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3D FLOW AND FIBRE ORIENTATION MODELLING OF COMPRESSION MOULDING OF A-SMC: SIMULATION AND VALIDATION IN SQUEEZE FLOW

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Abstract:

Keywords: Sheet Moulding Compound; Numerical Simulation, Fibre Orientation Modelling

1. Introduction

Sheet Moulding Compound (SMC) is a class of composite materials that have the possibility to be useful in automotive industrial applications, due to the possibility of obtaining comparatively short cycle times. More recently, Advanced SMC (A-SMC) has also been introduced, the main difference compared to earlier materials being that the fibres are now carbon and the volume fraction of fibres is higher (35% and higher compared to earlier 20-25%). Another important advancement is the rapid development cycles in the automotive industry means that it is necessary to be able to reliably numerically predict both the manufacturability and the mechanical properties of parts.

For the moulding process, fitted pieces of sheets consisting of fibres and resin are placed inside a heated mould; when the mould closes the SMC stack melts, flows out and fills the mould.

Process modelling of SMC is however rather complicated for a number of reasons, chief among these the complex material properties of SMCs and the presence of high volume fractions of fibres. These fibres and in particular their orientations will also greatly affect the mechanical properties of the parts. The focus of this work will thusly be on fibre orientation prediction.

The squeeze test rig that is studied in the work presented here is used for determining the viscous properties of materials. This initial study uses the geometry to compare the results of different simulation techniques.

Two different approaches are discussed here. In one a general fluid mechanics code, Ansys CFX, is used for modelling the movement of the SMC during the compression process, the results of which are then used as input for a Python script that calculates the evolution of the fibre placement and fibre orientation distribution. In the other approach, the more specialized composite software 3DTimon is used for determining both charge deformation and fibre evolution.

2. Methods

2.1 General code

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The movement of the charge during the compression of the mould is modelled using fluid mechanics by numerically solving the Navier-Stokes equations (see for instance Cengel and Cimbala [1]). Here the viscosity is modelled using the semi-empirical model suggested by Kluge [2],

$$\eta = 3\eta_0\left(1 + 100f_f + 1000f_f^2\right)e^{-B\left({1}/{T_0}-{1}/{T}\right)}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{n-1}\left(1+\dot{\gamma}^2\right)^{(n-1)/2} \tag{1}$$

in which η is the viscosity, T is temperature, B is a temperature constant, $\dot{\varepsilon}$ is a factor connected to how compressed the material is compared to its initial state, $\dot{\gamma}$ is the shear rate, n is a power law constant, and the subscript 0 indicates initial conditions.

The fibre orientation evolution is modelled using the model suggested by Folgar and Tucker [3] and Advani and Tucker [4], in which the fibres are assumed to be rigid ellipsoidal particles with a large aspect ratio, and that they are sufficiently large that Brownian motion can be neglected. There are a number of issues with this approach [5], but it is the approach taken in most commercial codes specializing in composites. Orientation tensors are used to describe the alignment with the principal axes. The time evolution of the orientation tensors can be described as

$$\frac{Da_{ij}}{Dt} = -\frac{1}{2}\left(\omega_{ik}a_{kj} - a_{ik}\omega_{kj}\right) + \frac{1}{2}\lambda\left(\dot{\gamma}_{ik}a_{kj} + a_{ik}\dot{\gamma}_{kj} - 2\dot{\gamma}_{kl}a_{ijkl}\right) + 2D_r\left(\delta_{ij} - \alpha a_{ij}\right) \tag{2}$$

where a_{ij} is the orientation tensor, ω is the vorticity tensor, $\dot{\gamma}$ is the shear rate tensor, α relates to how many spatial dimensions are considered and D_r is the rotary diffusivity. The fourth-rank tensor a_{ijkl} is approximated with the hybrid approach suggested by Advani and Tucker [6]

$$a_{ijkl} \equiv (1-f)\hat{a}_{ijkl} + f\tilde{a}_{ijkl} \tag{3}$$

in which $\hat{a}$ is a linear approximation, $\tilde{a}$ is a quadratic approximation and f is a scalar measure of the orientation. This approach has been implemented in a Python code, which uses the time evolution of the flow field predicted by CFX as input.

