Modeling the Squeeze Flow of a Thermoplastic Composite Tape During Forming.

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Abstract: Thermoplastic composite such as APC2 (Carbon/PEEK) are usually shipped as semi-finite tape products. Final product is obtained with forming by applying heat and pressure. A key phenomena is the squeezing of the tape. In this paper we compare the solution of the squeeze flow using a finite element method, an analytical model under lubrication assumption and experimental data. The finite element model is solved in two dimensions (plane strain) in COMSOL using a heat transfer and a flow modules solved on a moving mesh (ALE). The numerical and analytical values correlate well and validate the analytical lubrication assumption. On the contrary, the experimental values are not recovered showing that additional work on the modeling and/or behavior are needed..

Keywords: ALE, press forming, large deformation.

1. Introduction

Composite materials are of growing interest, especially in the aeronautical industry. This is mostly because of their competitive specific properties, namely strength and stiffness.

Thermoplastic composites offer new possibilities for aeronautical industry. Huge structures (several meters) could be processed rapidly and possibly replace the thermoset composites which need to be cured. The ability to melt the matrix gives new perspectives for processes.

When processing thermoplastic composites, one usually start with a preimpregnated composite tape. Several forming processes then allow to get the final part. One might use autoclave consolidation, press forming or automated tape placement. The present work aim at helping understanding the randomly oriented strand forming [1,6,7,8] (see figure 1). In all cases one wants to apply pressure and temperature that allow consolidation of the part.

Figure 1. Randomly oriented strands ready to be processed in a flat plate.

In order to better understand these processes, one always needs to understand how a single prepreg tape behaves under pressure and processing temperature. In this study, we propose to model the squeezing of a single APC2 (Carbon / PEEK) tape using finite element method. The simulation results are then compared to analytical predictions [1] obtained under the lubrication assumption and experimental values [2].

2. Governing Equations

2.1 Geometry

Because of the unidirectional fiber orientation, the geometry is supposed to be an extrusion in the direction of the tape. Moreover the fibers are very stiff compared to the matrix, such that the deformation in the direction of the fibers can be neglected. Therefore, the study is restricted to two dimensions with plain strain assumption.

In order to increase the resolution of the experimental measurements (presented in section 4 hereunder), instead of testing one single composite tape (which thickness is about one tenth of millimeter), the squeeze flow is performed on a unidirectional laminate. This turns out to be similar to assuming one very thick tape. The initial shape of the sample is 6.3x50x50. It is modeled in two dimension as a rectangle of dimensions h_0=6.3 mm by L_0=50 mm. (see Figure 2) [2].

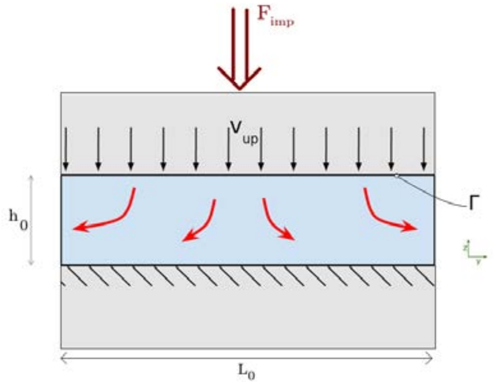

Figure 2. Initial geometry of the tape (in blue) and boundary conditions.

2.2 Heat transfer

In a first step, the sample is heated without applying pressure.

The temperature field is modeled using a classical heat transfer diffusion model. Even though we deal with a composite material that is non isotropic, the two dimensional working plane is orthogonal to the fiber direction. Therefore, the thermal conductivity used is simply the transverse homogenized thermal conductivity of the APC2 [5]:

$$k = 0.43\, W/m/K$$

The specific heat used is:

$$c_p = 2000\, J/kg/K$$

and the density

$$\rho = 2000\, kg/m^3$$

These values are adapted from literature [5,9].

The tape is considered initially at room temperature.

At time t=0, the sample is positioned in the press. Because the press is massive and in metal, we consider that it imposes its temperature. Dirichlet boundary conditions are then imposed on both the upper and lower layers:

$$T = 380°C$$

A convective cooling:

$$q = h(T - T_0)$$

is applied on the free left and right boundaries, where q is the heat flux, T the temperature T0=20°C is the air temperature and h=15W/m^2/K is the typical exchange coefficient used.

