COMPLEX STAMP FORMING OF ADVANCED THERMOPLASTIC COMPOSITES.

B. Rietman[1], U. Sachs[2], S.P. Haanappel[2], R. Akkerman[1,2]

[1] *University of Twente, Faculty of Engineering Technology, The Netherlands, r.akkerman@utwente.nl*
[2] *Thermoplastic Composites Research Center (TPRC), The Netherlands, remko.akkerman@tprc.nl*

Abstract

The inherent advantages of thermoplastics over the traditional thermoset composite systems are well recognized in the aeronautics community. The main advantages are the much faster processing and the higher toughness. The current advanced thermoplastic material systems provide excellent mechanical performance but their main disadvantage is the difficult processing. Ideally, future aircraft sub-components with complex shapes can be readily formed on the basis of pre-consolidated tailored laminates based on uni-directional plies. However, to exploit the full potential of thermoplastic composites models are to be developed in order to predict the process feasibility and product performance in an early stage of development.

This paper addresses a number of steps to increase the accuracy of stamp forming simulations and highlights promising results for identifying intra-ply shear and tool-ply behavior of thermoplastic composites. A comparison of the forming behavior of a doubly curved reference part with simulations will be presented. The paper concludes with remarks on necessary future research.

Introduction

One of the main advantages of thermoplastics is the possibility of melt shaping to obtain the final product shape. For neat thermoplastics a large number of processes, e.g. injection molding, thermoforming, is available. In the case of continuous fiber reinforced thermoplastics processing possibilities are limited, however. Thermoplastic composites have been a promise for structural and semi-structural parts for a long time because of their excellent properties, weldability and potential for fast and easy processing which allows for large series production as in e.g. automotive industry. Although a lot of research has been performed in the past years, still knowledge on long-time performance and especially processing conditions is lacking. Unless thermosetting, usually a forming stage at high temperatures is needed for TP composites to obtain the final part shape. This step may in the end give rise to problems like global shape deviations due to springback and springforward, and local process induced defects like wrinkles and folds. The alternative of in-situ placement of thermoplastic pre-impregnated tape to produce net shape parts, yet suffers from high cycle times and is therefore limited to small series production.

Stamp forming, or thermoforming, is a forming process for thermoplastic composite laminates. Starting point is a flat laminate which is heated above melting temperature of the matrix. The sheet is subsequently inserted between a heated male and female die mounted in a forming press. Upon closing of the tools the product is shaped. After the product has cooled down to handling temperatures the tools are retracted and the product is released. Typical cycle times are in the order 10-60 seconds. Although usually laminates with a constant cross section, or homogeneous lay-up, are used, local reinforcements might be used to improve the mechanical properties where needed. In this way tailored blanks with varying thicknesses and ply orientations are obtained. Their feasibility was discussed by Burkhart [1]. Due to their ease of processing, especially uni-directionally (UD) reinforced thermoplastics promise low cycle times and high throughput. Advanced tape placement can be used to tailor the homogeneous laminates before stamp forming.

In order to fully exploit the potential of TP composites the chosen design and the consequences for the production process and the product performance must be predicted and optimized in an early stage of development. Since the problem of finding an optimal lay-up including local reinforcements exceeds expert knowledge, software tools that support the design engineer are needed. The finite element method is well-established for simulations of product behavior and a number of general purpose software is commercially available on the market nowadays. Concerning the simulation of production processes and their feasibility there is still a gap to bridge. Especially the strong anisotropic behavior due to the continuous fiber reinforcements and the interrelation of the different plies combined with the viscoelastic nature of the thermoplastic matrix in the melting phase gives rise to problems. In order to incorporate this non-linear behavior the basic mechanisms have to be understood and comprised in mechanical models that allow for a finite element implementation.

Stamp forming of thermoplastic composites

In stamp forming a thermoplastic composite laminate consisting of a number of plies with different constitution and fiber orientation is pressed between two dies to become its final shape. The heating of the laminate above the melting point of the thermoplastic resin facilitates this process. In this process the product geometry directly influences the local deformations in the laminate, on its turn dependent on strong anisotropy of the different plies and the laminate as a whole. The fact that the matrix shows viscoelastic behavior above melt temperature makes the anisotropy even more pronounced.

