ON THE RELEVANCE OF THERMOMECHANICS AND CRYSTALLIZATION KINETICS FOR FINITE ELEMENT THERMOFORMING SIMULATION

Dominik Dörr[1,2], Luise Kärger[2], Frank Henning[2,3]

[1]SIMUTENCE GmbH, Karlsruhe, Germany
[2]Karlsruhe Institute of Technology, Karlsruhe, Germany
[3]Fraunhofer Institute for Chemical Technology, Pfinztal, Germany

ABSTRACT

Thermoforming of thermoplastic tapes is currently of great interest for the automotive industry, due to low cycle times, material efficiency and recyclability. Depending on material parameters and process conditions, however, manufacturing defects may occur. Finite Element (FE) forming simulation offers the possibility of a detailed a priori analysis of the deformation behavior of multilayered thermoplastic blanks during forming, considering material behavior and process conditions by means of constitutive equations and boundary conditions, respectively. Usually, thermoforming simulation is assumed to be iso-thermal, which is a reasonable assumption for temperatures above the onset of crystallization for semi-crystalline thermoplastics. Especially in a process design phase, however, the onset of crystallization cannot be excluded in general. This study presents a fully coupled thermomechanical approach for finite element forming simulation of thermoforming processes, predicting the evolution of temperature and crystallization of semi-crystalline thermoplastics. The approach is successfully validated for a generic geometry with a high agreement to experimental thermoforming tests. Finally, the relevance of including thermomechanics and crystallization kinetics is analyzed by means of a virtual sensitivity study. The study reveals that only by including those effects, the influence of all process parameters on formability can be predicted.

Keywords: Thermoplastic, Forming, Process simulation, Thermomechanical, FEA
Corresponding author: dominik.doerr@simutence.de

1. INTRODUCTION

Composite materials reveal a particularly high lightweight potential, due to their excellent weight-specific material properties and their capability to be tailored to specific applications [1]. While the automotive industry still mostly uses commodity materials such as steel and short glass fiber-reinforced composites [2], the aerospace industry is using high-performance materials since decades. This is attributable to automotive mass production, where the material dominates the overall costs. Hence, automotive industry requires highly automated and robust production technologies, which make a high investment affordable as long as material costs are sufficiently low.

Copyright 2020. Used by the Society of the Advancement of Material and Process Engineering with permission.

In general, it is necessary that system-efficient composite solutions are developed, which consider besides technical and technological targets also economical boundary conditions. For this reason, the increasing demand for the reduction of green house gas emissions can be an enabler for composites in automotive industry. However, too high production costs and a limited understanding of automotive-specific processes still hinder high-performance composites to enter the automotive mass-production market.

Continuously fiber-reinforced plastics (CoFRP), however, reveal an exceptional lightweight potential and are particularly suited for structural components, due to their excellent weight-specific properties [3]. Nevertheless, manufacturing of CoFRP for both automotive and aerospace applications involves different challenges. First, materials are mostly expensive. Therefore, material consumption needs to be optimized. Second, forming of two-dimensional blanks into a three-dimensional geometries substantially influences the fiber structure, which in turn influences dimensional stability in terms of spring-in and warpage, and structural performance. For these reasons, a reliable virtual prediction of forming behavior by means of forming simulation is of utmost importance to enable time- and cost-effective process and product design. Beyond that, prediction accuracy of subsequent simulation steps is in conjunction with a virtual process chain significantly increased [4]. Within a virtual process chain (cf. Figure 1), relevant information is virtually predicted, retained and passed on successively to subsequent simulation steps.

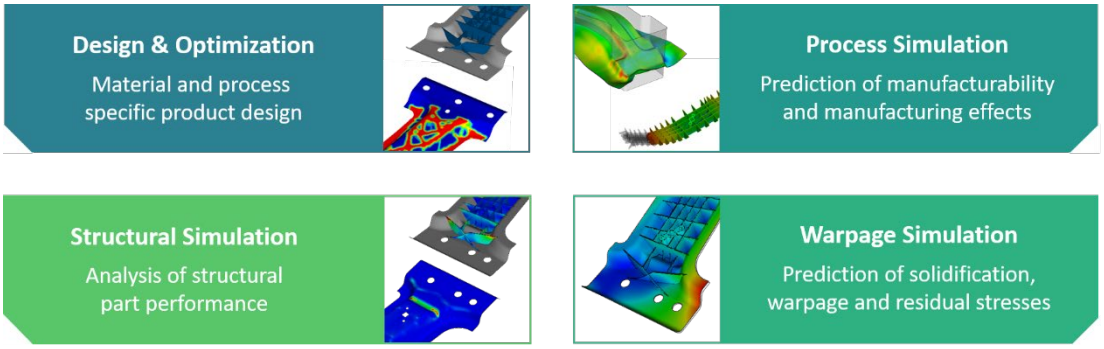


Figure 1: Schematic illustration of the sub-steps of a virtual process chain for the reliable virtual analysis of manufacturing and structural behavior of fiber-reinforced plastics.

Finally, achieving low cycle times is a challenge, which becomes increasingly important also for aerospace industry. Therefore, thermoforming of continuously fiber-reinforced thermoplastics (CoFRTP), also referred to as thermoplastic tapes, play an increasingly important role, due to low cycle times, material efficiency and recyclability [5,6].

