Thermoplastic composites forming simulation. Viscosity and thermal influence on draping.

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Abstract. Thermoforming thermoplastic prepregs is a fast manufacturing process. It is suitable for automotive composite parts manufacturing. The simulation of thermoplastic prepreg forming is achieved by alternate thermal and mechanical analyses. The thermal properties are obtained from a mesoscopic analysis and a homogenization procedure. The forming simulation is based on a viscous-hyperelastic approach. The thermal simulations define the coefficients of the mechanical model that depend on the temperature. The forming simulations modify the boundary conditions and the internal geometry of the thermal analyses. The comparison of the simulation with an experimental thermoforming of a part representative of automotive applications shows the efficiency of the approach.

THERMOFORMING OF THERMOPLASTIC PREPREGS

The thermoplastic composite thermoforming process consists of four principal stages (Fig. 1). First, the thermoplastic plate is heated by infra-red at a temperature which slightly higher than the melting point of the matrix. A robotic arm transports the heated prepreg blank to a mold that is heated at a lower temperature than the blank. This temperature is chosen to insure a good surface quality and a short cycle time. The mold closing shapes the composite part. A pressure is then applied in order to crystallize and consolidate the composite. This step must insure that there are few porosities in the composite part.

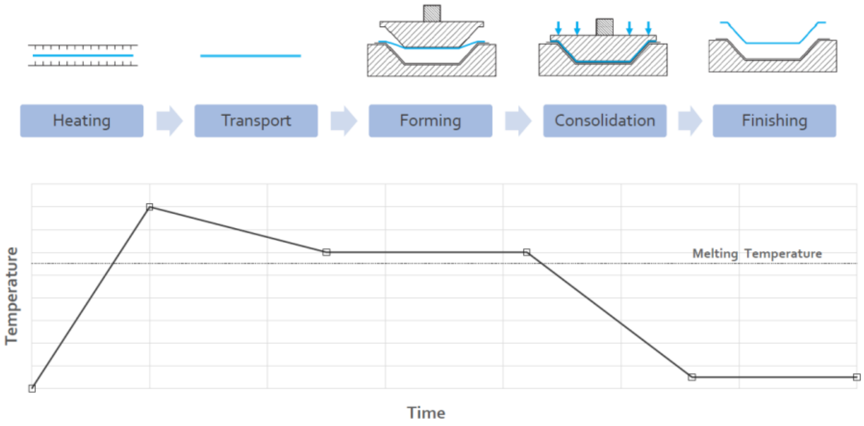

FIGURE 1. Stages of the Thermoforming process.

The thermoforming simulations aim to determine the feasibility of the process and the conditions for this feasibility. The in-plane shear angles, the possible wrinkles and the compaction/consolidation state are the principal quantities that characterize the thermoforming process and that will be calculated by the simulation. Because the

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mechanical behavior is strongly dependent on the temperature, thermal analyses and forming simulations are performed alternately. The thermal analysis gives updated parameters of the mechanical behavior. The forming simulation updates the geometry and the tool-blank contact zone of the thermal analysis.

The mechanical and thermal material properties must be known. In plane shear properties are analyzed by a bias extension test at high temperature [1]. Bending properties are determined using a cantilever bending test at temperature [2]. The thermal properties depends on the deformation, on the temperature and on the cooling rate. They are difficult to measure. In the present work, they are determined by a mesoscopic analysis

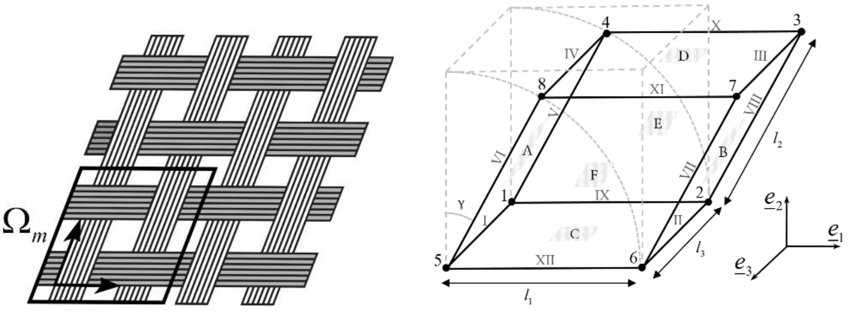
THERMAL ANALYSES

During the simulation of the process forming the temperature field is calculated in order to update mechanical parameters that are strongly thermo-dependent. To compute this temperature field the thermal properties of the composite at the macroscale must be known.

The thermal conductivities are determined by mesoscopic analyses. The woven reinforced prepreg has a periodicity that can be exploited to perform a homogenization simulation and get the macroscopic conductivity from the geometry of the mesostructure and to thermal properties of the yarns and of the polymer.

