Coupled heating-forming simulation of the thermoforming of thermoplastic composites

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Coupled Heating-Forming Simulation of the Thermoforming of Thermoplastic Composites

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Abstract:
A strategy for the simulation of the whole thermoforming process, from the infrared heating to the stamping, is presented here. Two loosely coupled simulation tools are being developed: the first one computes a realistic 3D, transient temperature field of the composite stack inside an infrared oven, considering the radiative, conductive and convective heat transfers; the temperature distribution is used as an input for the second that aims at simulating the thermomechanical behaviour of the composite during the forming step via a non-orthogonal constitutive model. The steps for the identification of the model parameters are introduced. Initial validation tests show realistic results in term of shear angle distribution.

Keywords: Forming, Thermoplastic Composites, Infrared Heating, Process Simulation, Thermomechanical

Introduction

Thermoplastic composites structural parts have recently started to make their way into the transportation sector [1], but the use of composites in the automotive industry is currently mostly limited to low volume production parts for luxury cars, due to high manufacturing costs and cycle time.

Manufacturing processes such as thermoforming seem well adapted for high volume parts, but to reach the production rates required by the automotive industry, those processing techniques must be optimized to understand and avoid the apparition of defects. In order to avoid expensive trial-and-error procedures after the mould fabrication, robust virtual manufacturing schemes are needed to efficiently find the best process parameters (pre-heat temperature, punch speed, consolidation time …), and predict the resulting mechanical properties of the part [2].

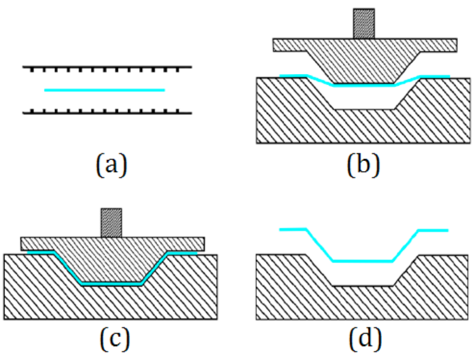

***Fig. 1:** Thermoforming process steps: (a) infrared heating, (b)-(c) forming and consolidation, (d) demoulding*

The thermoforming process consists in heating a laminate above the melting temperature of the thermoplastic matrix in an oven; it is then transferred to a press where it is formed and cooled down before demoulding. The sequential steps are presented in Fig. 1. Originally developed for thermoplastic sheets, it is now used for manufacturing thermoplastic composites parts as high production volumes are in demand.

Most of the current simulations of the thermoforming process consider only the mechanical draping of the part, while the effect is rarely investigated. It has been evidenced in recent research [3] [4] that the forming cannot be considered adiabatic : when the laminate contacts the mould, its temperature rapidly decreases which induces local rigidification that can lead to wrinkles. These heat transfer effects need to be studied as they represent a limit of the stamping process. The control of the laminate temperature during the entire process is therefore critical to ensure a good part quality.

This work adopts a comprehensive approach for the simulation of the thermoforming of thermoplastic preimpregnated composites. Two coupled simulation tools are being developed for the preheating phase and the forming phase respectively.

Heating simulation

The first stage of the thermoforming process aims at bringing the composite laminate to the processing temperature in an oven. Infrared oven are favored in industrial composite applications for their fast heat-up time and the good absorptivity of polymers to infrared radiations.

Most of the thermomechanical simulations of the forming assume an homogeneous temperature distribution in the preform at the beginning of the stamping stage [5]; this is however experimentally difficult to achieve as infrared heating can produce non-uniform temperature distributions with localized hot or cold spots. The aim of the heating simulation developed is to predict a realistic 3D temperature distribution in the composite stack during the preheating stage to be used as an input of the forming simulation; this tool also allows to optimize an oven configuration for a required temperature.

The simulation, developed with Comsol Multiphysics finite elements software, solves the 3D heat equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(\kappa \nabla T) + q_R + q_c \quad (1)$$

Where q_r and q_v are the radiative source term and convective losses respectively. The radiative term is treated as a view factor problem. Computation is realized using the hemicube method for the determination of the view factors. The entire environment of the oven (preform, lamps and reflectors) is modelled, and the convective losses are considered via a constant transfer coefficient.

Solving this equation requires the determination of the thermal properties of the lamps and composite, both in its non-consolidated and consolidated state . The considered material is a glass fabric/polyamide 6.6 thermoplastic composite developed by Solvay. It is supplied as a twill 2/2 woven fabric, powder-impregnated on both sides. Consolidated plates were manufactured using a in-house thermocompression machine.

This study was conducted at Institut Clément Ader, using a novel method based on infrared thermography and inverse analysis to identify the temperatures of the lamps and thermal conductivity tensor of the material [6]. This experimental setup also allowed to characterize the inter-ply thermal contact resistances in a non-consolidated composite stack.

