# MULTI-LAYER THERMOPLASTIC COMPOSITES MANUFACTURING PROCESSES: SIMULATIONS AND EXPERIMENTS

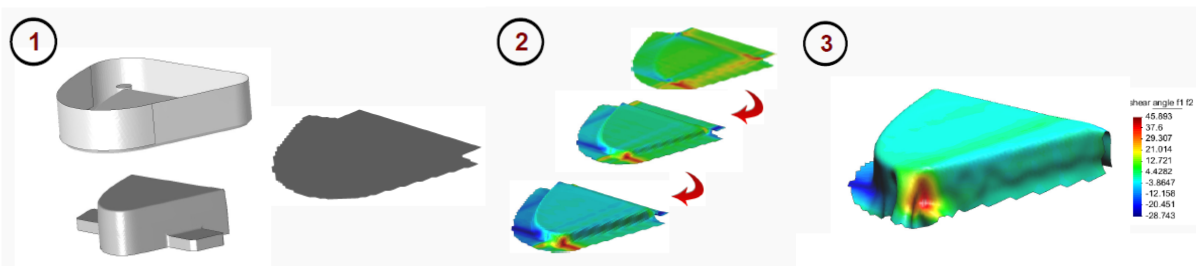
Dr. RENE TEN THIJE [a], SEBASTIAAN HAANAPPEL MSc [b].
a) AniForm Engineering B.V., Nieuwstraat 116, 7411 LP Deventer, the Netherlands. email: r.tenthije@aniform.com, tel: +31 (0) 6 4777 3226
b) TPRC, University of Twente, Drienerlolaan 5, P.O. Box 217, 7500AE Enschede, the Netherlands.

## SUMMARY

Press forming of multi-layer thermoplastic composite laminates is a fast and cost-effective method to produce thin shelled products. This paper shows that virtual forming provides designers with a tool to determine and to optimize the formability of these composite products. Forming simulations identify critical spots in the product design at an early stage and reduce costly product development times. Accurate characterization of the highly anisotropic composite materials is necessary for realistic forming predictions. Forming simulations of a thermoplastic multi-layer UD/PEKK and woven 8HS/PPS laminates are presented and validated against corresponding press trials. Fibre distribution and wrinkling patterns were compared and the results show good agreement.

## INTRODUCTION

The aerospace and automotive industry reduced product development times significantly by using the concurrent engineering approach. Design, manufacturing and performance are addressed in parallel and not by a conventional serial approach. The concurrent approach implies that the formability of a complex fiber reinforced composite must be considered during the design phase. This includes identifying and eliminating potential problems like springback, wrinkling and tearing, which are often seen in sharp corners and on doubly curved areas. A simulation tool that correctly predicts the behavior of multi-layer composites upon forming allows to create a first time right manufacturing process and avoids costly trial-and-error runs on the shop floor.




import tooling and blank | simulate the process | identify critical spots

*Illustration 1: Simulation of the production process with AniForm.*

The formablity of the multi-layer composite is assessed with the AniForm finite element code by following the steps shown in Illustration 1. The code accounts for large, non-linear deformations of highly anisotropic materials. A decoupled approach of membrane and bending mechanisms ensures realistic simulations of the forming process. The next section presents the primary deformation mechanisms of a continuous fiber reinforced material (CFRP). These are included and characterized for the multi-layer forming simulations presented thereafter. The forming simulations of a thermoplastic uni-directional (UD) laminate and a woven fabric based laminate are validated against press trials.

# MATERIAL CHARACTERISATION

The mechanical behavior of continuous fiber reinforced materials (CFRPs) upon forming differs significantly from other materials due to the presence of stiff fibers. The deformation mechanisms can be split into three main categories: intra-ply, inter-ply and out-of-plane mechanisms.

## Deformation mechanisms in CFRPs

A thorough understanding of the deformation mechanisms is not only necessary for accurate forming simulations, but also provides knowledge on how to reduce or avoid forming defects in CFRP products. Wrinkling, for example, depends on the ratio between the in-plane stiffness and bending stiffness of the laminate (ref 1.). Characterizing this ratio provides information on the susceptibility to wrinkling. Table 1 shows the primary deformation mechanisms in CFRPs from the three categories.