The periodicity of the material properties and geometry of the structure can be used to perform homogenization using specific boundary conditions. In this work, the equivalent conductivity tensor is calculated using homogenization technique proposed by [3] on a single RVE (Representative Volume Element).

The starting point is the use of the thermal gradient at the macroscopic scale (assumed known) to impose the boundary conditions at the mesoscopic scale. The macroscopic conductivity tensor is then estimated by averaging the resulting mesoscopic flux at the boundary conditions. This method have no restrictions on the behavior of the different constituents of the material (anisotropy, temperature dependence, etc.). It can take into account the geometric evolution of the structure after deformation



(a) (b)

FIGURE 2. RVE of a woven fabric (a). Parametrization of the boundary of the RVE (b).

Let's consider the volume containing the sheared RVE bounded by the faces A, B, C, D, E, F presented Fig. 2. Given the temperature at the macroscopic scale and at the mesocopic scale, the macroscopic temperature gradient and the mesoscopic averaged gradient verify the equality:

$$\frac{1}{V}\int_{\Omega_m} \underline{\nabla}_m T_m dV = \underline{\nabla}_M T_M \tag{1}$$

It is obtained by imposing at the edge of the mesoscopic structure the following conditions:

$$\begin{aligned} T_{m_B} - T_{m_A} &= \underline{\nabla}_M T_M \cdot \left(\underline{x}_B - \underline{x}_A\right) \\ T_{m_D} - T_{m_C} &= \underline{\nabla}_M T_M \cdot \left(\underline{x}_D - \underline{x}_C\right) \\ T_{m_F} - T_{m_E} &= \underline{\nabla}_M T_M \cdot \left(\underline{x}_F - \underline{x}_E\right) \end{aligned} \tag{2}$$

The point on side B, corresponds to the point of side A by simple periodic translation, and similarly for with or with. These conditions are known from the periodic boundary conditions and naturally lead to anti-periodic boundary conditions in terms of heat flows through the domain boundaries.

A set of simulations were perform for different in-plane shear angles and at different temperatures to express the macroscale conductivity as a function of shear angle and a function of the temperature in the orthonormal basis where is collinear to the fiber. The components of the conductivity tensor are plotted in the Fig. 3. They are later used during the forming simulation to compute the temperature field on the composite at the macro scale and determine the mechanical properties of the prepreg as depicted later.

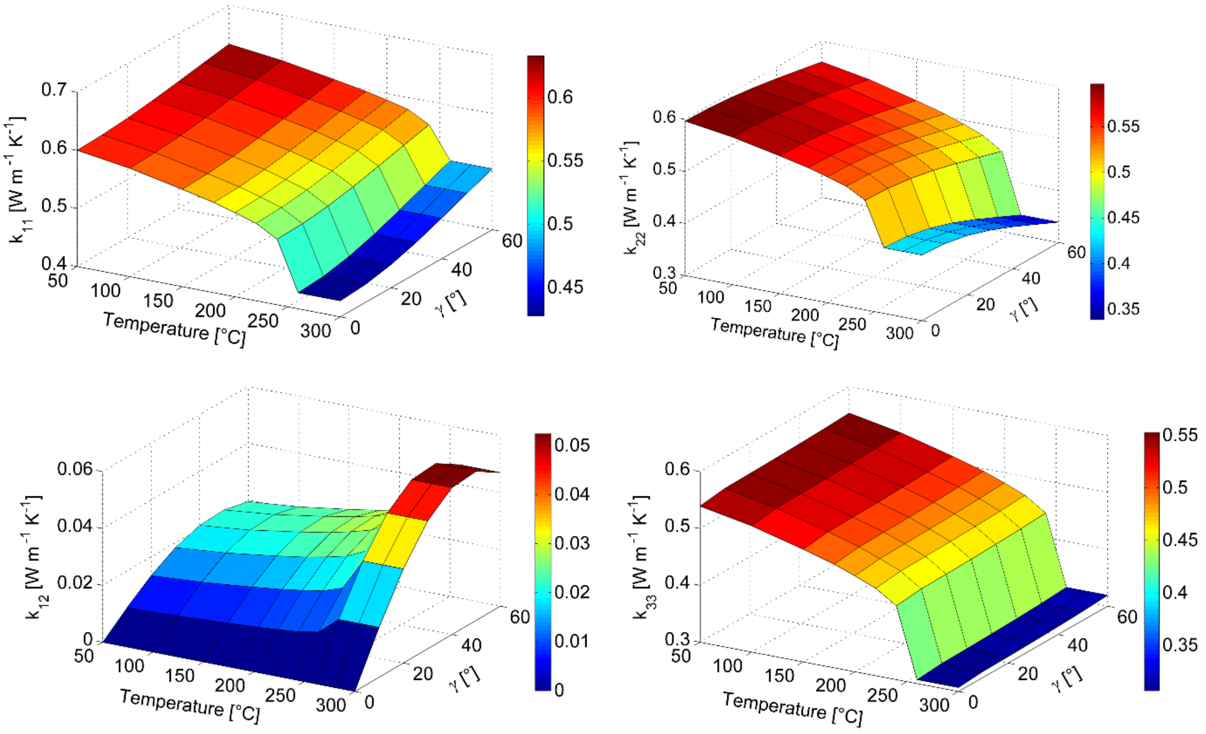


FIGURE 3. Computed conductivity components as a function of temperature and shear angle.