Fig. 2*: Experimental 1 lamp heating test bench*

The heat capacity and optical properties (reflectivity, emissivity) of the prepreg and consolidated composite plates were determined using DSC and infrared spectroscopy respectively. The material was shown to be opaque in the range of emission of the lamps, which conforts the choice of view factor over ray tracing strategy for computing the radiative heat transfer, as it allows for a faster computation while accurately representing the physics.

The modelisation of the lamps is based on the work of Monteix: only the tungsten filament is modelled as a cylinder of equivalent diameter taking into account the emissive surface of the spires. The temperature dependent emissivity and input power-temperature relation are considered for the tungsten.

After validation on the experimental set-up presented in Fig. 2, the ability of the model to optimize an infrared oven to minimize the temperature variation on a composite stack is investigated. An oven with 10 lamps disposed in two banks shifted by 4cm, with a center-to-center distance of 8cm between each lamp in the same bank. The oven configuration, viewed from the top, is shown in Fig. 3. On each bank (left and right), the lamps are numbered from the closest to the furthest of the plate symmetry axis.

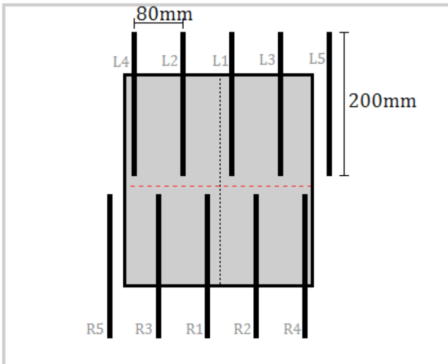

Fig. 3: *Oven configuration*

The composite stack is heated from the top only. In a first step, only the input power of the lamps is considered as a variable. The cost function to be minimized is therefore:

$$\min_{20 \leq P_i \leq 100} f(\boldsymbol{P}), f(\boldsymbol{P}) = \int_V \left(T(\boldsymbol{x}) - T_{obj}\right)^2 dV \quad (2)$$

With $\boldsymbol{P}$ a vector containing the individual input power values of the lamps. Given the symmetry of the oven, the dimension of $\boldsymbol{P}$ is reduced to 5 (i.e., $P(L_i)= P(R_i)$). The objective temperature is in this case 295°C, which is approximately 30° above the melting temperature of the thermoplastic matrix. Optimization is conducted in steady-state, using a Levenberg-Marquardt algorithm. The lamp input power is constrained between 20% and 100% of the nominal power to avoid under voltage. The temperature on the top of the composite stack along the red dotted line is shown in Fig. 4 before and after the optimization procedure.

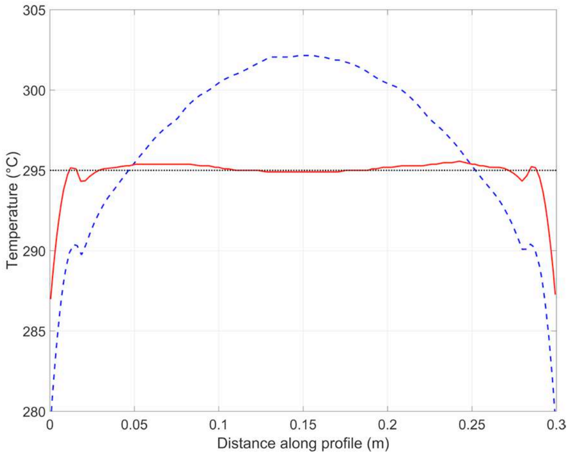

Fig. 4: *Temperature along horizontal profile, dashed line: before optimization, solid line: optimized input power*

The dashed blue line shows the temperature distribution along the profile with all lamps at the same input power (50% of nominal power). The solid red line corresponds to the temperature field after optimization, and exhibits a much flatter profile: the central hot spot is avoided.

The transfer phase between the infrared oven and the mold and die in the actual process allows considering a loose coupling between the two simulation tools: the three dimensional temperature field that results from the heating simulation will be used as an input for the forming model.

Forming simulation

The forming simulation is based on a non-orthogonal constitutive model based on the work of Khan [7] and Pierce [8]. This model considers the composite as a continuous, anisotropic media, and tracks the orientation of the yarns, thus allowing the prediction of possible defect locations by visualizing the shear angle distribution in the part. This is done via a material user subroutine VUMAT implemented in Abaqus/Explicit. The subroutine works by calculating the fibre directions from the deformation gradient; the incremental strain is rotated from the Green-Naghdi frame used by Abaqus to the fibre frame; the incremental stress is computed in this frame from the constitutive law and converted back to the Green-Naghdi frame. The constitutive tensor assumes the following form in the fiber frame:

$$C_f^1 = \begin{bmatrix} E_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & G_{12} \end{bmatrix}, C_f^2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \quad (3)$$

The superscripts 1, 2 represents the fiber directions, E the Young's modulus and G_{12} the shear modulus of the material. The advantages of this approach are the relative ease of implementation in commercial finite element codes, and the simplicity of the constitutive material tensor as the computation is conducted in the material frame.