Thermoforming processes are influenced by several parameters, like layup sequence, tool and laminate temperature, forming velocity or laminate gripping, as shown in experimental thermoforming studies by several authors [7,8,9]. Depending on these parameters and the formed geometry, manufacturing defects such as wrinkling are possible. These defects, as well as the modification of the fiber structure due to forming, are predictable by means of Finite Element (FE) thermoforming simulation. For this purpose, material behavior and process conditions are taken into account based on constitutive equations and boundary conditions, respectively.

In relation to the current interest in forming of CoFRP, commercial codes for macroscopic FE forming simulation have been developed. These are in particular the PAM-FORM [8] and the ANIFORM code [10]. Moreover, several codes for FE forming simulation have been presented in literature [11-14]. Thereby, recent approaches for thermoforming simulation of CoFRTP mostly assume thermoforming processes to be isothermal. Only few approaches consider yet the thermal behavior as well as the temperature-dependent forming behavior in terms of a thermomechanical coupling [15,16]. Both studies are restricted to temperatures well above the onset of crystallization of the investigated semi-crystalline thermoplastics. The onset of crystallization, however, induces a significant increase of mechanical properties [17,18]. Thus, it is to be expected that crystallization distinctively influences forming behavior. Since the onset of crystallization during forming cannot be excluded in general and especially prior to process optimization, a thermomechanical approach for thermoforming simulation considering also the crystallization kinetics of semi-crystalline thermoplastics is desirable for the virtual process design.

This paper presents the application of a coupled thermomechanical approach for thermoforming simulation considering besides temperature evolution also crystallization kinetics and developed by the authors [19,20]. Based on this, the phase transition from the molten to the solid material state is predicted and is taken into account for modeling of temperature- and rate-dependent thermoforming behavior.

The approach was originally developed at the Karlsruhe Institute of Technology (KIT) in Karlsruhe Germany [19,20] and is now being industrialized by the spin-off company SIMUTENCE. The software package called SIMUDRAPE comes as add-on for the commercially available Finite Element software ABAQUS/EXPLICIT and includes a fully automatized pre- and postprocessing as well as the above outlined methods for advanced contact and material modeling.

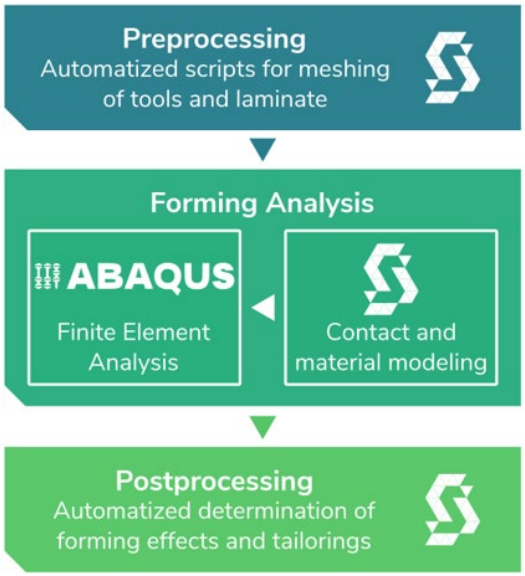


Figure 2: Schematic illustration of the working principle of SimuDrape add-ons for ABAQUS.

In the following, the coupled thermomechanical approach for thermoforming simulation is outlined in Section 2. Subsequently, Section 3 presents simulation results for a generic geometry for the isothermal and the thermomechanical case, including the comparison to experimental tests. Based on this, the necessity to account for thermal effects and crystallization kinetics is investigated.

2. SIMULATION APPROACH

FE forming simulation is based on constitutive modeling of so-called intra- and inter-ply deformation mechanisms (cf. Figure 3). Intra-ply mechanisms include membrane and bending behavior of the single ply and are usually modeled layer-by-layer by conventional shell elements, due to the high slenderness ratio of the single plies. Inter-ply mechanisms include the frictional behavior between the tool and the laminate, as well as frictional behavior and tacking between the single plies of the stacked laminate and are modeled by means of contact constitutive equations.

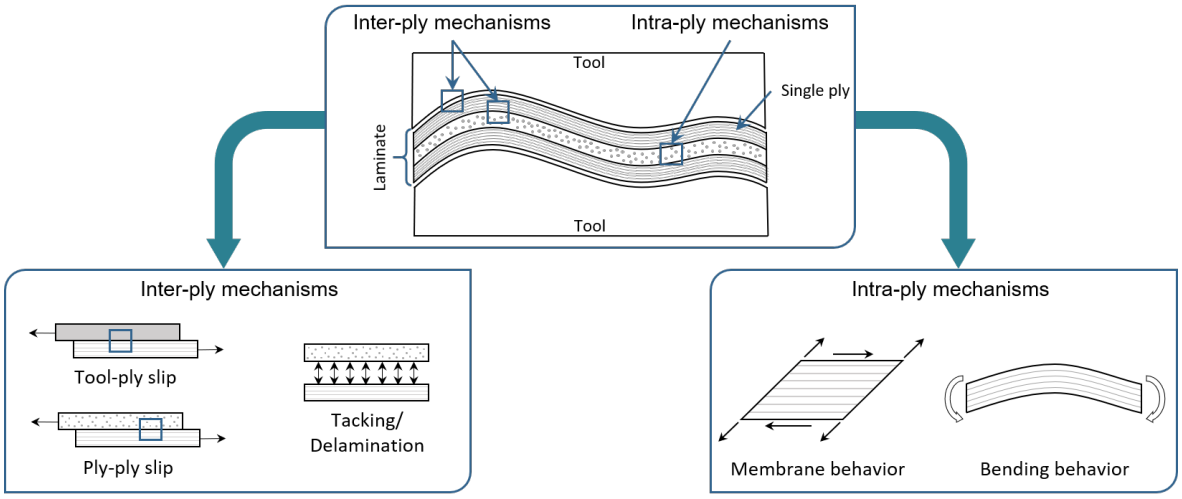


Figure 3: Schematic illustration of the deformation mechanisms during composite forming categorized into intra- and inter-ply mechanisms.