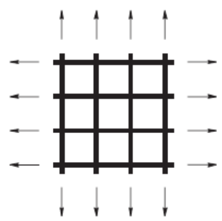
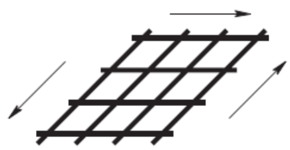
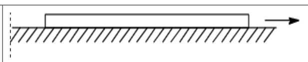
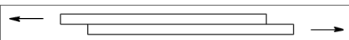
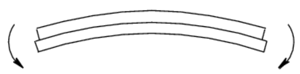
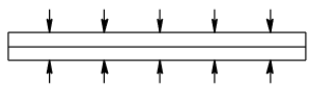
| | | | |
|---|---|---|---|
| **Intra-ply** | | | |
| |  |  | Characterized by:<br>• tensile test (a)<br>• bias extension (b)<br>• trellis frame experiment (b)<br><br>For UD materials:<br>• novel torsion experiment (b) |
| | (a) fibre loading | (b) intra-ply shear | |
| **Inter-ply** | | | |
| |  |  | Characterized by:<br>• frictional experiments (a,b) |
| | (a) tool-ply slip | (b) ply-ply slip | |
| **Out-of-plane** | | | |
| |  |  | Characterized by:<br>• free deflection test (a)<br>• forced deflection test (a)<br>• compression tests (b) |
| | (a) laminate bending | (b) compaction | |

*Table 1: Primary deformation mechanisms in CFRPs.*

Elongation of the fibers is often negligible compared to other deformation mechanisms. The fiber stiffness can be determined by a tensile test, but often values from literature are sufficient for standard glass or carbon fibre based composites. Intra-ply shear is the primary deformation mode when forming CFRPs into doubly curved shapes. This mode is also referred to as the trellis mode. The response of the laminate in shear will be rate and temperature dependent if the fabric has been impregnated. Two widely used experimental methods to examine the shear behavior of biaxial fabrics are the bias extension and the picture frame test. Bias and trellis experiments fail for most UD materials, due to the low mechanical integrity of the laminate at forming temperatures. A novel approach to measure the intra-ply shear properties of UD materials is briefly discussed in the next section.

Friction transfers the external loads into the material and can cause wrinkling or fiber buckling of internal plies or of the laminate as a whole. Two types of friction are distinguished. The first type is tool-ply friction, which occurs between the tool materials and the outer plies of the laminate. The second type is ply-ply friction, which occurs on the interface between the individual plies of a laminate. The effect of friction is often underestimated, but dominates the formability of many thermoplastic laminates (ref. 2.)

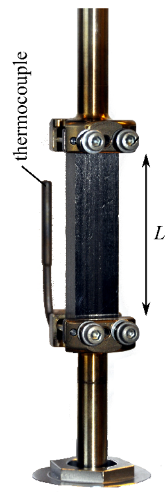
The bending stiffness of thin laminates is often negligible compared to the membrane stiffness. Nevertheless, this bending stiffness can not be ignored when addressing the laminate's tendency to wrinkle upon forming. Compaction of the plies is important in the consolidation phase of the production process. Poor compaction causes voids between the individual plies, resulting in inferior mechanical performance.

## Experimental characterization examples

The results of two characterization experiments are discussed: intra-ply shear property measurements of a uni-directional (UD) thermoplastic material and the frictional properties of a fabric reinforced thermoplastic material.

### Intra-ply shear properties of UD AS4 Carbon PEEK

The intra-ply shear properties have been measured for a CETEX Thermo-Lite® UD pre-preg material from Ten Cate. The composite consists of a PolyEther Ether Ketone (PEEK) semi-crystalline polymer with a AS4 carbon reinforcement. Illustration 2 shows a thick rectangular specimen that is mounted by a lower static fixture, and an upper movable fixture that conducts an oscillating torque from a controlled motor to the specimen. The measurements were conducted by using an Anton Paar MC501 rheometer.



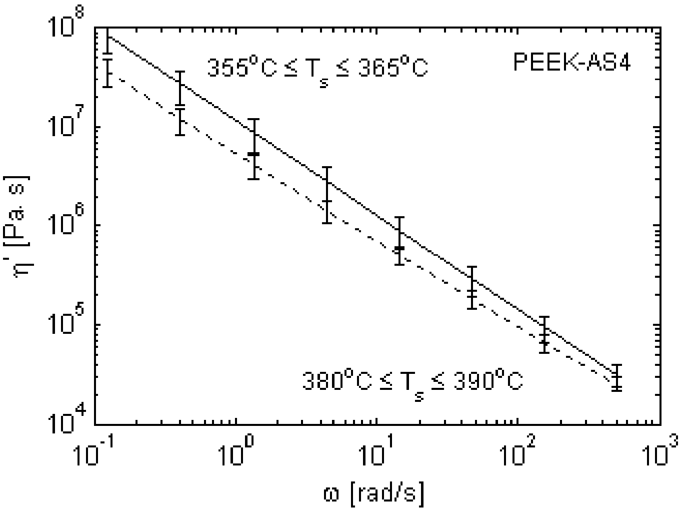




*Illustration 2: Picture with the mounted specimen at the left hand side. The right hand side shows the apparent viscosity, plotted against the angular frequency for a PEEK-AS4 specimen at two different temperatures.*

