EXPERIMENTAL AND NUMERICAL ANALYSIS OF FIBRE ORIENTATION IN INJECTION MOULDED SHORT GLASS FIBRE REINFORCED POLYAMIDE 6 NOTCHED SPECIMENS

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Abstract
Autodesk Moldflow Simulation Insights has been used to predict the fibre orientation within notched specimen injection mouldings. Currently available fibre orientation models including the classis Folgar-Tucker (FT), the modified version of Folgar-Tucker (MFT) and the Reduced Strain Closure (RSC) [1] *have been assessed, alongside the relative effects of their associated parameters, for their suitability for fibre orientation prediction. Compared to experimentally determined values the Reduced Strain Closure model was shown to most closely represent the fibre orientation within the moulded components.*

1. Introduction

In a previous work, the combined effect on fatigue behavior of fibre orientation and notch tip radius in injection moulded notched specimens made of short fibre reinforced polyamide was investigated experimentally. Fatigue tests were conducted on injection molded plates having two symmetric V-shaped notches, with a fillet radius varying from 0.5 to 2 mm. Fiber orientation inside the specimens was varied by injecting the plates longitudinally and laterally through a film gate on the top face and a side gate on the lateral face, respectively.
Results showed that fatigue strength is reduced compared with plain specimens, but it is not influenced significantly by the further variation of notch tip radius, with the exception of the case of the smallest notch fillet radius of 0.5 mm. In this case, a further reduction of the fibre strength is observed. A possible way to explain the observed behavior is to evaluate and compare stresses at the notch by numerical modeling of the mechanical behavior of the injection moulded specimens.

Modelling of injection moulded parts requires taking into consideration fibre orientation, by properly simulating the injection moulding process and by using software packages allowing for the evaluation of fibre orientation distributions and for transferring of this information to structural analysis modelers. The first step of this procedure is of paramount importance and results need to be validated against experimental evidences.

In this work we present the results of the numerical simulation of the injection moulding of the specimens used in the fatigue tests, and the comparison of the results with the fibre orientation patterns obtained experimentally by an optical method (i.e. by measuring the eccentricity of the elliptical footprints left by the fibres on the cutting plane). The simulation package, Autodesk MoldFlow Simulation Insights has been used in these simulations using experience gained from our previous studies.

The gauge section, the region around the notches and two sections away from the notch region were analysed. The injection moulding process was simulated for all six cases, i.e. for lateral and longitudinal injection of all three specimen types, having a notch root radius varying from 0.5 to 2 mm. This allows for comparing the fibre orientation patterns obtained numerically in the same areas, as required for the validation of the whole process, aiming at the stress analysis in the different specimens. Within this paper we summarise the results for one such geometry.

2. Sample testing

2.1 Fibre orientation measurement

Fibre orientation measurements were conducted at the University of Leeds using an optical microscopy technique [2, 3]. Samples were taken at two locations along the flow path (A and B, figure 1) and prepared as per published protocols [2, 3].

