Process Simulations for Composites Forming of UD Tape Laminates

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Thermoplastic composites are widely recognized for their high specific stiffness, strength and toughness, in combination with the opportunities for rapid processing and recycling. Experience has learnt that composites should not be treated as black metal, amongst others due to their specific deformation behavior during processing. Certain aspects are well known: a low shear resistance in fabric reinforced composites, high stiffness in the fiber directions, and a low resistance to extension transverse to the fibers in unidirectional plies. Other aspects are less well known and less well characterized yet, e.g. the frictional behavior between plies and between laminates and tools, and the bending behavior of composite laminates at forming temperatures. Novel developments in unidirectional laminate production pave the way for more optimized pre-forms (near net shaped with e.g. local reinforcement) for subsequent press forming. Design and processing with such tailored laminates involves complexities on the level of the separate plies and their interactions, but also on the level of the laminate as a whole, in terms of lay-up which can vary in orientation and thickness, and which can change during the forming process. Process simulations can help to improve control on the design and manufacturing development of thermoplastic composite products. Adequate process simulation tools are currently under development. Constitutive models of unidirectional plies and laminates still require considerable development, certainly when comparing to fabric reinforced composites, including characterization experiments and implementation in nonlinear finite element software. The methods are validated with press-forming experiments.

Introduction

During the last decades thermoplastic composites have been a promise for structural parts, mainly in aircraft industry. Thermoplastic composites combine the typical excellent mechanical properties of fiber composites with rapid processing and cost reductions, which makes them potentially more attractive than their thermoset counterparts. Nevertheless, large scale applications are still seldom. One of the main reasons is that there is still a lack of understanding concerning the complex forming behavior of fiber reinforced thermoplastics. Especially the shearing and bending behavior, as well as friction phenomena at forming temperatures are to be addressed, in order to exploit the large potential of thermoplastic composites.

Understanding alone however will not be enough. The results of ongoing research on before mentioned topics also have to become available in software tools for process simulation. Only in this way the complex behavior will be available in an early design phase allowing for feasibility studies and optimization of product performance.

The considered uni-directional (UD) fiber-reinforced tapes consist of aligned continuous fibers embedded in a thermoplastic matrix. The nature of the deposition process of UD tapes allows for smart tailored blank designs, e.g. locally stiffened parts by means of thickness and lay-up variations.
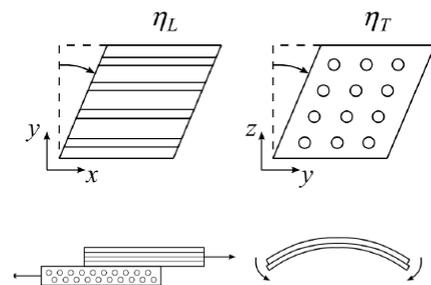

Figure 1. Basic deformation mechanisms during thermoforming

Typically laminates of UD tape are processed using press forming which is a fast forming process for thermoplastic composites materials. Pre-heated tailored blanks are inserted in a press with a toolset consisting of a die, a punch and blank holders. The press is closed with moderate closing speeds. A subsequent cooling cycle follows after which the product is released. The process is most suitable for series production with cycle times in the order of 10-60 seconds.

Figure 1 shows some of the basic deformation mechanisms that play a large role in thermoforming of UD stacked laminates. Next to in ply shear modes (top), sliding of plies against each other and bending of plies or stacks of plies appear as well. Together with stretching and tool interaction these mechanisms have to be considered within the forming simulations.

Material characterization

Thermoplastic UD tape materials are by nature strongly anisotropic. An extremely high modulus and strength typically is observed in fiber direction, whereas the matrix properties dominate in transverse direction. The latter leads to a low modulus and strength, however, with increased ductility. At forming temperatures, typically above the melt temperature of the thermoplastic matrix, this is even more pronounced.

A well-accepted constitutive model that combines the mechanical behavior of fibers as well as that of the viscous matrix for forming temperatures is the Ideal Fiber Reinforced Newtonian fluid Model (IFRM) [1]:

$$\boldsymbol{\sigma} = -p\mathbf{I} + T\bar{a}\bar{a} + 2\eta_T\mathbf{D} +$$
$$2(\eta_T - \eta_L)(\bar{a}\bar{a} \cdot \mathbf{D} + \mathbf{D} \cdot \bar{a}\bar{a}),$$

where the first term at the right hand side represents the hydrostatic pressure and the second term the fiber stress T related to fiber direction $\bar{a}$. The remainder describes the viscous behavior in transverse and longitudinal shearing direction, as in Figure 1, in which $\mathbf{D}$ is the rate of deformation tensor.