2.2 3D Timon

For the second approach, the software 3D TIMON is used, which is a software for modelling of composites manufacturing developed by Toray Engineering. The viscosity model used in these calculations is described as

$$\eta = \frac{\eta_0}{1+\left(\frac{\eta_0\dot{\gamma}}{\tau^*}\right)^{1-n}},\ \eta_0 = De^{-\frac{A_1(T-T^*)}{A_2+(T-T^*)}}, \tag{4}$$

where η is the viscosity, T is temperature, $\dot{\gamma}$ is the shear rate, n is a power law constant, D and A_1 are temperature constants and T^* and A_2 are factors connected to the flow pressure.

For fibre orientation modelling an approach referred to as Direct Fibre Simulation is used (see for instance [7]) in which the fibres are modelled as sequences of rigid rods.

2.3 Comparison

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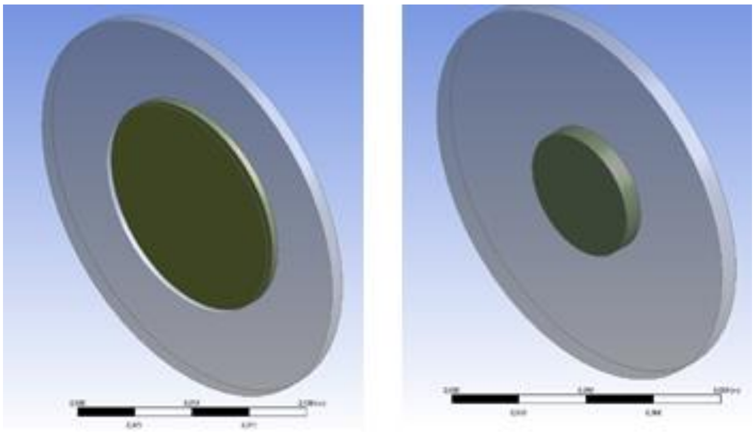

Figure 1: An isometric view of the geometry used in the first case (left) and the second case (right). The highlighted area indicates the initial position of the charge.

The geometries that are studied can be seen in Figure 1. It is a press tool used for rheological tests. Two different cases are set up, one in which the material initially covers the entire area under the press tool providing a constant area of applied pressure. In the simulation the tool is slightly larger so that there exists a cavity for the material to flow into. The second case has a higher stack with a smaller initial area of contact.

For comparison between the two approaches only the particles that remain below the press itself are studied. Using a Python script, several equidistant lines are drawn from the midpoint along the principal axes to the edge of the press, which are then further subdivided into segments. The orientation tensors obtained from both approaches can then be compared in the different subsegments.

3. Results and Discussion

3.1 Results for Case 1

The fibre orientation results for the two different approaches for the first case can be seen in Figures 2 and 3. In both these figures, the different zones indicate the distance to the midpoint, i.e., zone 1 is right at the centre and zone 4 is at the edge of the press and the values presented are based on averaging the component aligned with that axis. It can be seen in Figure 2 that the results are mostly in agreement in the inner zones and are in relatively good agreement in the out zones as well, even if the spread of results for the Python code is far greater. In Figure 3 it can be seen that the Python code predicts a significantly greater out-of-plane component than 3D Timon does.