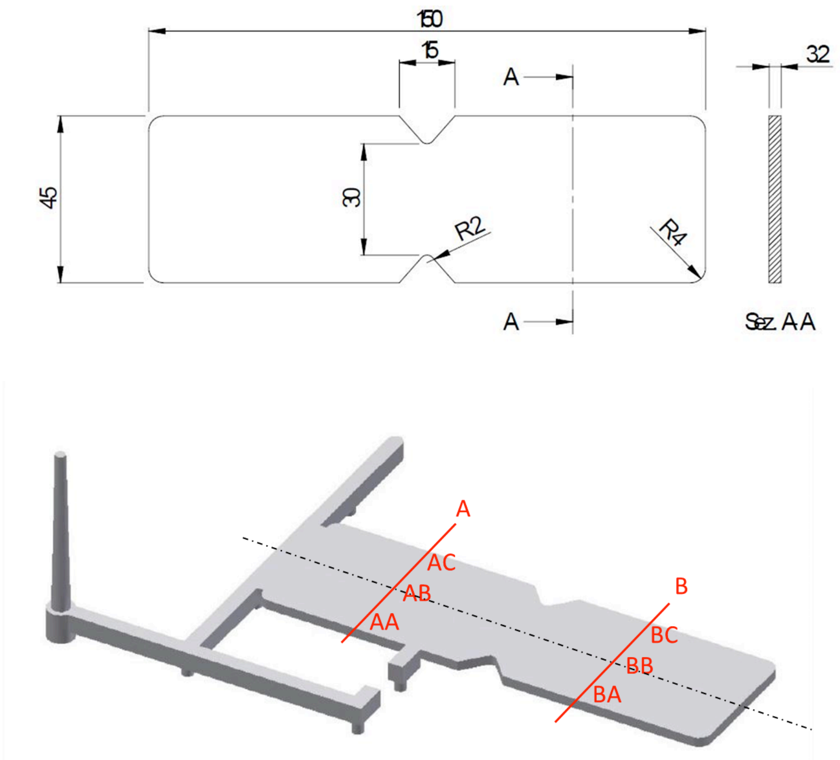

Figure 1**. Notch specimen geometry with fibre orientation measurement locations A and B**

Orientation angles θ and ϕ were averaged over the sample thickness at three points across the sample width (AA, AB, AC and BA, BB, BC for locations A and B) to produce orientation distribution plots across the plate width. A typical result is shown in Figure 2 for locations AA, AB and AC.

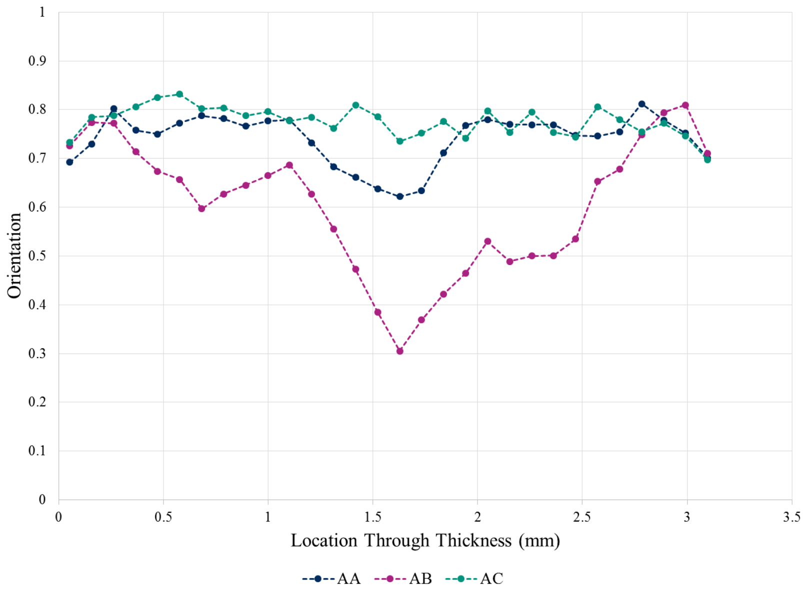

Figure 2. Typical fibre orientation data across the sample width

3 Injection Moulding Analysis

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, modified Folgar-Tucker or Reduced Strain Closure. A review of each of these models was presented by Wang et al (2010) [4] were each model was related to the second order orientation tensor [5], defined as

$$A = \langle pp \rangle \tag{1}$$

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.

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

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.

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

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

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

Table 1 summarises the feasible applications of the three fibre orientation models in terms of Autodesk Moldflow analyses alongside 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 Simulation Insights including limits of their respective parameters

3.2 Moldflow Models

Here we show midplane or 2 ½ D models, however it should be noted that dual domain analyses and fully three-dimensional models are also prevalent within the industrial community.

The midplane analysis of the end or longitudinally gated notched specimen have been constructed so that a line of elements are coincident with the sample locations A and B, either side of the notch. The final midplane analyses contained 16,000 elements each with 20 layers through the thickness. Alternative mesh densities were also studied and found to produce similar results to those shown here. Figure 3 shows the Autodesk Moldflow Simulation Insights model.