Traditionally used set-ups to identify the material parameters, like the Trellis (or picture frame) shear test, are complicated due to the low structural integrity at forming temperatures. Besides, a large variation between the identified parameters is observed [2]. Therefore reliable tests are needed. A setup using standard rheometer DMA device was developed to characterize the longitudinal shear viscosity **Error! Reference source not found.**[3].
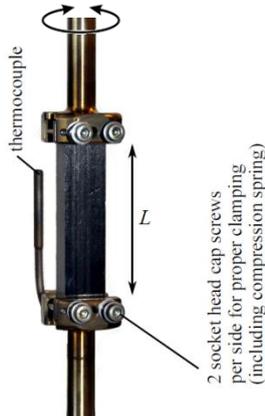
Figure 2. Torsion beam specimen with fixtures for longitudinal shear identification

Figure 2 displays a clamped torsion beam specimen of carbon reinforced PEEK-AS4 with a 60% fiber volume fraction. The specimen's geometry has been defined such that the exerted momentum was well above the accuracy of the rheometer and edge effects due to clamping can be neglected.

Oscillatory tests were conducted within an inert atmosphere at various specimen temperatures T_s. A typical result is shown in Figure 3.
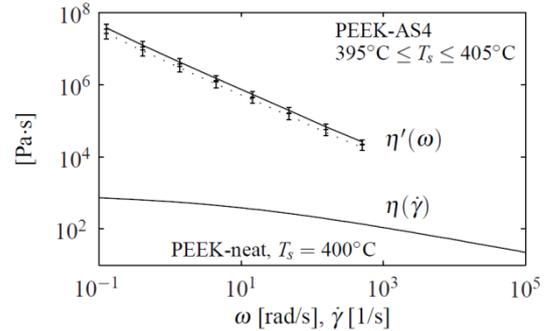

Figure 3. Measured apparent viscosity compared to the viscosity of neat PEEK

The apparent viscosity η' decreases linearly with the test frequency on a log-log scale, in this case with a coefficient of 0.9 which yields almost rigid plastic behavior with constant torque.

In order to use these results a conversion from the dynamic viscosity to the steady shear viscosity has to be made, using for instance inverse Fourier transforms from the linear visco-elastic theory or concepts such as the Maxwell viscosity [4].

Friction characterization

Friction between tools and plies and in between plies is influencing the forming results to a large extent. The shear behavior of the laminate, for instance, relates directly to interactions that take place on the ply-ply interface.

A basic relation for describing friction is given by Coulomb's law, which relates the friction force to the normal force by the coefficient of friction. This coefficient generally depends on contact pressure, temperature, and velocity:

$$\mu = \mu(p, T, U, \dots)$$

In order to identify friction a friction testing device has been developed where above mentioned conditions can be varied [6]. Since thermoforming of thermoplastic composites takes place in the molten phase, high temperature testing is a necessity (> 400 °C for PEEK composites). Figure 4 shows a picture of the device.
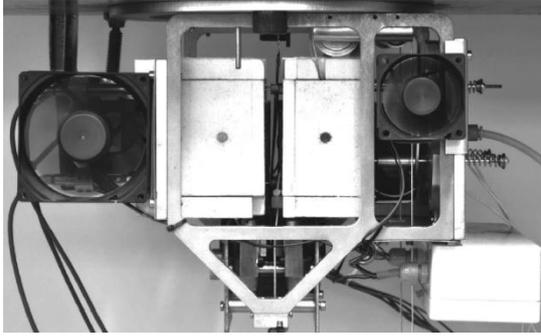
Figure 4. University of Twente friction tester

The pull through set-up for a universal testing machine consists of two heat-controlled flat platens that can be heated up to 450 °C. In the self-aligning system the normal pressure is applied using a flexible pneumatic actuator. During testing additionally to the forces also normal displacements and rotations of the platens are captured using LDVTs. Disposable metal foils are used to identify tool-ply friction without contaminating the platen surfaces. The coefficient of friction finally is calculated by

$$\mu = F_T/(2F_N)$$

Typical results for tool-ply friction tests of PEEK AS4 UD tape for different pull through velocities are shown in Figure 5.
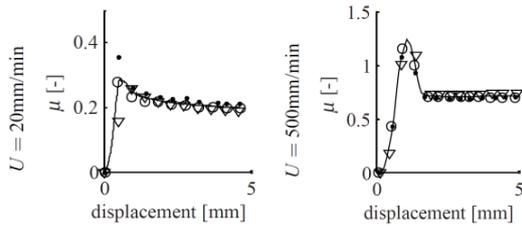

Figure 5. Typical friction coefficients during testing (T = 400°C, p = 50kPa)

The measurements reproduce well and show a typical start-up behavior with increased friction followed by a more or less stationary value. The start-up effects increases with velocity and must be attributed to non-linear visco-elastic behavior of the thermoplastic matrix during the instantaneous start of the test. In [7] it was shown that during the steady state phase the friction coefficient remains quite constant, while the tilting of the blocks can still show some variations. How the absolute tilt affects the friction coefficient still needs to be assessed.