NUMERICAL SIMULATIONS AND COMPARISON WITH EXPERIMENTAL PROCESS

The coupling between the thermal and mechanical problem is obtained by performing alternately mechanical computations (that modify both the boundary of the thermal problem and the values of the thermal conductivity as described in section 3) and thermal computations (that modify the mechanical properties). The processing time is 19 s (for the forming stage). This confirms the process is fast. The thermal conductivity is obtained from the homogenization procedure presented. The update of the temperature distribution in the material is considered since the contacts surfaces increases during forming. It is assume that the contact conductance between the tools and the prepreg is constant and equal to 1000 [Wm-2K-1] although this property depends on the contact pressure, the temperature and the physical and geometrical properties of the materials [4]

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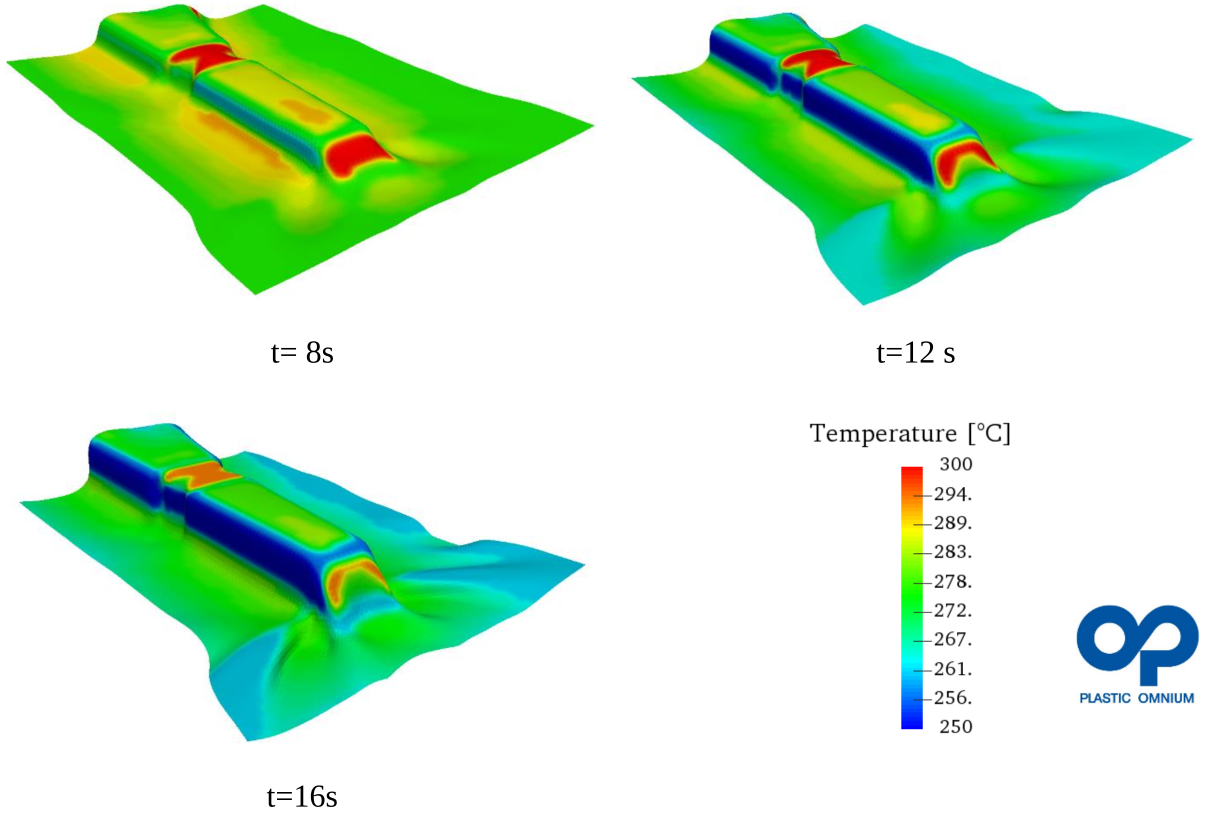
t= 8s

t=12 s

t=16s

FIGURE 4. In-plane temperature distribution during forming.

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