MODELING AND CHARACTERIZATION OF THERMOPLASTIC COMPOSITES PEEK/CARBON

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1 Introduction

Thermoplastic composite materials are available in many forms and are produced by using a variety of manufacturing methods. One of these methods is the stamp-forming. It consists in stamping a preheated flat laminate (or blank) between two heated mold halves defining the part geometry. The modeling of the stamp-forming of thermoplastic composites involves three necessary steps: i) the first step is to determine the deformation mechanisms during the forming process; ii) the second step is to develop or identify a mathematical model that can take into account these mechanisms; iii) the third step is to identify the parameters of the model using different characterization tests performed following standard tests or from recognized approach.

2 Modeling and characterization tests

2.1 Mechanisms of deformations during the forming

The mechanisms of deformations in stamp-forming can be split into several ones such as intra-ply, inter-ply and out-of-plane mechanisms [1] as shown in Figure 1.

![Fig. 1. Primary mechanisms of deformations [1]](image)

2.2 Mathematical model

For modeling fabrics impregnated by a viscous fluid, a mathematical model was proposed by Spencer [2]. This model can be used for composites reinforced by two families of fibers. In this model, the Cauchy stress tensor of a Fabric Reinforced Viscous Fluid (FRVF) with two directions of reinforcement has the following form [2]:

\[
\sigma = -pI + T_a A + T_b B + 2\eta_1 (A D + D A) + 2\eta_2 (B D + D B) + 2\eta_3 (C D + D C) + 2\eta_4 (C^T D + D C)
\]

(1)

where \(\eta_1, \eta_2, \eta_3, \eta_4\) are viscosities, \(D\) the rate of deformation tensor, \(p\) the pressure, \(T_a\) and \(T_b\) the tensions of fibers respectively in directions \(a\) and \(b\) (fiber directions), and \(F\) the deformation gradient. The viscosities are in general functions of \(a\) and \(b\) which in turn are related to the angle \(2\phi\) between the two fiber directions by:

\[
a \cdot b = \cos 2\phi,
\]

(2)

The tensors \(A\), \(B\) and \(C\) are given by:

\[
A = a \otimes a, \quad B = b \otimes b, \quad C = a \otimes b, \quad C^T = b \otimes a
\]

(3)

or under following index forms:

\[
A_{ij} = a_i a_j, \quad B_{ij} = b_i b_j, \quad C_{ij} = a_i b_j, \quad C^T_{ij} = b_i a_j
\]

(4)
where the symbol $\otimes$ stands for the tensor product, the superscript $T$ denotes the transpose and $\mathbf{a}$, $\mathbf{b}$ denote the actual fiber directions related to the initial directions $\mathbf{a}_0$ and $\mathbf{b}_0$ by

$$\mathbf{a} = F \cdot \mathbf{a}_0 \quad \mathbf{b} = F \cdot \mathbf{b}_0$$  \hspace{1cm} (5)

For unidirectional (UD) composites, Eq (1) reduces to the following formula:

$$\sigma = -p\mathbf{I} + T_\alpha \mathbf{A} + 2\eta D + 2\eta (\mathbf{A} \cdot \mathbf{D} + \mathbf{D} \cdot \mathbf{A})$$  \hspace{1cm} (6)

for which $\eta = \eta_T$ and $\eta_T = \eta_L - \eta_T$ with $\eta_L$ and $\eta_T$ representing the longitudinal and transverse viscosities respectively. This formulation for unidirectional composites is called the Ideal Fibre Reinforced Newtonian fluid Model (IFRM) in the literature.

2.3 Material characterization and identification of material parameters

To obtain the model parameters, laminates made of unidirectional PEEK-carbon CETEX TC1200 lamina from TenCate have been used. The parameters of the material model must be determined by a series of experimental tests of characterization and identification procedure (for example, fitting method). Aniform™ the finite element software for composite forming, needs four kinds of material properties: (i) the modulus of elasticity of fibers, (ii) the mechanical behaviour of the matrix (iii) the friction coefficient between a ply and the tool surface and in between two plies and (iv) the bending parameters. To gather these properties it is necessary to perform four kinds of experiments: (i) intra-ply shear tests, (ii) tool-ply friction tests, (iii) ply-ply shear tests and (iv) bending tests [3,5] schematically presented in Figure 2.

2.3.1 Intra-ply shear test

Different tests can be used to characterise the intra-ply shear, namely bias-extension and picture-frame (or trellis frame) for bidirectional composites and the torsional test with a rheometer for unidirectional composites (Figure 3 and Figure 4). These test methods can be used to determine the transverse and longitudinal viscosities, respectively $\eta_T$ and $\eta_L$ (according to fibers directions) of unidirectional reinforced plies at temperature over the melting temperature of the resin [3].
Some results of torsion tests on a laminate made of unidirectional PEEK/Carbon plies are presented by Haanappel [5]. In his study, only the longitudinal viscosity was determined at high temperature (\( \eta_L = 300 \text{ kPa-s} \) at 390°C). The transverse viscosity was missing due to the deconsolidation of the sample at high temperature.