For the approach applied for thermoforming simulation in this study, the commercial FE solver ABAQUS/EXPLICIT in combination with several user-subroutines is applied. In the following, the governing equations for thermal and mechanical modeling, as well as for thermomechanical coupling are outlined.

2.1 Modeling of thermal behavior

The governing equation for modeling of thermal behavior is the heat balance equation, in combination with the generalized Fourier's law for heat conductivity:

$$\underbrace{\int_{\Omega}\left(\rho c_p \dot{T}\delta T\right)\mathrm{d}V}_{\delta W^{\mathrm{cap}}} = \underbrace{\int_{\Omega}\left(\boldsymbol{\lambda}\cdot\mathrm{grad}(T)\right)\cdot\left(\mathrm{grad}(\delta T)\right)\mathrm{d}V}_{\delta W^{\mathrm{cond}}} + \underbrace{\int_{\Gamma_{\Omega}}(s\delta T)\mathrm{d}A}_{\delta W^{\mathrm{surf}}} - \underbrace{\int_{\Omega}(r\delta T)\mathrm{d}V}_{\delta W^{\mathrm{source}}}, \qquad (1)$$

where T is the temperature, ρ the material density, c_p the heat capacity, $\boldsymbol{\lambda}$ the orthotropic heat conductivity tensor, s a surface flux on the boundary and r a volumetric heat flux. To predict thermal behavior in thermoforming simulation, the capacity term δW^{cap}, the conductivity term δW^{cond}, and the source term $\delta W^{\mathrm{source}}$ are used to model intra-ply heat capacity, conductivity and latent crystallization heat, respectively. In contrast, the surface flux term δW^{surf} is adopted to account for the inter-ply heat conductivity as well as for convection and radiation at the free surfaces, due to the exposure of the hot laminate to a cooler environment. Thereby, inter-ply heat conductivity includes the heat exchange between the single plies of the laminate as well as between the tool and the laminate. The latter is also referred to as tool-ply gap conductance.

During cooling of a semi-crystalline thermoplastic from a temperature well above the melting temperature, the thermoplastic undergoes a partial alignment of the molecular chains during solidification, which is called crystallization, and which defines the transition from the molten material state to the solid material state. In order to predict the relative crystallinity α throughout thermoforming, a wide range of cooling rates has to be captured. A suitable approach under this

requirement is the approach originally presented by Ziabicki [21] and the enhancement to several cooling rates by Sierra et al. [22], as shown in our previous work by Kugele et al. [23]. This approach combines Nakamura's equation [24]

$$\dot{\alpha} = nK(T)\big(1-\alpha(t)\big)\ln\Big(-\big(1-\alpha(t)\big)\Big)^{\frac{n-1}{n}}, \tag{2}$$

based on the Avrami index n and the crystallization rate constant K, with an empirical description of the crystallization rate constant given by [21]

$$K(T) = K_{\max}\exp\left(\frac{-4\ln(2)\,(T-T_{\max})}{D^2}\right). \tag{3}$$

Here, $K_{\max}$, $T_{\max}$ and D are material parameters for one specific cooling rate. By means of the determination of these parameters for various cooling rates, crystallization is predictable over a wide range of cooling rates [23].

2.2 Modeling of mechanical behavior

The coupled thermomechanical approach includes besides modeling of thermal behavior also temperature- and crystallization-dependent mechanical behavior, as outlined in the following.

2.2.1 Intra-ply deformation behavior

Mechanical modeling of intra-ply deformation is based on a conventional shell approach, which is implemented in the commercial FE solver ABAQUS in combination with several user-subroutines. The related mechanical virtual internal energy is given by

$$\delta\Pi = \int_V \left[\underbrace{\boldsymbol{S}^{\mathrm{mem}}\left(\frac{\partial \boldsymbol{E}}{\partial \boldsymbol{r}_i}\right)\delta\boldsymbol{r}_i}_{\delta\Pi^{\mathrm{mem}}} + \underbrace{\boldsymbol{S}^{\mathrm{ben}}\left(\frac{\partial \boldsymbol{E}}{\partial \boldsymbol{d}_i}\right)\delta\boldsymbol{d}_i}_{\delta\Pi^{\mathrm{ben}}}\right]\mathrm{d}V. \tag{4}$$

where $\boldsymbol{E}$ is the Green–Lagrange strain, $\boldsymbol{r}_i$ the nodal displacements, $\boldsymbol{d}_i$ the nodal unit director base, and $\boldsymbol{S}^{\mathrm{mem}}$ and $\boldsymbol{S}^{\mathrm{ben}}$ the second Piola–Kirchhoff (PK2) stress for membrane and bending behavior, respectively. Different constitutive equations are evaluated for membrane and bending behavior, resulting in a physical decoupling of membrane and bending behavior. This decoupling is essential for intra-ply modeling in thermoforming above the recrystallization temperature (molten material state), due to the high stiffness in fiber direction and the comparably low bending stiffness, which is induced by the possible relative motion between the fibers at processing conditions, implying that conventional plate theories are not applicable. In contrast, conventional plate theory is applied below the crystallization temperature.