The fibers may be assumed to remain elastic during the whole processing cycle and due to their high stiffness fiber stretching may be neglected. Considering Figure 1, there are four other deformation modes related to the mechanical behavior of thermoplastic composites during forming.

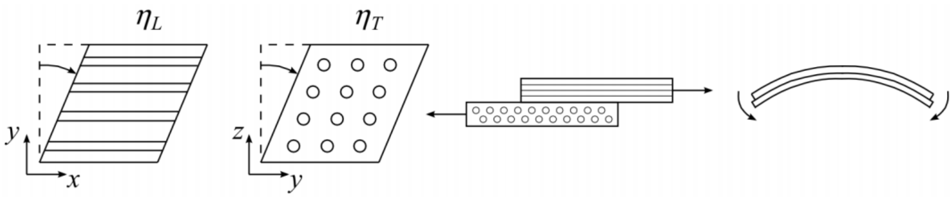

Figure 1: Deformation modes related to the formability of thermoplastic composites. From left to right: intra-ply longitudinal shear; intra-ply transverse shear, inter-ply slip, out-of-plane bending

In-plane deformations like stretching and shearing appear during the forming process. Principally two different shear mechanisms can be distinguished, longitudinal and transverse shear with respect to the fiber orientation. Slippage between the different plies is the basic mechanism for developable (single curvature) surfaces. Bending gives rise to slippage, which will occur within the resin rich interfaces of the stacked plies. For doubly curved parts (not developable) the most important deformation mode is intra-ply longitudinal shear. An overview is given by Campbell [2].

Typical failure modes that can be observed during processing of UD thermoplastic composites are buckling, wrinkling, fiber failure, ply breakage due to thinning, delamination and deconsolidation. Buckling and wrinkling are the major failure modes in composites and are generally triggered by in-plane compressive stresses. In order to pre-tension the fibers, and thus prevent for buckling, so-called blank holders can be used. During the process of stamp forming buckled regions that arise may be leveled out and translated into intra-ply shear, redistributed in more and smaller buckles, or folded into wrinkles. These phenomena are shown in Figure 2. Both latter alternatives are undesired. Intra-ply longitudinal shear is the driving mechanism to level buckles that arise during forming. Since this is to a certain extent hindered by inter-ply friction behavior we have to deal with a susceptible interaction of both effects. Low pressing speeds accommodate inter-ply shearing and to some extent prevent for buckling.

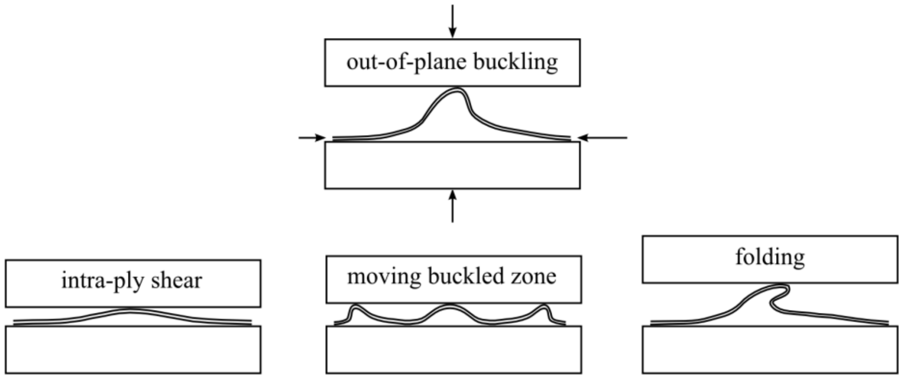

Figure 2: Phenomena originating from out-of-plane buckling upon closing of the tools

Next to the complex behavior of the laminate itself, also the interaction of the laminate with the tools contributes to the deformation behavior and thus the final product shape. The mechanical behavior of thermoplastic composites will be discussed more in detail in the next section.