The model, originally developed for draping simulations of dry fabric, is currently being extended to take into account the temperature dependent behaviour of the resin through its contribution to the shear modulus of the material. Identification of the shear behaviour is done via bias-extension tests, to allow an easy inclusion of the setup in an environmental chamber for experiments around the processing temperature.

Fig. 5 shows a fabric sample undergoing bias extension at room temperature. The evolution of the shear angle is observed by digital image correlation, and direct optical measurements.

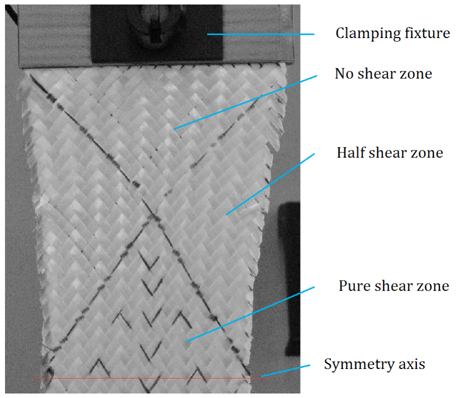

Fig. 5: *Bias extension test on twill 2/2 glass fabric*

An experimental hemispherical punch apparatus is developed at Queen's University Belfast to validate the model formulation with stamping experiments. The fabric is held into place by the mean of a spring-actuated clamp to easily vary the clamping force, while the punch itself is mounted on a 60kN Promess press unit.

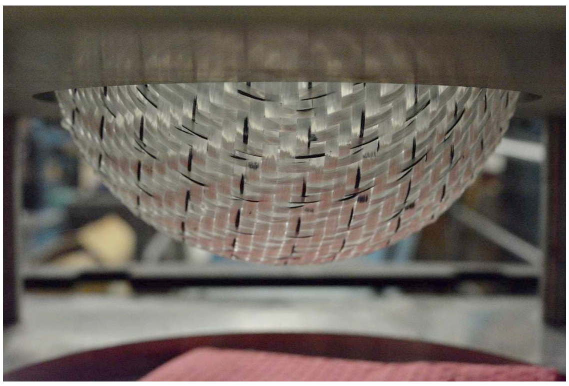

Fig. 6: *Forming experiment, hemispherical punch on glass fabric*

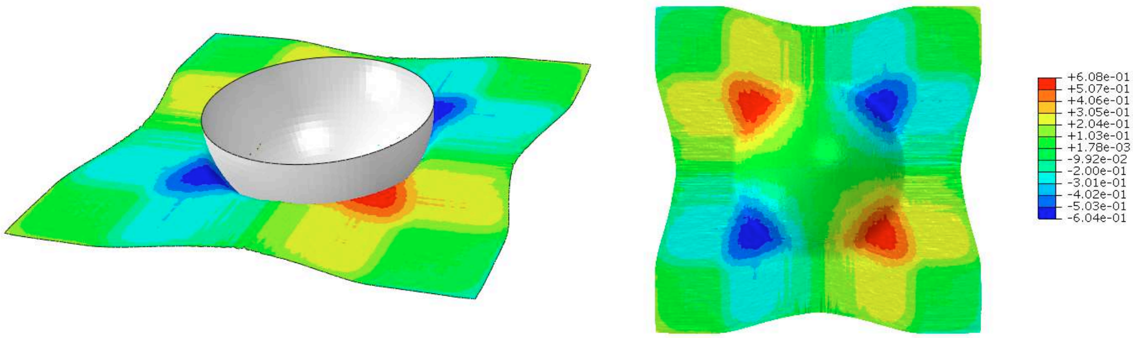

***Fig. 7:** Shear angle distribution after stamping, left: isometric view, right: bottom view*

An example of the shape of the fabric after deformation by the punch is shown in Fig. 6, with the camera direction aligned with the warp yarns. The first validation simulations (see Fig. 7) show a good qualitative agreement with the experiments in terms of shear angle distribution and draw-in profiles, with the zones of maximum shear appearing at a 45° angle from the principal fiber directions.

The hemispherical punch will be used coupled with an infrared oven as a complete, instrumented lab-scale thermoforming setup to investigate the effect of temperature on the type and onset of defects generated. A separate study to understand the ply-ply and ply-mould frictional behaviour is also planned.

Conclusion

Understanding the thermomechanical behaviour of thermoplastic composites during the thermoforming process is critical to accurately predict the defects that can appear during the manufacturing.

In this article, the strategy for the development of a predictive, virtual manufacturing tool that relies on two coupled simulations of the infrared heating and forming steps has been presented. The material characterization procedure has been introduced for the thermophysical and mechanical properties, and is currently underway for high temperatures.

The first validation test cases used for the simulations show the pertinence of the approach with promising qualitative results; these will be confirmed with the complete thermoforming setup being finalized.

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