For the simulation with Aniform\textsuperscript{TM}, it will be supposed that either the transverse viscosity is the same as the longitudinal viscosity (in this case, the fiber-matrix interactions are not taken into account) or the longitudinal viscosity is double the value of the transverse viscosity (in this case, the fiber-matrix interactions are taken into account) (Table 1).

Table 1. Parameters from intra-ply mechanisms

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_L )</td>
<td>300 kPa-s</td>
<td>600 kPa-s</td>
</tr>
<tr>
<td>( \eta_T )</td>
<td>300 kPa-s</td>
<td>300 kPa-s</td>
</tr>
</tbody>
</table>

2.3.2 Tool-ply and ply-ply friction tests

Different set-ups for the characterization of tool-ply and ply-ply friction have been developed by several research groups [3]. For the friction characterization, the set-up from ThermoPlastic Research Center (TPRC) in the Netherlands is used (Figure 5).

![Fig. 4. Left and center, axial intra-ply shear; right, transverse intra-ply shear [4]](image)

![Fig. 5. Left: Tool-ply characterization set-up. Right: Schematic response that was typically observed [5]](image)

A specimen with typical dimensions of 50x200 mm was used. The friction coefficient is determined by the following equation:

\[
\mu = \frac{F_p}{2F_n}
\]

where \( F_p \) is the test force and \( F_n \) is the normal force.

2.3.2.1 Results for tool-ply friction test

For the tool-ply friction, three velocities were considered (\( U=20\text{mm/min} \), \( U=100\text{mm/min} \) and \( U=500\text{mm/min} \)). The applied pressure was 10kPa and the temperature was set at 400°C. Each test was repeated three (3) times using Marbocote release agent (a semi-permanent mould release agent used in most composite manufacturing processes) on the tool surface. Typical friction coefficients are shown in Figures 6 to 8.

![Fig. 6. Friction coefficient (P=10kPa, U=100mm/min and T=400°C)](image)
2.3.2.2 Results for ply-ply friction test

For the ply-ply friction (for a 0/90 interface), three velocities were considered (U=20mm/min, U=100mm/min and U=500mm/min). The pressure was 10kPa and the temperature was set at 400°C. Each test was repeated three (3) times. Figures 9 to 11 show typical test results.
2.3.4 Bending test

For DKT Kirchoff shell element, to improve the simulation results in Aniform™ [6] in terms of bending, bending test must be carried out. Two different types of bending test were performed as explained below.

2.3.4.1 Three (3) point bending test

Three (3) point bending test was carried out using Dynamic Mechanical Analysis (DMA) machine. The tests were performed at 340°C near the melting temperature of PEEK for the unidirectional specimen. Typical results are shown in Figure 12.

The flexion modulus was obtained by combining the storage and loss moduli using the following relationship:

\[
\begin{align*}
E^* &= E' + iE'' \\
E &= \text{Norm}(E^*) = \sqrt{E'^2 + E''^2} \\
\tan(\delta) &= \frac{E''}{E'}
\end{align*}
\]

where:
- \(E\) : flexion modulus
- \(E'\) : Storage modulus
- \(E''\) : Loss modulus

\text{Fig. 12. Three (3) point bending test performed in DMA at 340°C}

\text{Fig. 13. Bending fixture in a standard rheometer [5]}

In this test [7], the temperature was fixed at 400 °C and the two (2) different types of velocity were used (1 rpm and 10 rpm) for 8 plies and 4 plies. Each test was repeated three (3) times with sample of size 35 mm X 25 mm. Figures 14 to 17 show the test results.
3 Forming simulation on Aniform™ [6]

A forming simulation was carried out with the mold and cavity designed by the Université du Québec à Trois-Rivières (UQTR) using the parameters of the material model obtained from the characterization tests presented above. For the simulation, the laminate was composed of 24 layers ([0/90]s) of CETEX TC1200 unidirectional PEEK-carbon (dimension 240 mm X 160 mm). Figures 18 and 19 show respectively the finite element mesh of the model (punch and cavity) including the laminate and the deformed laminate after running the program. Parameters for simulation below are available in Table 1 and Table 2.

Table 2. Parameters from inter-ply and out-of-plane mechanisms

<table>
<thead>
<tr>
<th>Tool-ply contact</th>
<th>Ply-ply contact</th>
<th>Bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>2</td>
<td>$\mu$ 0.9</td>
</tr>
<tr>
<td>$\eta$</td>
<td>4 kPa-s</td>
<td>$\nu$ 0.329</td>
</tr>
</tbody>
</table>
The thickness distribution of one layer can be obtained from the simulation as shown in Figures 20 to 22.
Fig. 22. Thickness evolution for layer 1 at the end of simulation on line Y= +40 mm.

4 Conclusion and outlook

- To characterize the composite material, one needs to take into account the intra-ply, inter-ply and out-of-ply mechanisms of deformation.
- The simulation in Aniform works well with the parameters measured from the characterization tests.
- The material parameters will be validated by comparing numerical simulations and stamp-forming experimental results.

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References