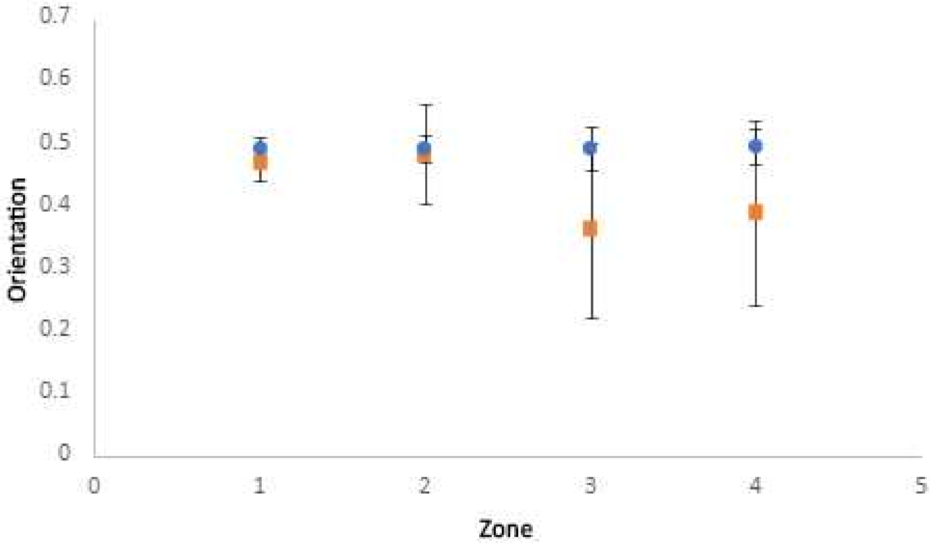

Figure 2: Average values with error bars of the components aligned with the principal flow direction, i.e. a_{11} in the lines along the x axis and a_{22} in the lines along the y axis. Blue circles are taken from 3DTimon, and orange squares are taken from Python.

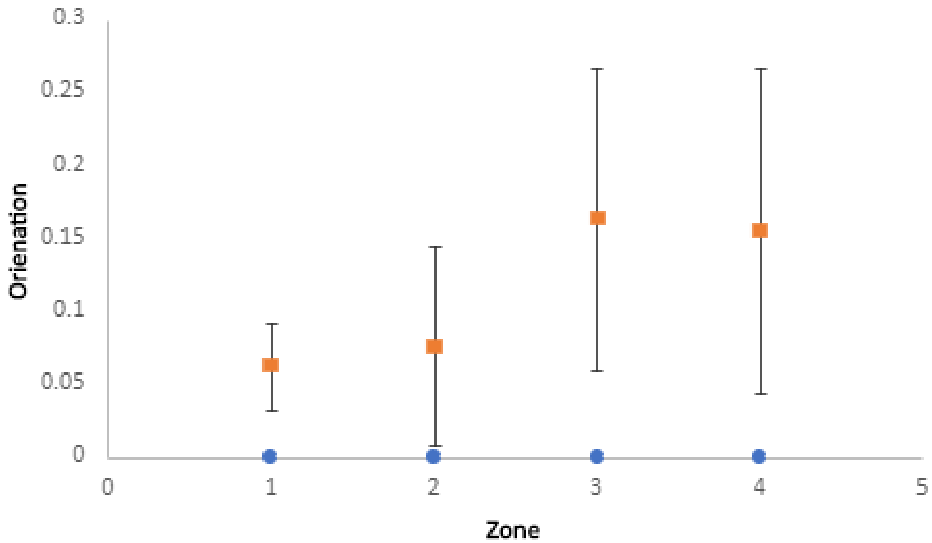

Figure 3: Average values with error bars of the out-of-plane components. Blue circles are taken from 3D Timon, and orange squares are taken from Python

3.2 Results for Case 2

The fibre orientation results for the two different approaches can be seen in Figures 4 and 5 It can be seen in Figure 4 that the results align very well in the centre of the press, but that they diverge significantly as the distance from the midpoint increases. A trend for greater flow direction alignment can be seen for the 3DT Timon results; no such trend can be seen for the Python implementation. It can also be seen in Figure 5 that 3D Timon here as well predicts almost no out-of-plane orientation, while the Python implementation once again predicts far more significant out-of-plane components, especially in the zones farther from the midpoint.