For material modeling, it is distinguished between the molten and the solid material state. In each case, the same constitutive equations are applied for both membrane and bending behavior but with different material parameters. For the molten material state, hyperviscoelastic constitutive equations are applied, to account for the rate- and temperature-dependent intra-ply deformation behavior. In contrast, hyperelastic constitutive equations are applied for the solid material state,

since rate-dependency is expected to be negligible compared to the molten material state. Moreover, it is assumed that the free energy stored in the molten material state fully dissipates with the onset of crystallization. Based on this, the total deformation gradient $\boldsymbol{F}$ is multiplicatively decomposed into a solid part $\boldsymbol{F}^{\mathrm{solid}}$ and a molten $\boldsymbol{F}^{\mathrm{molten}}$ part by

$$\boldsymbol{F} = \boldsymbol{F}^{\mathrm{solid}} \cdot \boldsymbol{F}^{\mathrm{molten}}, \tag{5}$$

where the molten part is defined by the onset of crystallization. Based on this, the deformation state at the onset of crystallization $\boldsymbol{F}^{\mathrm{molten}}$ is introduced as new reference configuration for the evaluation of the solid constitutive equations.

2.2.2 Inter-ply deformation behavior

Inter-ply deformation behavior, including the tacking in normal direction and friction in tangential direction, is modeled by means of contact constitutive equations implemented in user-subroutines. This is necessary, since based on ABAQUS built-in methods, the simultaneous tacking in normal direction and sliding in tangential direction at the tool-ply interfaces cannot be accounted for.

The related contact constitutive equations are regularized by means of the Penalty method in both normal and tangential direction. The tacking in normal direction is modeled by means of an additional stiffness, if the contact is under tension and as long as a maximum admissible distance between the interacting surfaces is not exceeded. In tangential direction, pressure- and rate-dependent friction is modeled for the molten material state by $\boldsymbol{\tau}^{\mathrm{molten}}$, whereas purely elastic tacking is modeled for the solid material state by $\boldsymbol{\tau}^{\mathrm{solid}}$:

$$\boldsymbol{\tau}^{\mathrm{molten}} = \left(\mu p + \eta\left|\dot{\boldsymbol{\xi}}\right| + \tau_0\right)\frac{\dot{\boldsymbol{\xi}}}{\left|\dot{\boldsymbol{\xi}}\right|}\ , \qquad \boldsymbol{\tau}^{\mathrm{solid}} = \epsilon\boldsymbol{\xi}, \tag{6}$$

where $\boldsymbol{\xi}$ is the tangential displacement vector, $\boldsymbol{\tau}$ the tangential stress, p the transversal pressure, μ, η and τ_0, material parameters, respectively, and ϵ the tangential solid stiffness.

2.3 Thermomechanical coupling

To account for temperature-dependent thermoforming behavior, related constitutive equations are evaluated as a function of temperature in the molten material state. To account additionally for a possible phase transition during forming, constitutive equations are evaluated for the solid and the molten material state simultaneously. For intra-ply modeling, the resulting stress tensors for the molten material state $\boldsymbol{S}^{\mathrm{molten}}$ and the solid material state $\boldsymbol{S}^{\mathrm{solid}}$ are superimposed based on the relative crystallinity α by

$$\boldsymbol{S} = (1-\alpha)\boldsymbol{S}^{\mathrm{molten}} + \alpha\boldsymbol{S}^{\mathrm{solid}}, \tag{7}$$

which guarantees a smooth transition between the molten and the solid material state. A similar approach is applied for inter-ply behavior for the constitutive equations given in Equation 6.

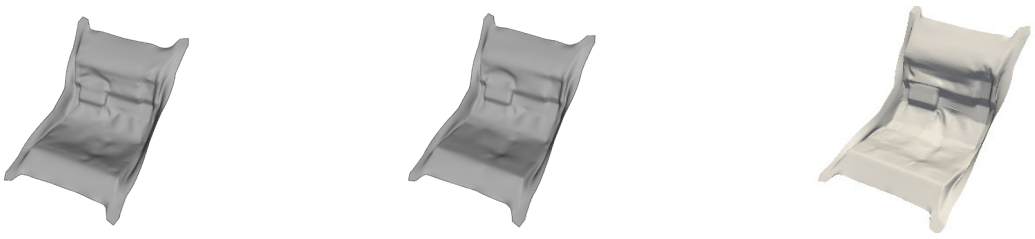
3. VALIDATION

The above outlined coupled thermomechanical approach is finally applied to thermoforming simulation of a generic geometry for an orthotropic and a quasi-isotropic layup. Each of the 8 single plies is modeled by means of separate element layers with 42,672 elements per layer. The tools are modeled as discrete rigid surfaces with a constant temperature, since their deformation and heating during forming is expected to be negligible. The tool kinematics is modeled by a displacement boundary condition in real-time, to accurately account for rate-dependency and thermal behavior of the laminate. Laminate gripping is modeled following the approach proposed by Poppe et al. [28] based on so-called connector elements, which is necessary to accurately account for the kinematics of the pneumatic needle grippers, since these can rotate and elongate during forming. For modeling of thermal and mechanical behavior, the approach outlined in Section 2 is adopted and parameterized for a PA6-CF tape. Details on the parameterization can be found in our previous studies [19,20]. For validation of the above outlined thermoforming simulation approach, the simulation results are compared to surface measurements of experimental tests. Thereby, the results of the thermomechanical approach as well as the results of an isothermal approach, which is achieved by assuming a constant laminate temperature of 270 °C, are considered. Based on this, the necessity to account for thermal effects and crystallization kinetics in thermoforming simulation is investigated.