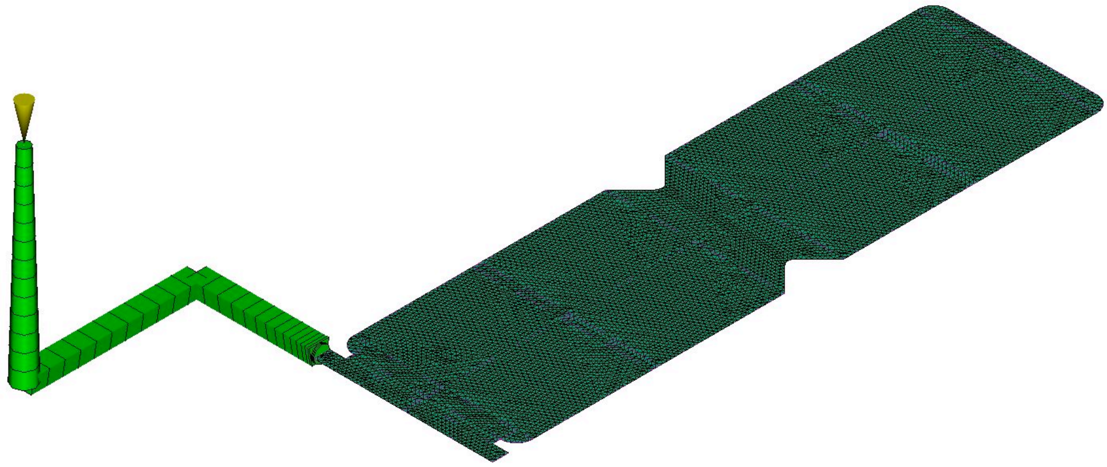

Figure 3. Notch specimen Autodesk Moldflow Simulation Insights model.

Previous work into the fibre orientation of both Polyamide 6 and Polypropylene short glass fibre reinforced injection mouldings [6] has shown that tuning of the various model parameters can significantly increase the accuracy of FOD predictions. Based on centre gated discs and end gated flat plates optimum values for thin walled mouldings were found to be as shown in Table 2.

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 2. Optimum values for fibre orientation prediction models based on the analysis of centre gated discs and end gated plates.

It should be noted that the traditional Folgar-Tucker model is no longer used as it is prone to over prediction of skin and core orientation.

4 Results

Due to the nature of the gating system on the notch sample described above, the filling and resultant fibre orientation is different on both sides of the geometry. Figure 4 shows the prediction results for the average fibre orientation (ie through all 20 thickness layers) in the X direction, along the plate length, based on the default parameters for the modified Folgar-Tucker model.

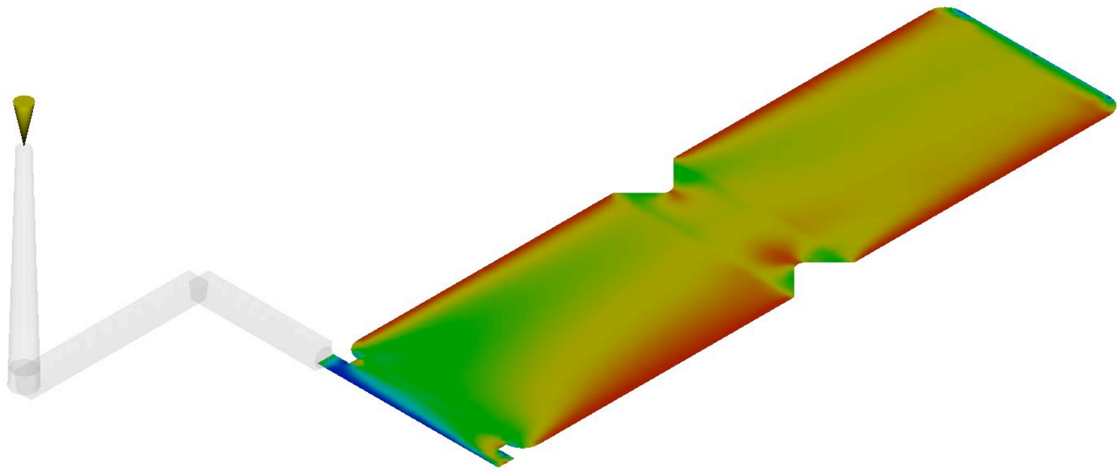

Figure 4. Fibre orientation prediction within the sample geometry

Figures 5 and 6 show the fibre orientation prediction results for the modified Folgar-Tucker model using both the default parameter as selected by Autodesk Moldflow (D_z = 0.1435, c_i = 0.0021) and the optimum parameters described above, for locations AA and AC. As the figures show, both the default and optimum parameters predict a higher degree of skin alignment in the direction of flow but correctly predict the lack of a core region at location AC. The default and optimum predictions at locations AC are identical.