Mechanical behavior of thermoplastic UD composites

Starting point for modeling stamp forming is a thorough understanding of the macroscopic behavior of the composite, involving thermoplastic matrix properties as well as the properties and nature of the fiber reinforcement. For thermoplastic UD laminates the fiber-matrix-interaction plays an important role in the intra-ply behavior. The out-of-ply behavior involves the interaction of different plies among each other and the interaction of the outer plies with the forming tools. Due to the nature of the composite the viscosity of the matrix plays a major role in the sliding behavior. However, also the lay-up and the local sliding direction are of great importance. In complex geometries the out-of-ply behavior and friction between tools and laminate may lead to strong non-linearities (folding) that limit producibility and product performance.

Constitutive behavior

In the previous section on stamp forming it was discussed that three significant deformation mechanisms define the deformation behavior of the laminate: intra-ply shear, inter-ply slip and bending. From these mechanisms intra-ply longitudinal shear was identified to be the driving mechanism for prevention of wrinkling and is therefore discussed in this paper.

The material behavior of the thermoplastic laminate is build up of the basic mechanisms discussed before. The well-known Ideal Fiber Reinforced Newtonian fluid Model (IFRM) [3] combines the intra-ply behavior in one constitutive relation:

$$\boldsymbol{\sigma} = -p\mathbf{I} + T\bar{a}\bar{a} + 2\eta_T\mathbf{D} + 2(\eta_L - \eta_T)(\bar{a}\bar{a}\cdot\mathbf{D} + \mathbf{D}\cdot\bar{a}\bar{a}) \quad \text{(Eq. 1)}$$

The Cauchy stress tensor is expressed by a combination of hydrostatic pressure p, a fiber stress T in local fiber direction $\bar{a}$ and the viscous behavior of the matrix. The latter describes the viscous behavior in transverse and longitudinal shearing direction. **D** is the rate of deformation tensor. Incompressibility, fiber inextendability as well as Newtonian behavior are assumed; viscoelasticity is therefore not accounted for, neither is the well-known non-linear shear thinning behavior.

In order to identify the intra-ply shear viscosities a number of methods have been published in literature, however different methods can yield results with differences of several orders of magnitude. An overview of testing methods is given by Harrison et.al. [4]. It mainly comprises plate-plate rheometry and picture frame tests. A basic sensitivity study of stamp forming simulations using the extreme values for the shear viscosities from literature showed considerable distinctions in defects development [5]. Therefore a new intra-ply shear characterization method was developed using thick torsion beam specimens with fibers in axial direction. These were dimensioned such that a standard rheometer can be employed.

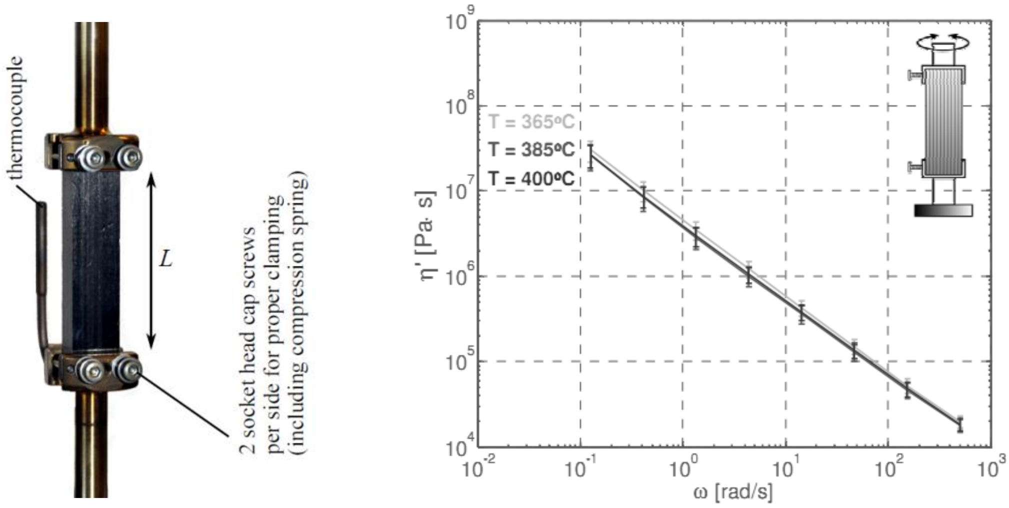

Figure 3: Torsion beam set-up for longitudinal shear identification (left); measured dynamic viscosity versus angular frequency (right)