3.1 Orthotropic layup

Figure 4 shows the comparison of thermoforming simulation results to surface measurements of the according experimental results under application of the thermomechanical and related isothermal approaches at several remaining tool travels Δz and for the orthotropic layup. A good agreement of the obtained overall shape and outer contour is observed for both layups. However, in a more detailed comparison it is observed that some local defects are predicted only by the thermomechanical approach, in particular for the large evolving fold above the bigger corner bending. This forming defect is clearly predicted by the thermomechanical approach, especially in Stage 2. Moreover, local wrinkling around the beads is predicted more pronounced by the thermomechanical approach. This is in good agreement with the experimental tests and the difference can be reduced to local cooling and crystallization of the laminate, as shown for several remaining tool travels Δz in Figure 5 for the lowest ply. Here, comparably low cooling due to free convection and radiation is observed for the free surfaces. In contrast, distinct local cooling due to tool-ply contact (gap conductance) is observed. Thereby, local crystallization is observed in these areas already during forming. Besides this, local wrinkling is directly reflected in the temperature distribution, due to the local tool-ply contact.

Stage 1: $\Delta z = 17.5$ mm



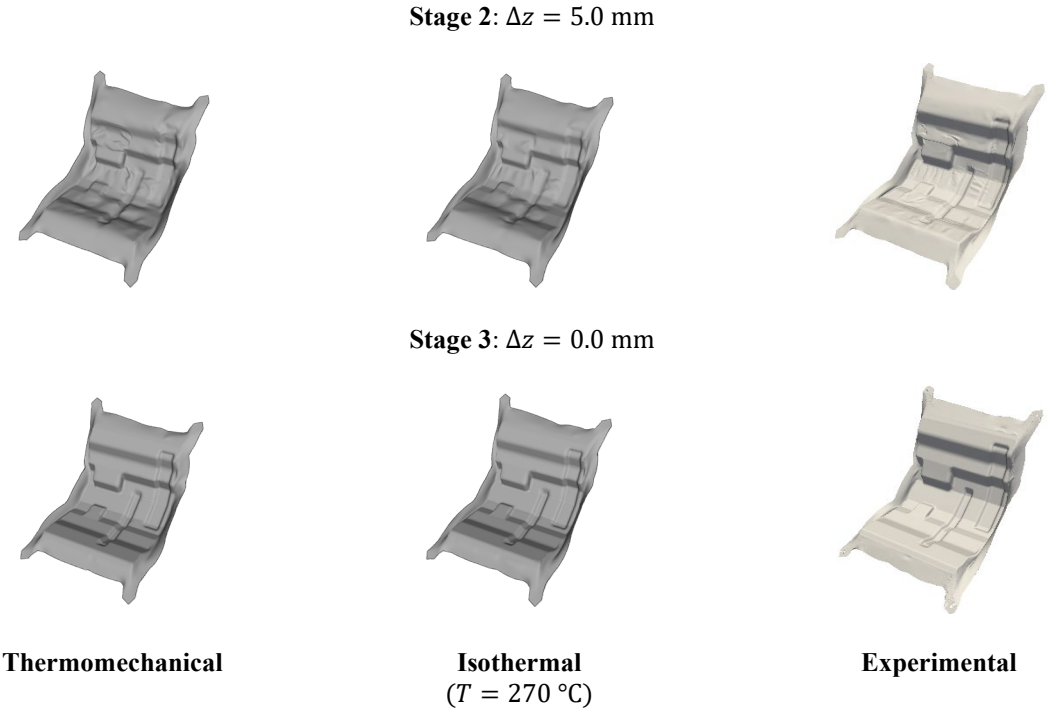


Figure 4: Comparison of thermoforming simulation, under application of the thermomechanical and the isothermal (T = 270 °C) approach to 3D measurements of experimental tests at several remaining tool travels Δz, for the orthotropic layup ($[0;90]_{2s}$), and for a tool temperature of 110 °C [20].

.