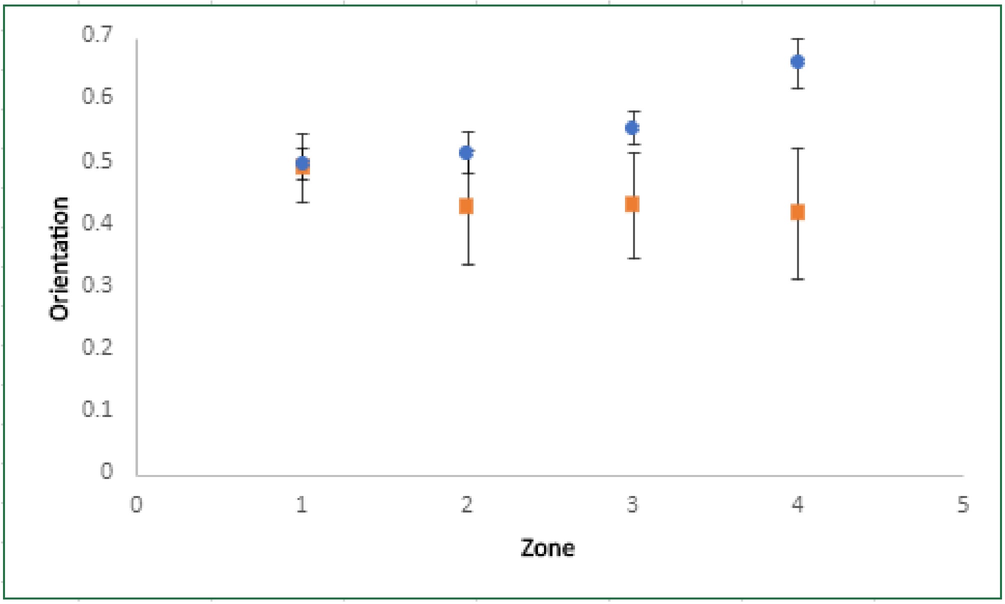

Figure 4: Average values with error bars of the components aligned with the principal flow direction, i.e. a_{11} in the lines along the x axis and a_{22} in the lines along the y axis. Blue circles are taken from 3DTimon, and orange squares are taken from Python.

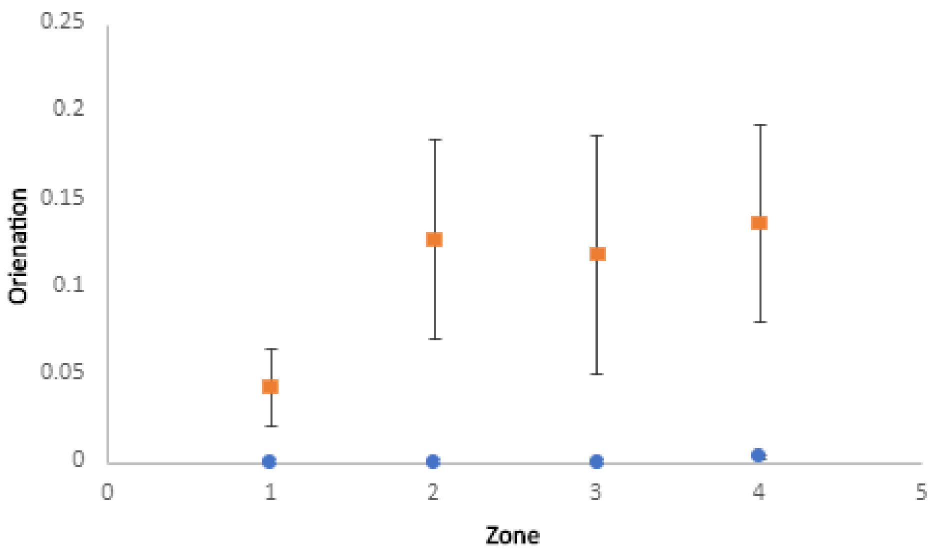

Figure 5: Average values with error bars of the out-of-plane components. Blue circles are taken from 3D Timon, and orange squares are taken from Python.

3.3 Discussion

A general trend that can be observed from these results is that the Python implementation has a far greater variation in results overall than 3D Timon. It can also be observed that the Python implementation predicts far more motion in the out-of-plane direction than the 3D Timon model does. In both Figure 2 and 4 the trends are different between the two methods with the greater out-of-plane alignment being a likely explanation for these results. While the reason for this discrepancy is not entirely clear, the greater focus on three-dimensional modelling in the general software is one possible cause.

4. Conclusions

Comparisons between two fibre orientation approaches for two different cases have been presented. One approach is based on a general fluid mechanics code, the results of which are then used as input for a Python code based on [4] for modelling fibre orientation, while the other uses a specialized composite code where fibre orientation is calculated in accordance with [7]. The trends in the two different codes are slightly different with a main factor being greater out-of-plane components predicted by the general approach. The results from the Python code also have a greater spread. Continued refinement of the Python code, as well as comparisons to experiments will be the subject of future work.

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