2.2 Fluid Mechanics

Once steady state is reached in temperature, a load is applied on the press. Because flow occurs mostly in the transverse direction, a fluid behavior is considered for the composite tape. An equivalent non-linear viscosity following a Carreau law is assumed:

$$\boldsymbol{\mu = \mu_0 (1 + (\lambda D_{eq})^2)^{\frac{n-1}{2}}}$$

where $\boldsymbol{\mu_0}$, $\boldsymbol{\lambda}$ and are material parameters that are found in the literature [1] for APC2:

$$\boldsymbol{\mu_0 = 2.5 \times 10^6 Pa.s}$$
$$\boldsymbol{\lambda = 50s}$$
$$\boldsymbol{n = 0.65}$$

Note that while processing such highly viscous materials, the inertia terms can be neglected, such that the flow is a purely Stokes flow (low Reynolds number).

The boundary conditions on the lower part of the tape is a zero velocity.

The left and right boundaries are let free.

The boundary condition on the upper part needs more care since the mold is force controlled. (i) The mould motion constrains a uniform downward velocity $\boldsymbol{v_{up}}$ on the upper boundary. (ii) this velocity $\boldsymbol{v_{up}}$ is such that the resulting load applied on the mold is the applied force. Therefore, on the upper boundary $\boldsymbol{\Gamma}$ (see Figure 2), we have:

$$\boldsymbol{v = v_{up}}$$

$$\boldsymbol{\int_{\Gamma} P\, dS = F_{imp}}$$

P being the pressure and $\boldsymbol{F_{imp}}$ the applied force on the mould.

3. Use of COMSOL Multiphysics

Few difficulties arise while trying to solve the presented thermo-mechanical problem.

3.1 Modules used

We want to solve successively two different physics. Heat transfer to predict the first heating step, and mechanics to predict the squeeze flow. COMSOL multiphysics turns out to be perfectly fitted to handle these two physics: three modules are used successively: (i) a heat transfer in solid module to solve the transient conduction problem. It is very classical and should not need further explanation. (ii) a fluid flow (laminar) module in conjunction with a moving mesh module to solve the fluid mechanics, The unknown at each point are then: the temperature the two component of the velocity and the pressure.

3.2 Fluid Mechanics specificity

The deformation that the tape undergoes needs a special care. Indeed, we need to keep track of the geometry change while the tape spreads out of the mold. Because of the large deformation occurring (see figure 5), an ALE method is used. It is implemented in COMSOL using the moving mesh module. The mesh horizontal and vertical velocities on the boundaries are prescribed as the fields u and v of the flow model.

The fluid mechanics is a nonlinear problem. A Carreau law is used for viscosity. The inertia terms are neglected. Nonlinear solving is performed automatically using the default COMSOL settings.

In order to model force controlled upper mold, a rigid body representing the upper part of the mold is added to the fluid problem. A rectangle of dimension $h_m = 30mm$ by $L_m = 50mm$ is appended on top of the tape (see Figure 3). A fake viscous material with a very high viscosity $\mu = 10^8 \text{Pa.s}$ is assigned such that it behaves as a rigid body. An homogeneous vertical load $P_{imp} = F_{imp}/L_m$ is then applied on the upper part of this mold to represent the applied force. This workaround is a way to model the force driven mould. Note that the heat transfer is not solved in the mold.

Finally, note that the platen matches the initial size of the sample (see Figure 5). A free boundary condition (outlet, zero pressure, no viscous flow) is therefore set on the lateral boundaries. It results in a "fountain effect", such that no load is applied on the matter that flowed. In the eventual case where the platen would be larger than the initial sample size, such that the flow would be restricted between the platens, one would need to modify this boundary condition (and ensure, for instance, a zero vertical velocity).

3.3 Meshing and Solving

A maximum mesh size of 1e-3m is set in the tape domain and the default "coarser" setting is chosen for the fake mold domain. The resulting mesh is shown on Figure 3.

Two transient solvers are then added. One for solving the first heating step where only heat transfer problem is solved. The time range is set as 0:20:1000s.

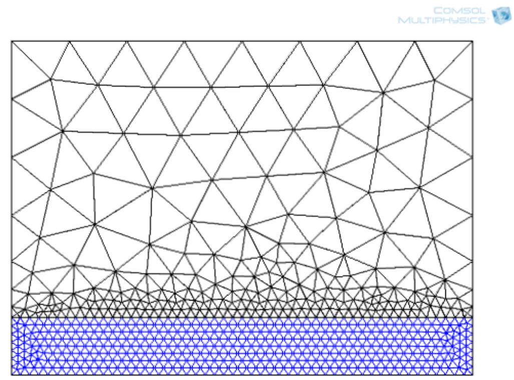

Figure 3. Geometry and mesh in COMSOL

The second solver solves the fluid flow and the moving mesh only. The time range is set to 0:1:150s in agreement with the experimental measurements.