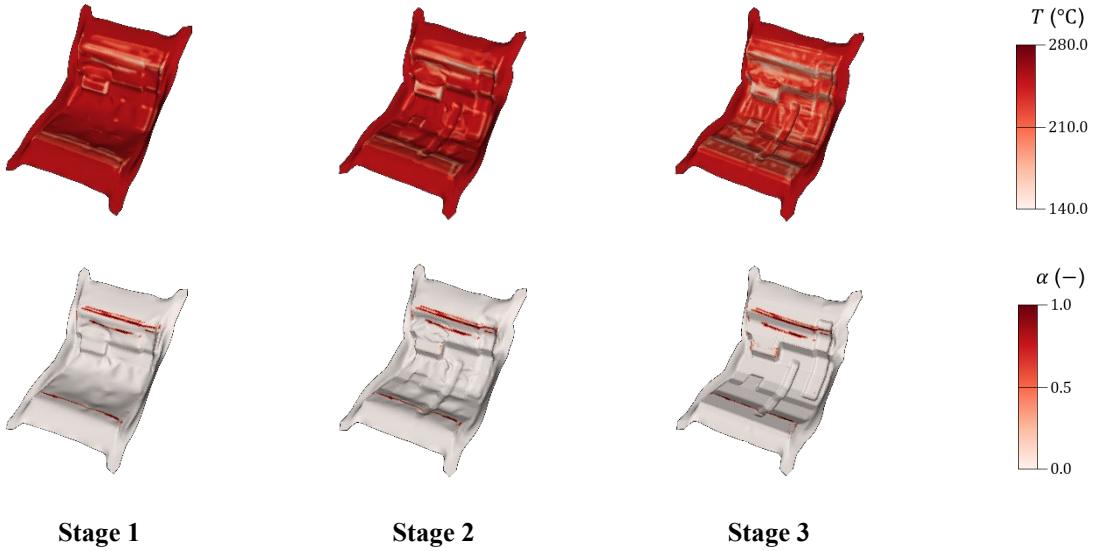


Figure 5: Temperature T (top row) and relative crystallinity α (bottom row) for the orthotropic layup ($[0;90]_{2s}$) at several remaining tool travels Δz, obtained from the thermomechanical approach [19].

3.2 Quasi-isotropic layup

Figure 6 shows the comparison of thermoforming simulation results under application of the thermomechanical and the isothermal approach to surface measurements of the according experimental results for the quasi-isotropic layup at several remaining tool travels Δz. Distinctive wrinkling behavior is observed throughout forming in the experimental test, which is captured clearly by both simulation approaches. Increased wrinkling behavior, however, is predicted by the thermomechanical approach. Here, a high degree of agreement to the experimental tests for the amount, direction and location of wrinkles is observed. In contrast, less pronounced wrinkling is predicted under application of the isothermal approach. Additionally, slight deviations are observed for the unfolding and sag of the laminate in the outer areas, especially for Stage 3.