The right hand side of Illustration 2 shows the measured apparent viscosity against the angular frequency at different specimen temperatures $T_s$. An increase in temperature results in a decrease of the apparent viscosity. The graphs show shear thinning behavior, which can be described by a power law viscosity model. More details on the shear property measurements of UD materials can be found in (ref. 3.).

### Tool-ply and ply-ply frictional properties of glass reinforced 8HS/PPS

Both tool-ply and ply-ply friction were characterised for a polyphenylene sulfide (PPS) material, reinforced with a CETEX® SS303 glass fibre 8H satin weave from Ten Cate. Pre-consolidated laminates were cut into strips and tested with a novel friction tester at different slip velocities, normal pressures and temperatures (ref 4.). Illustration 3 shows the results of the friction experiments at a temperature of 310 ºC, at three slip velocities and at two normal pressure values.

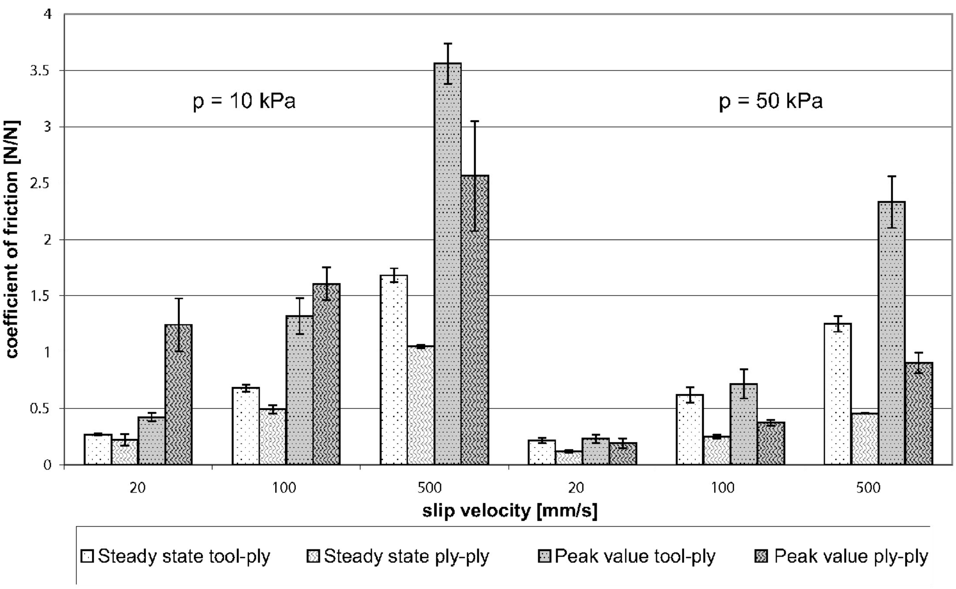



*Illustration 3: Tool-ply and ply-ply of an 8HS glass PPS weave at 310 ºC at normal pressures of 10 and 50 kPa. The error bars denote the standard deviation.*

The figure shows peak values and steady state values of the coefficient of friction. The frictional force shows a peak value right after the initiation of slip and settles at a lower value after a while, the steady state value. Some coefficients of friction exceed the value of one, especially when the exerted normal pressure is low. The polymer 'sticks' to the surfaces and introduces a resistance against slip, which is present even when no normal pressure is applied. All steady state coefficients of friction are lower for ply-ply friction when compared to tool-ply friction. The thickness of the polymer film that separates the slip surfaces can be a possible cause for this phenomenon. A thicker film will decrease the shear rate in the film and hence will decrease the frictional force. For the peak values this is not always the case, when looking at the results for the lowest normal pressure. In general, the effect of the slip velocity indicates that (elasto-)hydrodynamic lubrication is the dominant friction type.

## SIMULATIONS AND VALIDATION EXPERIMENTS

Two forming cases will be analyzed with the AniForm finite element code. Experimental material characterization results are used to fit appropriate material models. The forming predictions are validated against corresponding press trials.