Figure 3 at the left hand side shows a torsion beam specimen together with the fixtures. The dimensions of the specimen have been determined by means of a numerical clamping sensitivity study with the finite element software AniForm that employs the IFRM model. It was shown that for thick specimens the influence of the fixtures is reduced and that the identified dynamic shear viscosity approaches the Newtonian viscosity from the IFRM model. This has lead to a free specimen length of 47mm as well as cross-sectional dimensions of 13x10mm^2. The specimens of Cetex® Thermo-Lite® TC1200 AS4/PEEK provided by Ten Cate (80 layers press-consolidated with a fiber volume fraction of 60%) have been tested dynamically at different forming temperatures in a nitrogen environment.

Although bulging of the bar end faces is not restrained, such that the fibers are not stressed right away, the mechanical response shows a large elastic contribution (G' >> G"). This explains the somewhat unexpected curves in the right-hand side of Figure 3, which can be interpreted as an elastic response. Converting the dynamic viscosity into a storage modulus shows almost frequency independent elastic response indeed.

Friction behavior

As stated before local buckles can be leveled by intra-ply shearing in combination with inter-ply slippage at the resin rich interfaces. In order to predict the buckling and wrinkling beforehand, the friction between the different plies as well as between tools and skin plies has to be known. In order to identify friction parameters numerous experimental set-ups have been developed. An overview of different testing devices is given in [7]. Akkerman et. al. [8] developed a self-aligning pull-through friction tester to identify inter-ply as well as tool-ply friction. The device can be mounted on a standard tensile testing machine and temperature, pulling velocity and pressure can be controlled.

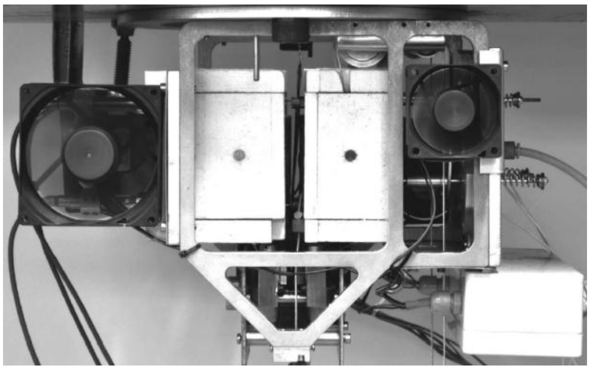

Figure 4: University of Twente friction testing device

This friction device is shown in Figure 4. The sample is inserted between the heated rigid tool blocks that are subsequently closed thus heating the specimen. After the specimen reached the predefined testing temperature is pulled through the device. During testing the pulling force, temperatures, gap and tilt angle evolution are monitored. In order to prevent the tool blocks for contamination with thermoplastic resin, disposable thin metal foils cover the tools.