4. Experiments

The experimental investigation is fully described in [2]. A press was specifically designed for the purpose. It consists of a press that includes a load cell to check the applied force, an LVDT to measure the platen displacement and two platens heated using heating cartridge (see Figure 4).

Three experiments using three different applied forces (445N, 1334N and 2224N) were performed. The thickness decrease is measured versus time.

5. Analytical Model

Squeeze flow has been widely studied in the literature. The mostly used assumption is to consider a lubrication assumption: the thickness is an order of magnitude smaller than the width and the vertical derivatives are an order of magnitude higher than the horizontal ones [1, 3, 4, 10].

Considering a fluid behavior, this assumption usually allows to separate the two space variables. This model can be solved analytically in the case of a Newtonian fluid [1, 10] or a simple power-law behavior [4], but needs to be solved using numerical methods in the case of a more non Newtonian behavior, such as a Carreau law [1] or in the case of temperature dependency [3].

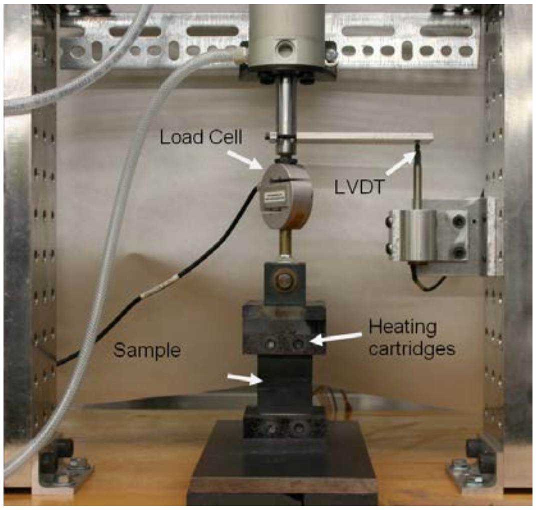

Figure 4. Test fixture for squeeze-flow experiments.

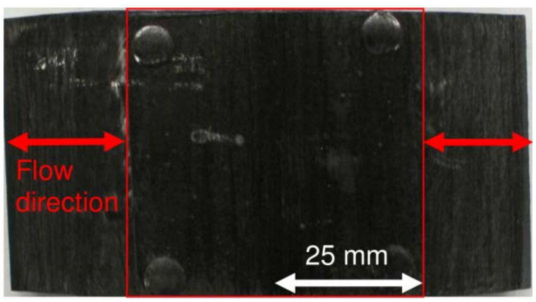

Figure 5. A sample after experiment. The platen size matches the initial sample size.

In our case, the analytical model resulting from the lubrication assumption writes:

$$\frac{d}{dy}\left(\mu\frac{du}{dy}\right) = -\frac{dP}{dx}$$

$$\int_{-h/2}^{h/2} u\,dy = x.v_{up}$$

$$\int_{-L/2}^{L/2} P\,dx = F_{imp}/W$$

where u is the horizontal velocity, that depends on x and y. P is the pressure that depends on x only, and W is the depth of the sample in the third direction. One might refer to [1] for a detailed description of this model.

This model is solved using finite differences in MATLAB and predicts v_{up} and therefore the platen displacement at each time step.

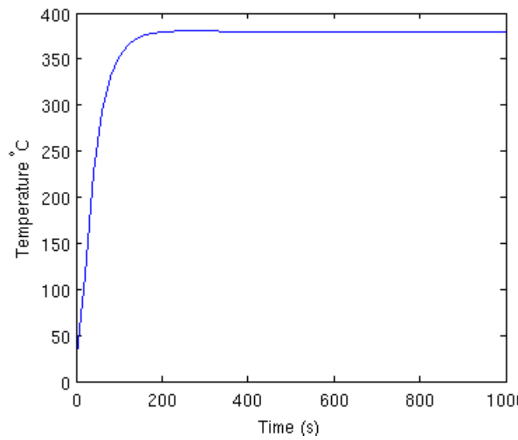

Figure 6. Temperature at the center of the plate versus time.