## Gulfstream G650 tail component

This validation case deals with a stiffener component of the horizontal tail plane of a Gulfstream G650 business jet. The product is susceptible to shape distortions. Wrinkling and springback are frequently observed during the manufacturing of these products.

The press forming trials were performed at Fokker AESP, where pre-consolidated laminates were press-formed between the two steel mould parts. Ten Cate Advanced Composites supplied the glass fibre 8H satin Cetex© SS303 weave for the experiments. The layup of the 4-ply blank was $[0/90,-45/45]_s$. The blanks were heated by infra-red panels up to 325 ºC and subsequently press-formed.

## Modelling

Illustration 4 shows the meshed tools and the blank geometry that were used to form the stiffener component.

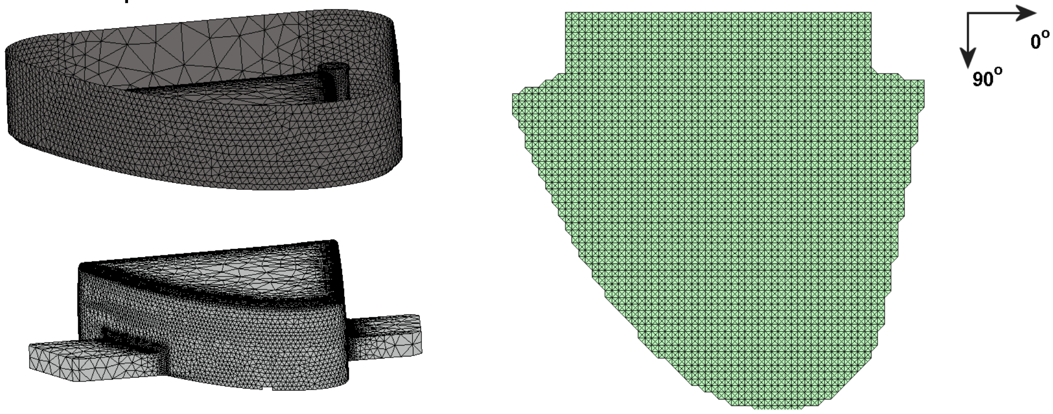



*Illustration 4: The discretized tooling on the left hand side and the blank shape on the right hand side.*

The height of the tools is 50 mm. The tools are assumed to be rigid. The forming of a single layer and a two layer product was simulated. It is assumed that the two layer simulation with a [0/90,-45/45] layup will show a similar behavior as the four layer laminate that was used in the forming trials. Each layer of the laminate contains around 10 thousand triangular shell elements. The closing speed of the press equals 10 mm/s. The forming process is assumed to be isothermal, with a temperature of 310 ºC.

## Results and discussion

Illustration 5 shows the predicted shear angles of the single layer simulation. The shear angles along the path that is indicated in the figure are plotted in Illustration 6. This figure also shows the predicted shear angles for the single and multi-layer product and the measured shear angles for the press formed trial product. No experimental results are available for the single layer case. The shear angles were measured at an approximated interval distance of 4 mm for three products. The average of the measured shear angle plus and minus the standard deviation is indicated with the range plotted in Illustration 6. In general, the predicted and measured shear angle agree well. Most of the curve fits within the measured bandwidth. The curve shows some deviation on the 140 to 200 mm interval, where the simulation predicts a slightly higher shear angle.

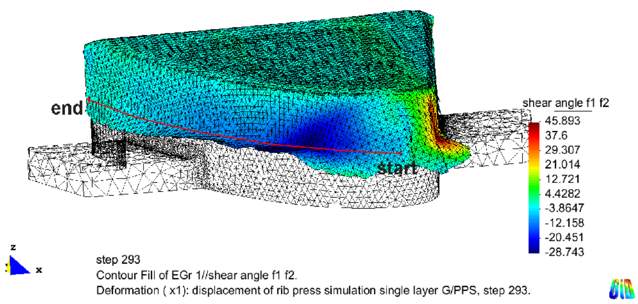



*Illustration 5: Predicted shear angles in the single layer product after the press forming cycle.*