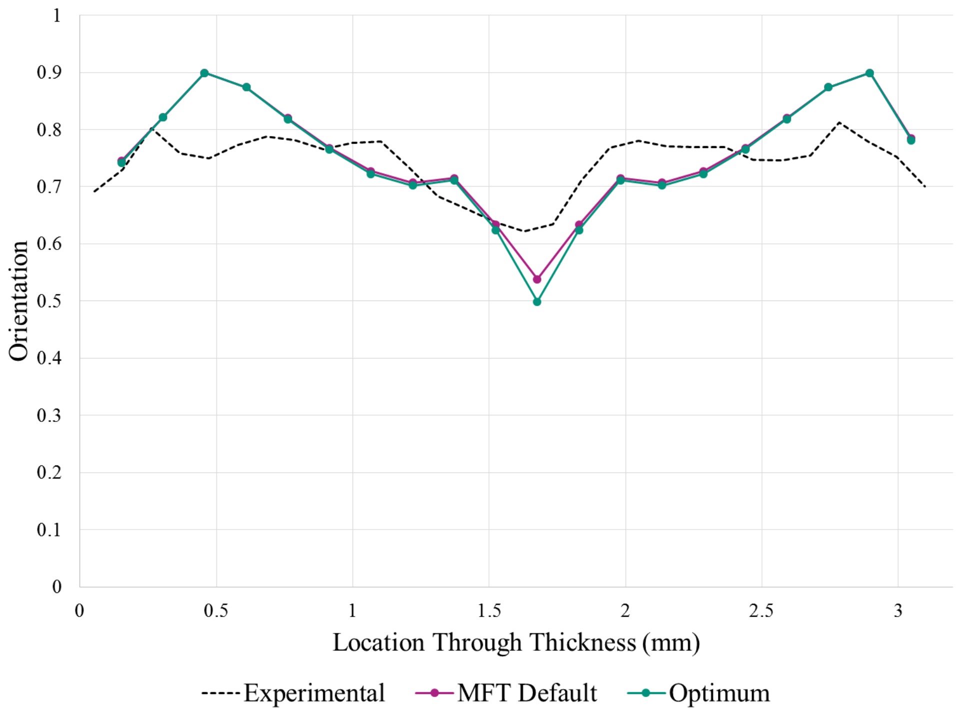

Figure 5. Fibre orientation prediction of the modified Folgar-Tucker model at locations AA

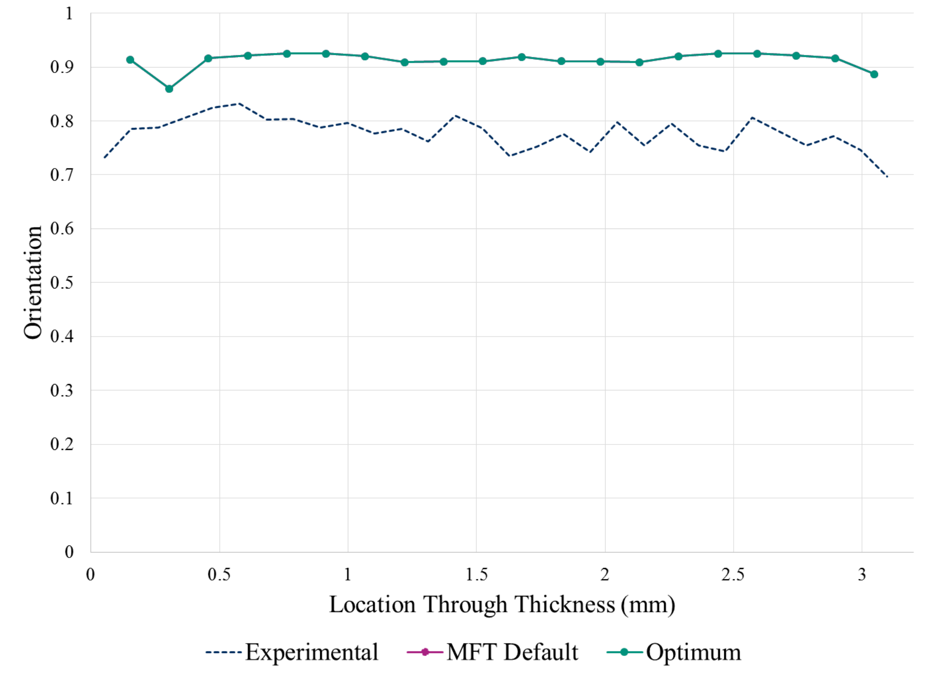

Figure 6. Fibre orientation prediction of the modified Folgar-Tucker model at locations AC

The Reduced Strain Closure model with the optimum values from previous studies shows a significant improvement over the modified Folgar-Tucker at both of these locations as shown in Figures 7 and 8.