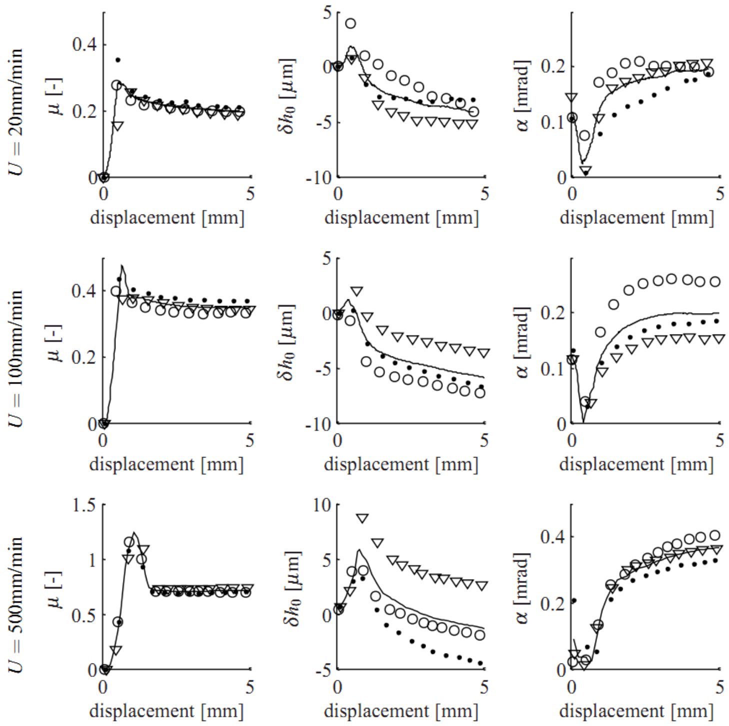

Figure 5: Measurements of (from left to right) friction coefficient, average relative gap and misalignment angle as function of displacement for different pulling velocities. AS4 carbon fiber / Polyetheretherketone (PEEK) UD tape, fibers aligned to pulling direction, T = 400°C and p = 50kPa.

In Figure 5 above some measurement results for Cetex® Thermo-Lite® TC1200 AS4/PEEK UD tape provided by Ten Cate are shown. The material was tested on using 3 different pulling velocities, temperatures of 400 and 420°C and pressures of 10 and 50kPa. The measurements for each dataset have been performed threefold. For each of the testing velocities the resulting coefficient of friction $\mu = F_T/(2F_N)$, average gap change as well as the tilting angle are plotted as a function of the displacement. In all the results a start-up effect can be recognized of about 2mm where after the parameters more or less develop stationary. This is especially the case for the friction coefficient at higher velocities. Also the reproducibility of the results for friction is very well. Although the tilting angle and the gap width evolve clearly during testing, the friction seems to be insensitive for these changes, especially considering the large variations in gap evolution and tilting angle.

With increasing velocities an increase in friction, gap change as well as in the misalignment angle is to be seen. The peak values of the friction are likely to be correlated to the viscoelastic nature of the polymer film. A common way to classify friction results is by using the Stribeck curve. Figure 6 shows the experimental steady state values of friction as a function of the Hersey number $He = \eta U/p$.

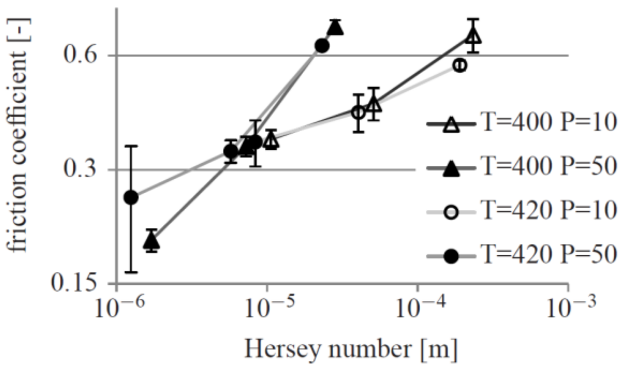

Figure 6: Stribeck curve for steady state friction

The measured values show the tendency that friction increases with increasing velocity. According to the shape of the Stribeck curve, it is assumed that we deal with hydrodynamic lubrication. However the theoretical result that all measurements should coincide on one Stribeck curve is not given for UD plies, in contrast to previous work on comingled fabric where it was the case [7]. The deviations from a single curve are especially due to the measurements with different normal pressure values. Since the polymer film shows non-Newtonian behavior, shear thinning and elastic effects will play a role. In fact, long influence of viscoelasticity on lubrication is a long standing problem in tribology [9]. Shear thinning can be accounted for if the thickness of the film is known, however it is hard to measure. It should be recognized that the only significant difference is the different surface topology of UD and fabric. In fabric the undulations will lead to a buildup of pressure. In future, macroscopic modeling of the wedge problem employing of viscoelastic fluids will contribute to the understanding of the experimental results [7][9].

Nevertheless the measured friction values for tool-ply interaction can be applied in numerical models for stamp forming since the conditions during testing and processing are the same. Further work needs to be done with respect to tool-ply friction with different tool materials and roughnesses, as well as ply-ply friction dependent on fiber orientations.