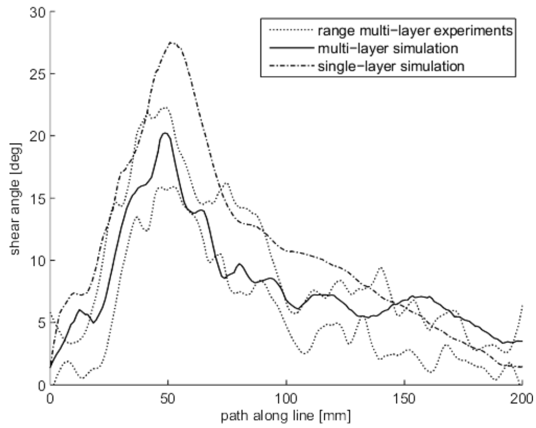



*Illustration 6: Measured and predicted shear angles along the path indicated in Illustration 5.*

The predicted maximum shear angle is significantly higher for the single layer simulation, when compared to the multi-layer simulation. The single layer laminate shears much easier, since there are no additional layers with intra-ply friction that restrict this deformation mode. The individual layers of the multi-layer laminate deform in different directions upon forming and due to the inter-ply friction the formability of the laminate as a whole is reduced. The single layer simulation therefore shows almost no wrinkles, while the multi-layer simulation and the demonstrator products show much more wrinkling.

## UniDirectional (UD) carbon PEKK material

This demonstrator is part of an ongoing research within the TPRC (www.tprc.nl) consortium, where the thermoforming of tailored blanks of UD thermoplastic materials is addressed.

Forming experiments were performed with blanks, having a polyetherketoneketone (PEKK) thermoplastic matrix, and a UD carbon fiber reinforcement. A sketch of the dome shaped tooling can be found in Illustration 7. Although the geometry looks rather simple, the double curvature is an excellent way to test the formability of laminates. Non-uniform shear, friction and bending trigger the onset of wrinkling. The blanks have a diameter of 217.5 mm and a quasi-isotropic $[0/90/45/-45]_S$ lay-up. The laminates were heated up to 360 °C and formed between the preheated steel male and the cold rubber female part. The blanks were supported by four laminate holders as shown in Illustration 8. These holders locally restrict some deformation due to the resulting normal forces and lower temperatures. These holders are included in the simulation. The blank is modeled as a four layer [0/90/45/-45] stacked blank. The forming process is assumed to be isothermal.

### Results and discussion

Illustration 8 shows the experimental and simulated forming results at two instances. The left hand side shows the situation in which the mould parts were not fully closed yet. It shows the out of plane buckling of the laminate. The right hand side shows the final product. Some buckled regions have been folded into a wrinkle, while others have been flattened by the closing moulds.

