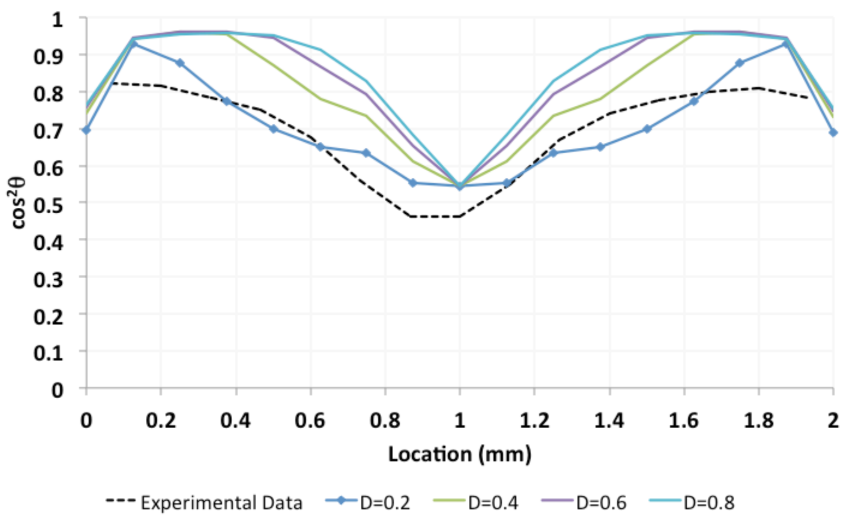

Figure 4. Midplane analysis fibre orientation predictions using the modified version of the Folgar-Tucker orientation model, at location A

Decreasing values of the thickness moment of interaction parameter Dz have the effect of smoothing out the fibre orientation through the thickness of the sample, with a Dz value showing a close approximation to the experimental data.

4.3 Reduced Strain Closure

The Reduced Strain Closure model showed the closest agreement with experimental measurements of fibre orientation. Figure 5 shows a reduced data set of RSC orientation predictions at location B.

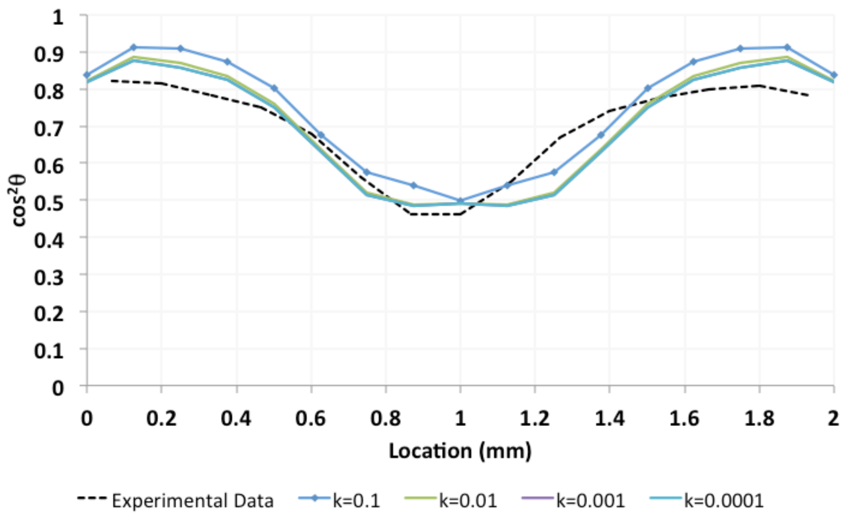

Figure 5. Midplane analysis fibre orientation predictions using the RSC orientation model, at location B

4.4 Optimum fibre orientation predictions for midplane analyses

Based on the results shown above the optimum values of each fibre orientation model have been specified so that the orientation at both locations A and B closely approximate the experimental data. Figure 6 shows the optimum fibre orientation predictions at both locations A and B, with optimal values of each model parameters shown in Table 3.