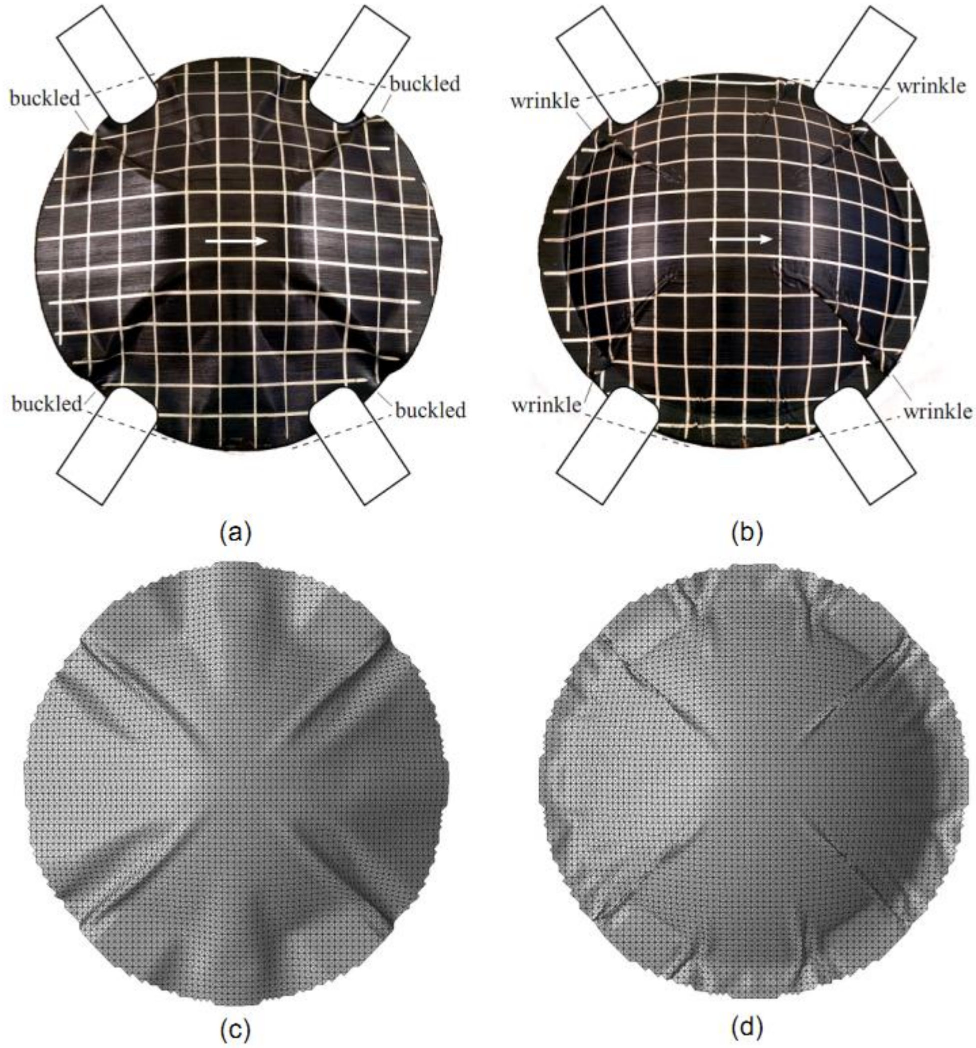

Figure 7: Comparison of experiment (top) and simulation (bottom): intermediate forming result with tool distance of 20mm (a) and final shape (b). Intermediate (c) and final simulation result (d). AS4 carbon fiber /Polyetherketoneketone (PEKK) quasi-isotropic $[0/90/45/-45]_S$ lay-up

Simple dome application

In this section the FE-Software AniForm is used to simulate a doubly curved dome demonstrator [11]. The objective is to show the development of defects like buckling and wrinkling and compare them to experimental results. The experiments cover a thermoplastic UD composite of AS4/PEKK with quasi-isotropic layup $[0/90/45/-45]_S$. The dome has a diameter of 177.5 and a height of 35mm; the initial diameter of the blank is 217.5mm. The steel male mould is heated, the rubber female mould is at room temperature. The blank is pre-heated to 380°C. In order to transport the blank and restrain the fibers four blank holders are used, see Figure 7.