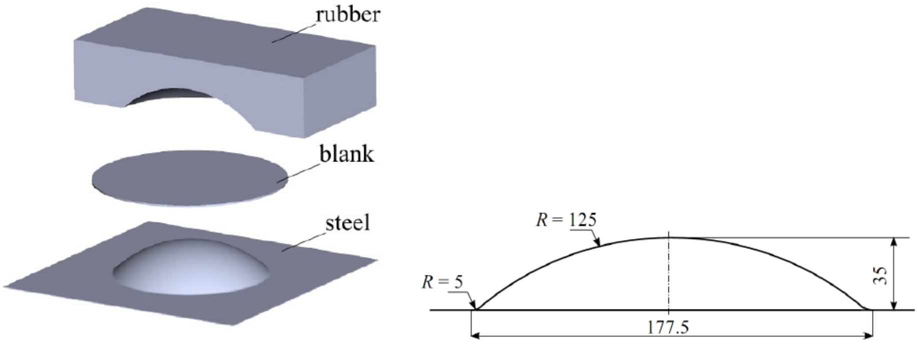



*Illustration 7: The tooling of the UD carbon PEKK demonstrator.*

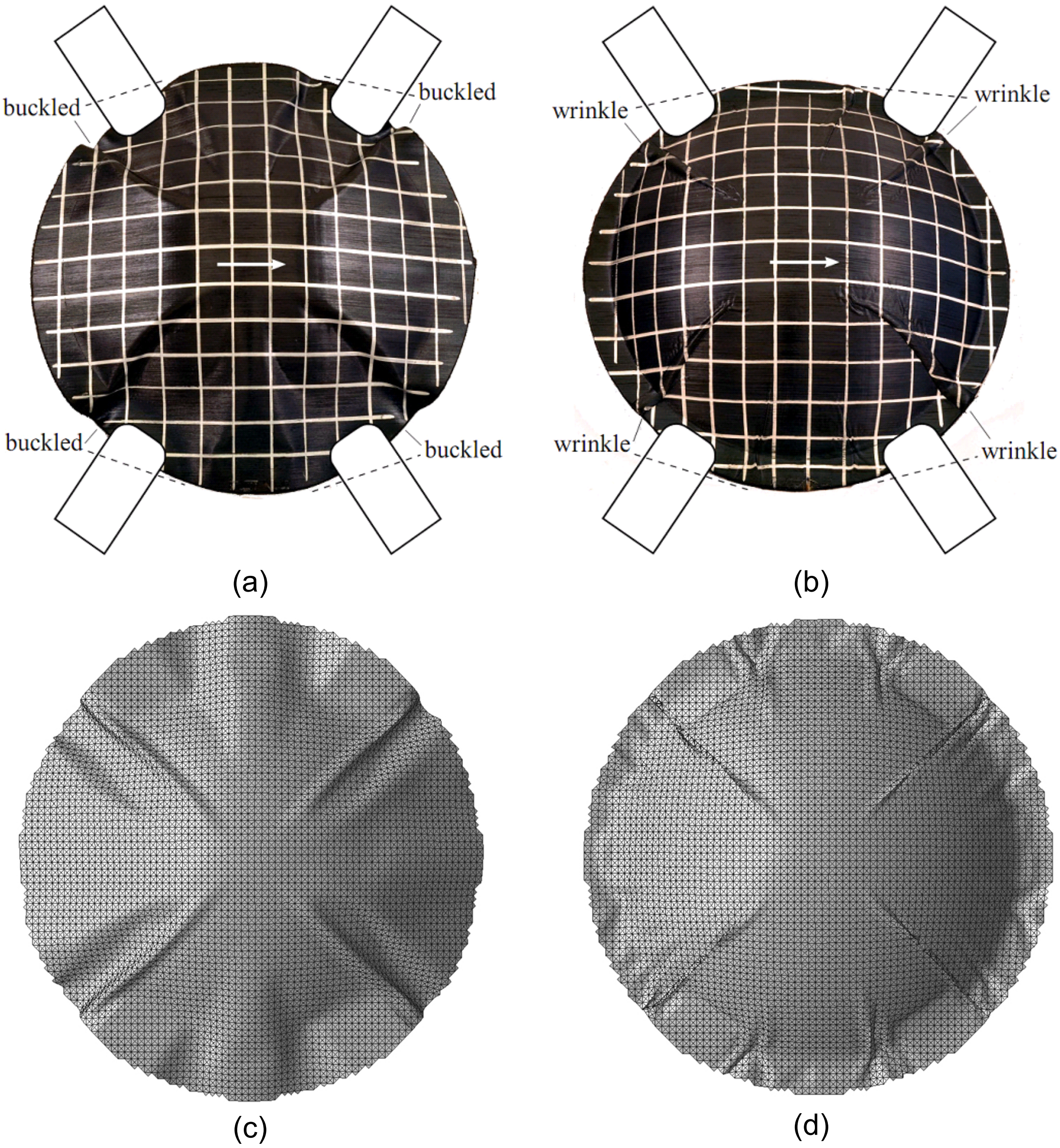



*Illustration 8: Thermoforming results: (a) intermediate forming result, distance between tools: 20 mm. (b) Final shape of the formed dome. (c) Intermediate simulation result and (d) final simulation result.*

The simulated and experimental results show similar wrinkling patterns. Large wrinkles are observed in both the press trials and the simulated end product in the ±45º directions. These wrinkles originate from the blank holder positions. Smaller wrinkles develop next to the large wrinkles.

## CONCLUSIONS AND OUTLOOK

The press forming of reinforced multi-layer laminate was successfully simulated with the AniForm finite element code. A thermoplastic matrix material with a uni-directional and a woven fabric reinforcement, respectively, were considered. The results of characterization experiments were translated to model parameters and included in the simulation. Accurate forming simulations of multi-layer composites require accurate characterization of shear and bending properties of the laminate, as well as tool-ply and ply-ply frictional properties. The simulations were validated against corresponding forming experiments by comparing the fiber distribution and the wrinkling pattern. The agreement between the predicted and measured results is good. The forming simulations allow designers of composite products to optimize the manufacturing cycle of multi-layer products in an early stage, avoiding time and resource intensive trial-and-error procedures on the shop floor.

Current and future research aim at further development of a smart multi-layer element for fast and accurate forming simulations of multi-layer laminates. Modeling all layers within one element in the thickness direction reduces the number of elements and the complexity of the contact logic significantly. Hence, it increases the robustness and speed of the simulation.

## ACKNOWLEDGEMENTS

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