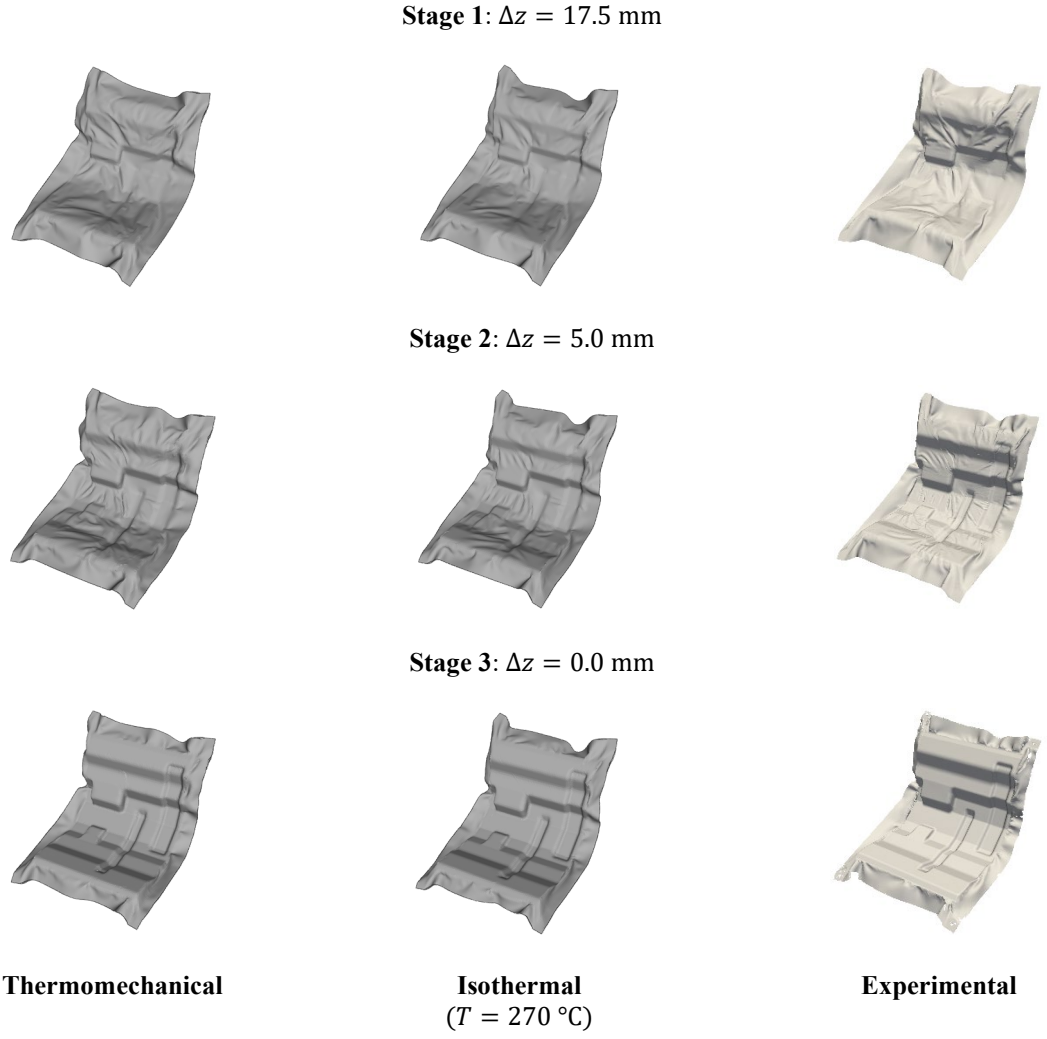


Figure 6: Comparison of thermoforming simulation, under application of the thermomechanical and the isothermal (T = 270 °C) approach, to 3D measurements of experimental tests at several remaining tool travels Δz, for the quasi-isotropic layup ([0; 45;90;45]s), and for a tool temperature of 110 °C [20].

4. CONCLUSIONS

A coupled thermomechanical approach for thermoforming simulation of continuously fibre-reinforced thermoplastics implemented in the commercial FE solver ABAQUS in combination with several user-subroutines is presented. This approach is now being industrialized under the product name SIMUDRAPE by the KIT spin-opff company SIMUTENCE. Following this approach, mechanical behavior is modeled by means of hyperelastic and hyperviscoelastic constitutive equations. Modeling of thermal behavior takes heat loss due to radiation, convection and heat conduction as well as the prediction of crystallization kinetics during forming into account. The phase transition is predicted by the relative crytallinity and is taken into account for mechanical modeling by means of temperature- and crystallinity-dependent material properties.

The application of the coupled thermomechanical approach to a generic geometry shows an improved agreement to the according experimental forming tests compared to the related isothermal approach. For the orthotropic layup, it is observed that some forming defects are captured by the thermomechanical approach only. In contrast, distinct wrinkling behavior of the quasi-isotropic layup observed in the experimental tests is captured basically by both approaches. Wrinkling behavior, however, is predicted too less pronounced for the isothermal approach. This results from distinct local cooling of the laminate, obviously not captured by the isothermal approach, but observed for the thermomechanical approach locally at the tool-ply contact areas. Besides this, local recrystallization is observed already during forming. In this study, recrystallized areas result mainly from the initial positioning of the laminate onto the lower (female) tool at the part flanges. This could possibly be prevented by an adapted process strategy. Nevertheless, the simulation results reveal that recrystallization already during forming cannot be excluded in general, especially prior to process optimization, which is expected to be an important finding for the virtual process design.

With an eye towards industry 4.0, the presented approach is considered as a next step in direction of a holistic thermoforming simulation approach, by taking into account temperature- and rate-dependency of the formed material, as well as the phase transition from the molten to the solid state. These material characteristics are usually not yet taken into account for thermoforming simulation. However, the validation of the presented approach has proven to improve the prediction accuracy. Therefore, the capability of thermoforming simulation to be applied to an a priori virtual process design is improved. Nonetheless, the proposed model has some limitations. First, only adapted heat loss in the vicinity of the tools, but no radiative heat transfer between the tool and the laminate is accounted for in thermal modeling. Taking into account this effect might improve thermal modeling, but would require further advanced modeling techniques and a distinctively higher computational effort. Second, no thermal expansion and shrinkage due to crystallization is taken into account so far. These effects are expected to not significantly influence forming behavior itself. However, consideration of these effects would enable the prediction of residual stresses and shape distortions, if recrystallization is occuring already during forming. Third, it is assumed in the presented approach that the free energy of the molten phase fully dissipates during solidification. This approach is expected to be reasonable for formability prediction, since local solidification represents the loss of formability. The free energy of the fibers, however, would most likely influence the prediction of residual stresses and shape distortion. Finally, the solid phase is assumed to behave purely. The consideration of plasticity and damage could be interesting to be investigated for locally solidified areas.