In order to make use of these results for software predictions models are to be developed. In Figure 6 all results are summarized in so-called Stribeck curves for friction using the Hersey number $He = \eta U/p$, are shown. Here η is the viscosity of the lubricant, i.e. the PEEK matrix.
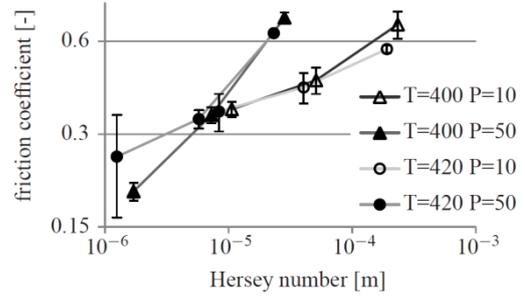

Figure 6. Measured steady state friction coefficients for PEEK AS4 UD tape at different pressure and temperature combinations

The fact that friction increases with the Hersey number yields the conclusion that friction takes place in the fully hydrodynamic regime. Theoretically however, all tests should coincide on one single curve. Apparently, a pressure change leads to a significantly different friction behavior, possibly caused by a macroscopic change of the interface geometry. Stribeck curves have the advantage of a very straightforward implementation in a finite element software code for thermoforming.

Modeling approach

For modeling stamp forming processes the highly non-linear behavior, for instance due to material behavior and contact, has to be accounted for. Implicit finite element codes have a proven track record of tackling these kind of problems. Here the commercially available spin-off software AniForm was employed [8].

Each ply is discretized using 3-node triangular elements. Constitutive models are assigned according to a decoupled approach, i.e. a membrane (in-plane behavior) and a Kirchhoff (out-of-plane behavior) element. The fiber orientation is updated every step in order to incorporate the strong material anisotropy. Contact between different plies and between plies and tools is modeled using a penalty method. A viscous friction model relates the friction force to the relative velocity of the involved surfaces.

Experimental verification

The modeling approach has been verified using reference parts with dome geometries; see Figure 7. Due to the nature of doubly curved parts, material excess during forming results in in-plane shear and/or wrinkling [5].

Two different lay-ups of UD Carbon/PEKK plies have been used. Figure 7 and Figure 9 clearly show the large dependency of the final result on the lay-up. Where the use of a 0/90 lay-up shows wrinkles at the blank holders, the double curva-

ture in the tools yields severe wrinkling in the case of a quasi-isotropic lay-up.
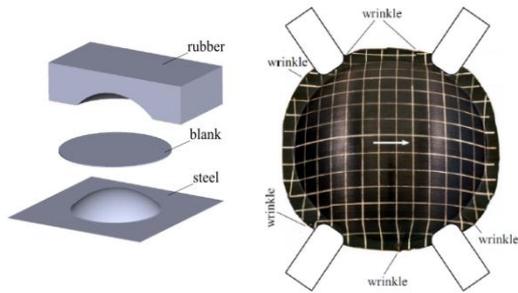

Figure 7. Forming tooling and thermoforming results of the [0/90]$_S$ lay-up

In order to show the influence of the shear viscosity a number of simulations with values from literature [2] have been performed, see Figure 8.
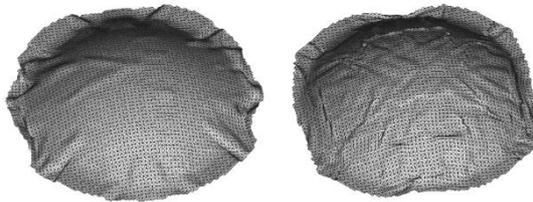

Figure 8. Simulation results with $\eta_L = 300 \ kPas$ and $\eta_L = 6 \ kPas$

It is clearly seen that the wrinkling behavior is completely different. The simulation with $\eta_L = 300$ kPas however predicts the winkles at the right location.

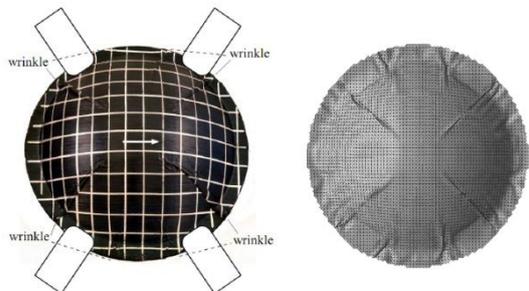Figure 9. Experiment and simulation for the [0/90/45/-45]s lay-up

Figure 9, finally, presents an acceptable well agreement for the case of the quasi-isotropic layup using the same value as before mentioned. This underlines the necessity of accurate parameter identification methods.

Conclusions

In order to exploit the large potential of thermoplastic composites, dedicated CAE tools are inevitable. FE-based software solutions allow for optimization of production processes and product performance in an early development stage thereby taking the complex material behavior into account. In this paper a number of topics in order to reach this goal were addressed. It could be shown that with the presented developments concerning finite element techniques, material and friction modeling, some of the phenomena can be predicted acceptably well. However, it should be clear that this is only possible if reliable material parameters and testing methods are available. Therefore, further research will be strongly focused on increasing the accuracy of the forming predictions, extended to different thermoplastic composites systems.

Acknowledgements

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