The experiment was performed twice, until complete closure (top right) and until a remaining clearance of the tools of about 12mm (top left). It can be clearly recognized that in due forming fiber buckling occurs at 45 degree orientation. From the top left picture it is seen that the blank holders influence this buckling behavior. In further processing some of the surface waviness is leveled out due to intra-ply shearing and inter-ply slippage. Nevertheless, the main fraction is folded to form unacceptable wrinkles, as illustrated by the mechanism in Figure 2. This behavior is acceptably well captured by the finite element simulation as shown in the pictures bottom left and right. In the simulation the IFRM model was used to model the membrane stresses. Bending is modeled using an orthotropic elastic model on ply level. Friction was incorporated using a viscous model. The buckling and folding behavior of the single plies in the experiment as well as the relative slip of plies among each other is an issue to be resolved in the near future.

Conclusions

Thermoplastic composites feature excellent properties with respect to stiffness to weight ratio, toughness properties and certainly ease and cost of processing. Stamp forming is an applicable process for production of tailored thermoplastic composite parts. In order to verify the feasibility of the stamp forming process and the final product performance, in the end leading to optimized design and processing parameters, accurate software tools are needed. In this paper a number of mechanisms that play an important role in stamp forming were addressed and methods for identification and characterization of material and friction parameters were presented. A comparison of experiment and simulation for a doubly curved part showed a good agreement for buckling and wrinkling behavior and illustrates the importance of reliable material parameters.

Future work is focused on the identification of bending behavior of single and stacked plies at high temperatures. Furthermore the observed inconsistency concerning the Stribeck curves of UD prepreg needs to be clarified. Finally, the whole picture needs to be completed and verified with industrially relevant demonstrators that use tailored blanks.

Acknowledgements

This project is funded by the Thermoplastic Composite Research Centre (TPRC). The support of the Region Twente and the Gelderland & Overijssel team for the TPRC, by means of the GO Programme EFRO 2007-2013, is gratefully acknowledged.

References

[1] *Feasibility of continuous-fiber reinforced thermoplastic tailored blanks for automotive applications*, A. Burkhart and D. Cremer, Proceedings of the 5th Annual SPE Automotive Composites Conference, 2005.
[2] *Structural composite materials.* F.C. Campbell. ASM International. 2010.
[3] *Rheological characterization of anisotropic materials*, T.G. Rogers. Composites, 20(1), 21-27, 1989.
[4] *Rheological behaviour of preimpregnated textiles*, P. Harrison, M.J. Clifford. In: Design and manufacture of textile composites, ed. A.C. Long, Woodhead Publishing Ltd., Cambridge, UK, 2005.
[5] *Forming predictions of UD reinforced thermoplastic laminates*, S.P. Haanappel, R. ten Thije, and R. Akkerman, Proceedings of the ECCM 14, 2010.
[6] *In-Plane Shear Characterisation of Uni-Directionally Reinforced Thermoplastic Melts*, S.P. Haanappel, R. ten Thije, U. Sachs, A.D. Rietman and R. Akkerman, Proceedings of the 14th Esaform Conference, 2011.
[7] *Friction testing of thermoplastic composites*, U. Sachs, S.P. Haanappel, B. Rietman and R. Akkerman, Prodeedings of SEICO conference, 2011.
[8] *Tool-Ply Friction In Composite Forming,* R. Akkerman, M. P. Ubbink, M. B. de Rooij, and R. H. W. ten Thije, Proceedings of the 10th ESAFORM Conference on Material Forming, 2007.
[9] *On non-Newtonian lubrication with the upper convected Maxwell model*, X.K. Li, Y. Luo, Y. Qi and R. Zhang, Applied Mathematical Modelling 35, 2011.
[10] *Friction in Forming of UD Composites*, U. Sachs, R. Akkerman, S.P. Haanappel, R. ten Thije and M.B. de Rooij, Proceedings of the 14th Esaform Conference, 2011.
[11] *Large deformation simulation of anisotropic material using an updated Lagrangian finite element method,* R. H. W. ten Thije, R. Akkerman, and J. Huétink, Computational Methods in Applied Mechanics and Engineering, 196:3141-3150, 2007.