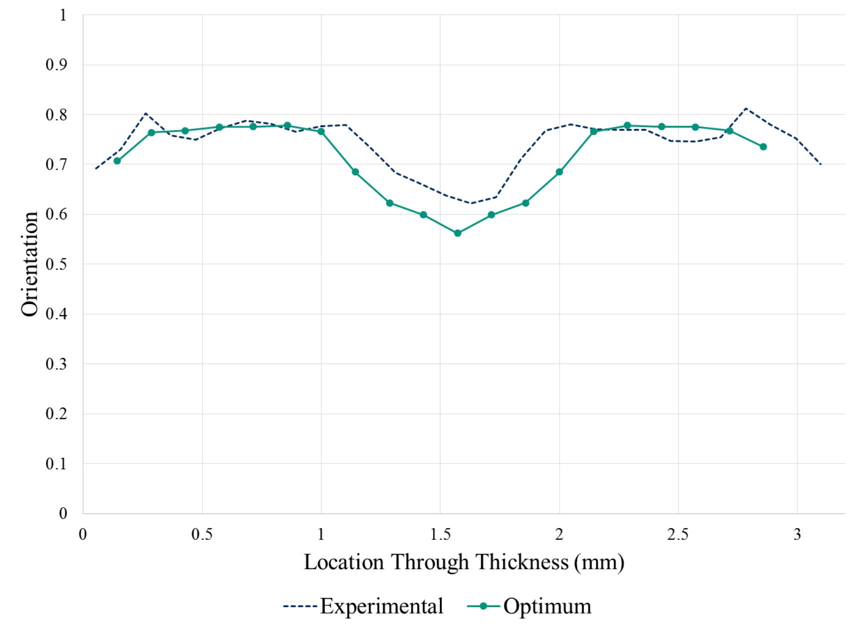

Figure 7. Fibre orientation prediction of the reduced strain closure model at locations AA

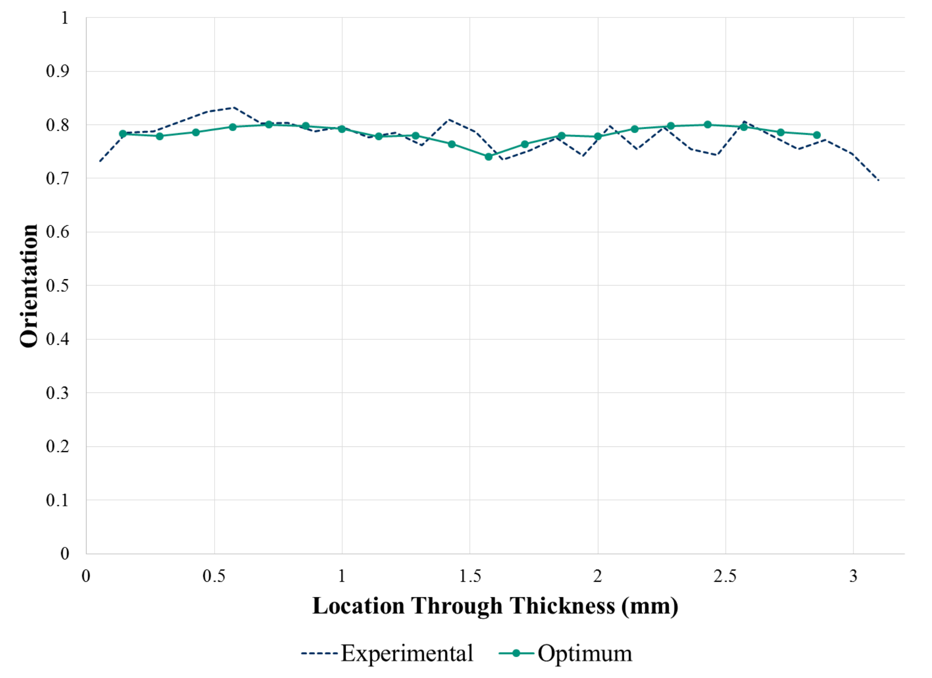

Figure 8. Fibre orientation prediction of the reduced strain closure model at locations AC

Similar results have been found for locations BA, BB and BC and will be presented during the ECCM conference.

5 Conclusions

The Reduced Strain Closure model has been shown to most closely mimic the fibre orientation within centre gated discs, end gated plates and notched samples (shown here). Based on these preliminary results the work is being extended to accurately model the fibre orientation around the notch tip in order to feed future fatigue analyses.

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