Fibre Orientation Model	c_i	D_z	k
Folgar-Tucker	0.03	-	-
Modified Folgar-Tucker	0.0057	0.15	-
RSC	0.0057	-	0.1

Table 3. Optimum fibre orientation model parameters for the 2 mm flat plate geometry

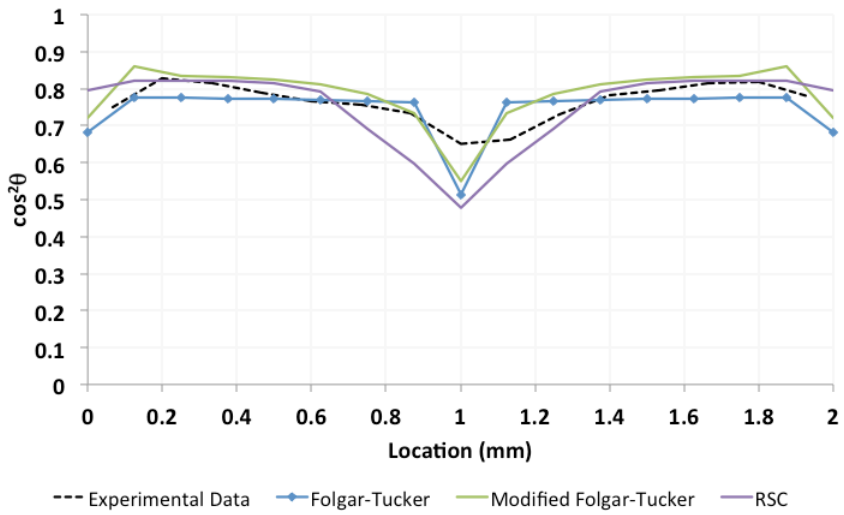

Figure 6. Optimum midplane fibre orientation predictions at locations A and B for the Folgar-Tucker, Modified Folgar-Tucker and Reduced Strain Closure models

4.5 Three-dimensional analysis results

The modified version of the Folgar-Tucker model is not available for three-dimensional analyses in Autodesk Moldflow. However, using the optimum coefficients described above, the Folgar-Tucker and RSC models have been trialed with 3D models. Figure 7 shows the 3D fibre orientation predictions at location A for the Folgar-Tucker and RSC models.

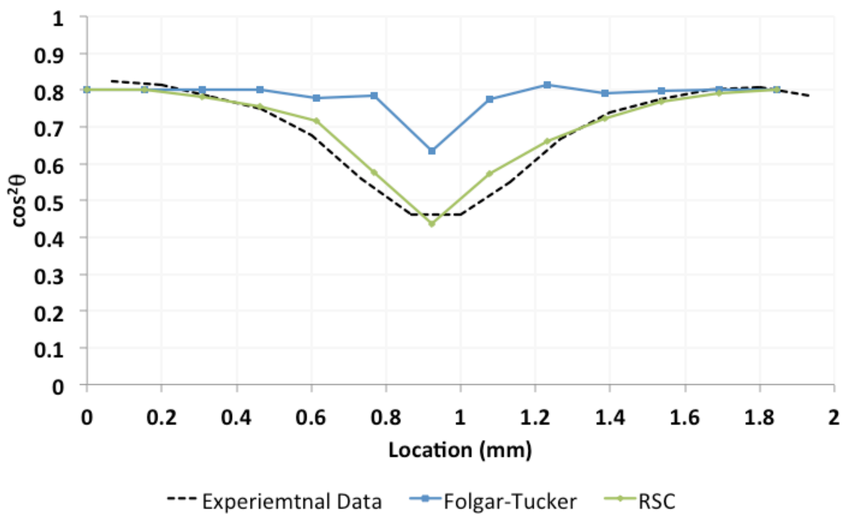

Figure 7. 3D optimum coefficient fibre orientation predictions using the Folgar-Tucker and RSC models

As with the midplane analyses, the 3D model using the RSC fibre orientation predictive model closely approximated the actual fibre orientation found within the 2 mm plate. The traditional Folgar-Tucker model over predicted the level of orientation at location A.

5 Conclusions

The Reduced Strain Closure fibre orientation model has been shown to significantly improve orientation predictions compared to the original Folgar-Tucker and modified version of Folgar-Tucker for midplane analysis of a 2 mm flat plate. In three-dimensional analyses the RSC also performed well compared to the Folgar-Tucker model, the modified version being unavailable for this type of analysis. However, at this time the designation of the scalar parameter k still requires significant experimental data as no route has been found to calculate this parameter. Previous work has shown that k can depend not only on the material being moulded but also on the type of geometry and inlet flow conditions [9, 10]. Work is continuing in this area.

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