5. REFERENCES

1. F. Henning, L. Kärger, D. Dörr, F. J. Schirmaier, J. Seuffert, and A. Bernath. *Fast processing and continuous simulation of automotive structural composite components*. Composites Science and Technology, (171):261–279, 2019.
2. E. R. Fuchs, F. R. Field, R. Roth, and R. E. Kirchain. *Strategic materials selection in the automobile body: Economic opportunities for polymer composite design*. Composites Science and Technology, 68(9):1989–2002, 2008.
3. M. F. Ashby. *Materials selection in mechanical design*. Elsevier/Butterworth-Heinemann, Amsterdam, 4. edition, 2011.
4. L. Kärger, A. Bernath, F. Fritz, S. Galkin, D. Magagnato, A. Oeckerath, A. Schön, and F. Henning. *Development and validation of a CAE chain for unidirectional fibre reinforced composite components*. Composite Structures, (132):350–358, 2015.
5. K. Friedrich and A. A. Almajid. *Manufacturing Aspects of Advanced Polymer Composites for Automotive Applications*. Applied Composite Materials, 20(2): 107–128, 2013.
6. P. K. Mallick, editor. *Materials, design and manufacturing for lightweight vehicles*. Woodhead Publishing in materials. CRC Press, Boca Raton, 2010.
7. T. Joppich, D. Doerr, L. van der Meulen, T. Link, B. Hangs, F. Henning. *Layup and process dependent wrinkling behavior of PPS/CF UD tape-laminates during nonisothermal press forming into a complex component*. AIP Conference Proceedings 1769: 170011, 2016.
8. P. de Luca, P. Lefébure, A.K. Pickett. *Numerical and experimental investigation of some press forming parameters of two fibre reinforced thermoplastics: APC2-AS4 and PEI-CETEX*. Composites Part A: Applied Science and Manufacturing, 29(1–2): 101–10, 1998.
9. A. Benkaddour, G. Lebrun, L. Laberge-Lebel. *Thermostamping of [0/90] n carbon/peek laminates: influence of support configuration and demolding temperature on part consolidation*. Polymer Composites: 22-42, 1998.
10. S. P. Haanappel, R. ten Thije, U. Sachs, B. Rietman, and R. Akkerman. *Formability analyses of uni-directional and textile reinforced thermoplastics*. Composites Part A: Applied Science and Manufacturing (56): 80–92, 1998.
11. Y. Gong, X. Peng, Y. Yao, Z. Guo. *An anisotropic hyperelastic constitutive model for thermoplastic woven composite prepregs*. Composites Science and Technology (128): 17–24, 2016.
12. P. Harrison, R. Gomes, N. Curado-Correia N. *Press forming a 0/90 cross-ply advanced thermoplastic composite using the double-dome benchmark geometry*. Composites Part A: Applied Science and Manufacturing (54): 56–69, 2013.
13. P. Boisse, N. Hamila, A. Madeo. *The difficulties in modeling the mechanical behavior of textile composite reinforcements with standard continuum mechanics of Cauchy. Some possible remedies*. International Journal of Solids and Structures (154): 55–65. 2016.
14. L. M. Dangora, C. J. Mitchell, J. A. Sherwood. *Predictive model for the detection of out-of-plane defects formed during textile-composite manufacture*. Composites Part A: Applied Science and Manufacturing (78): 102–12, 2015.

15. M. Machado, L. Murenu, M. Fischlschweiger, Z. Major. *Analysis of the thermomechanical shear behaviour of woven-reinforced thermoplastic-matrix composites during forming.* Composites Part A: Applied Science and Manufacturing (86):39–48, 2016.

16. E. Guzman-Maldonado, N. Hamila, N. Naouar, G. Moulin, P. Boisse. *Simulation of thermoplastic prepreg thermoforming based on a visco-hyperelastic model and a thermal homogenization*. Materials & Design (93):431–42, 2016.

17. T.G. Donderwinkel, B. Rietman, S.P. Haanappel, R. Akkerman. *Stamp forming optimization for formability and crystallinity*. AIP Conf Proc 1769: 170029, 2016.

18. S. Ropers. *Bending behavior of thermoplastic composite sheets: viscoelasticity and temperature dependency in the draping process*. AutoUni - Schriftenreihe Vol. 99. Wiesbaden and s.l.: Springer Fachmedien Wiesbaden; 2017.

19. D. Dörr. *Simulation of the thermoforming process of UD fiber-reinforced thermoplastic tape laminate*s, Doctoral thesis, Karlsruhe Institute of Technology (KIT), 2019.

20. D. Dörr, T. Joppich, D. Kugele, F. Henning, L. Kärger: *A coupled thermomechanical approach for finite element forming simulation of continuously fiber-reinforced semi-crystalline thermoplastics*, Composites Part A: Applied Science and Manufacturing (125): 105508, 2019.

21. A. Ziabicki. *Fundamentals of fibre formation: the science of fibre spinning and drawing.* John Wiley & Sons Ltd; 1976.

22. J.D. Sierra, M.d.P. Noriega, J.F. Gómez, J.M. Pastor. *Isothermal and non-isothermal crystallization kinetics for blends of polyamide 6 and polypropylene*. International Journal of Plastics Technology 2(5):1–5, 2006.

23. D. Kugele, D. Dörr, F. Wittemann, B. Hangs, J. Rausch, L. Kärger, et al. *Modeling of the non-isothermal crystallization kinetics of polyamide 6 composites during thermoforming*. AIP Conf Proc. 1869: 030005, 2017.

24. K. Nakamura, T. Watanabe, K. Katayama, T. Amano. *Some aspects of nonisothermal crystallization of polymers. I. Relationship between crystallization temperature, crystallinity, and cooling conditions.* Journal of Applied Polymer Science 16(5):1077–91, 1972.

25. D.P.H. Hasselman, K.Y. Donaldson, J.R. Thomas. *Effective thermal conductivity of uniaxial composite with cylindrically orthotropic carbon fibers and interfacial thermal barrier*. Journal of Composite Materials 27(6):637–44, 1993.

26. D. Kugele, J. Rausch, J. Kriegeseis, K. Gündisch, L. Kärger, F. Henning. *On the thermal behavior of thermoplastic laminates during transfer - a novel wind-tunnel approach*. Proceedings ECCM17, München, Germany.

27. D. Kugele, J. Rausch, P. Müller, L. Kärger, F. Henning. *Temperature distribution in thickness direction of thermoplastic laminates during thermoforming*. Proceedings international conference of automotive composites (IJAUTOC 2016), Lisbon, Portugal.

28. C. Poppe, T. Joppich, D. Dörr, L. Kärger, F. Henning. *Modeling and validation of gripper induced membrane forces in finite element forming simulation of continuously reinforced composites*. AIP Conf Proc 1896: 030002, 2017.