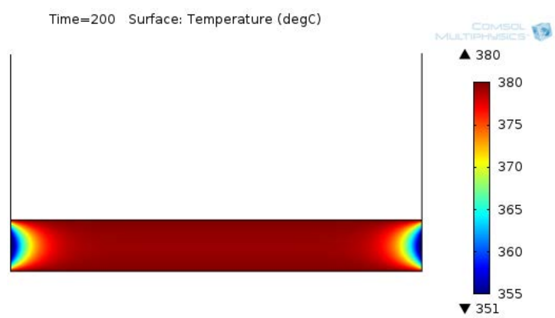

Figure 7. temperature field at time t=200s

6. Results

6.1 Heat transfer

The heat transfer solution shows that the first heating step is quite fast. Figure 6 shows that after about 200 seconds, steady state is reached in the tape. Moreover, the temperature in the sample is almost homogeneous. It varies within 25°C, very locally at the edges in contact with the air, as shown on figure 7.

This confirms that an isothermal condition can be assumed for the flow. Temperature can be assumed constant and equal to the mould temperature as soon as the sample is kept for at least 200s between the heated platens.

6.2 Squeeze flow

As an illustration of the finite element resolution of the fluid flow, Figure 8 shows the velocity field at final time, in the case of an applied force of 1335N.

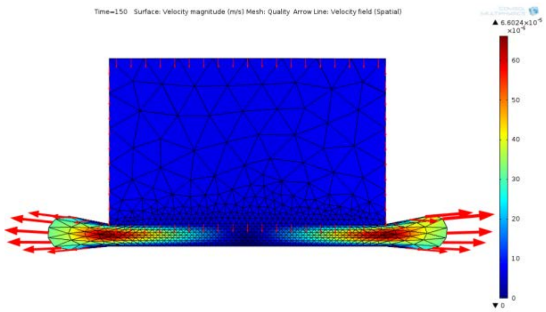

Figure 8. Velocity field at time t=150s, applied force : 1335N.

Figure 9 presents the plate thickness evolution (computed as the average internal boundary coordinate) versus time for different imposed force on the platen. The plain lines represent the finite element prediction computed with COMSOL; the dashed line the analytical model prediction under lubrication assumption using MATLAB; and the dots the experimental values.

8. Discussion

We observe a good agreement between the analytical model and the Finite Element model. This shows that the lubrication assumption stands, even in this very thick tape case were the width to thickness ratio is only around 10. In the thinner case, which corresponds to the industrial tape thickness, the lubrication assumption is therefore even more valid.

Nonetheless, we observe a large difference between the modeled thickness evolutions and the experimental measurements. This denotes a mistake in the modeling.

The material data taken from the literature might not be accurate. A better characterization or using an inverse method is currently under investigation.

But more than that, this shows that a purely viscous behavior is probably not valid to represent the composite. One should notice that the experimental thickness reaches an asymptote on Figure 9. It reflects that we reach a minimum thickness where the fiber network prevents any further squeeze. On the contrary, any viscous fluid model will predict a thinning as long as the closing force is applied and therefore zero thickness limit. The viscous behavior classically used in the literature [1, 3, 4, 10, 12] is therefore not valid .

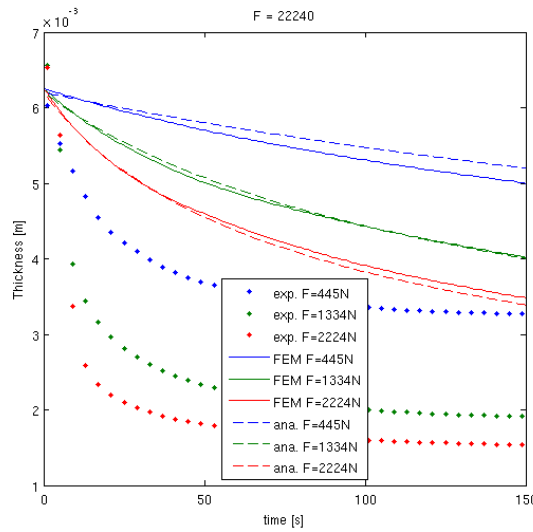

Figure 9. Sample thickness evolution as measured experimentally, predicted with the finite element model and predicted with the analytical model.

The error might also come from the sticking contact (no slip) assumption on the lower and upper boundary. Indeed, the composite might slip along the platens. A improved model, including such a friction behavior is also under investigation [11]

7. Conclusions

The present work focuses on the squeeze flow behavior of a prepreg composite tape. A heat transfer analysis showed that the isothermal assumption considered in the underlying flow problem is valid after a characteristic time of 200s for the thickness considered (~6mm).

The flow problem solved using COMSOL showed that

1- The analytical model under lubrication assumption gives results similar to the 2D finite element resolution. This validates the lubrication assumption classically assumed in the literature [1, 3, 4, 10, 12].
2- The models cannot predict the experimental results accurately. This is more likely due to the viscous behavior assumption which does not stand for a composite material. Further research is to be done in order to better describe the composite behavior.

9. References

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