# Development of a Modular Draping Test Bench for Analysis of Infiltrated Woven Fabrics in Wet Compression Molding

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**Keywords:** Wet compression molding (WCM), Textile Testing, Viscous Draping, Forming, Woven Fabrics

**Abstract.** The wet compression molding (WCM) process enables short cycle times for production of fiber-reinforced plastics due to simultaneous infiltration, viscous draping and consolidation in one process step. This requires a comprehensive knowledge of occurring mutual dependencies in particular for the development of process simulation methods and for process optimization. In this context, it is necessary to develop suitable test benches to enable an evaluation of the outlined viscous draping behavior. In order to evaluate and suitably design the draping process, grippers are mounted on a surrounding frame, which enables targeted restraining of the local material draw-in during forming. In supporting the development of the new test bench, first experimental and simulation results are compared, which thereby enables a first validation of the simulation approaches. Results show a good agreement between experimental and numerical results in terms of shear deformation and final gripper displacement under dry and viscous conditions. Results recommend that future development for investigations of viscous draping effects should focus an enabling measurement of gripper displacement during the forming process. Beyond that, the modular test bench design enables experimental and virtual draping optimization and deduction of blank holder concepts for WCM tools.

## Introduction and State of the Art

The WCM process is a promising option for the serial production of fiber-reinforced plastics with a thermoset matrix [1-3]. the WCM process with simultaneous fiber forming and press process (4), starting from cutting and stacking of the fibers (1) to the demolding of the final part (5).

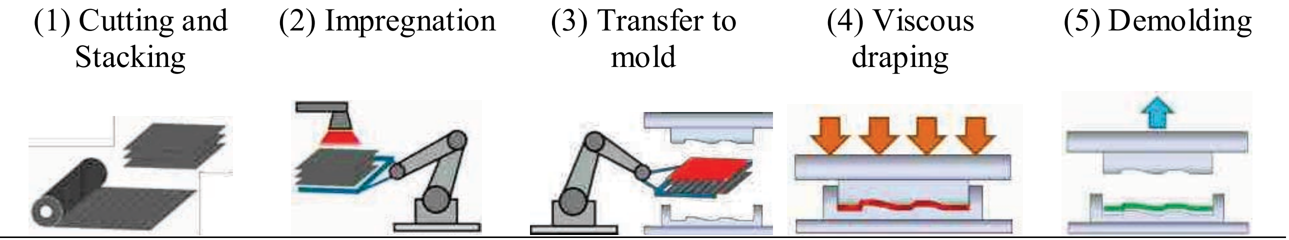


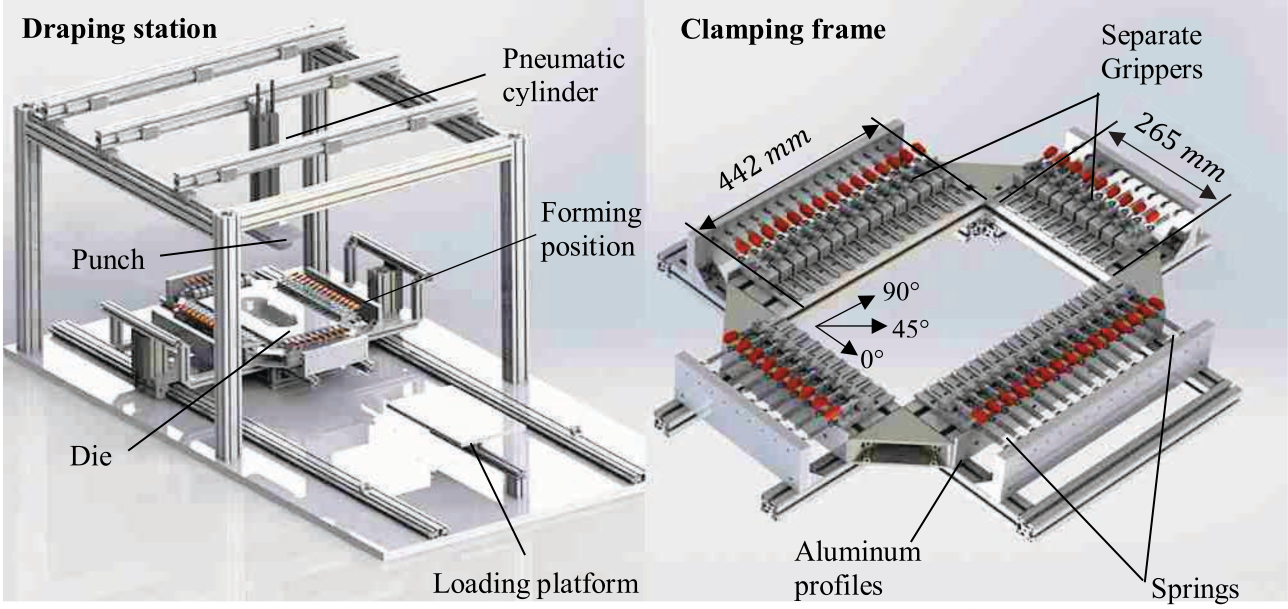
Figure 1: Schematic process steps of the Wet Compression Molding process (according to [4, 5]).

In contrast to the widely used Resin Transfer Molding (RTM) process, in which the pre-shaped dry preform is impregnated inside the press during an injection step, the impregnation in the WCM process takes place outside of the press (2). After the transport (3), the dry two-dimensional layers are formed into the three-dimensional part geometry in the actual press step (4). The forming of the textile thus takes place in an impregnated state (viscous draping). The number of publications in the

field of WCM process is currently low. Previous investigations mainly evaluate the influence of process parameters on the finished part. Interrelations between process boundary conditions and surface characteristics (e.g. folds and dry spots) [2], the difference between varied designs of wall thickness transitions [3] as well as the influence of closing speed, resin temperature and infiltration time on resin expansion within a cavity [6] are investigated. Beyond that, Heudorfer et al. [7] show an influence of resin amount and infiltration time on the mechanical performance of the final parts. Similar to the geometry in the present study, Kahn et al. [8] developed an experimental Double Dome forming tool to validate their numerical forming simulation approach. First investigations on dependencies of the infiltration state show differences between dry and wet interlaminar friction [4]. The impact of infiltration on the shear behavior of infiltrated woven fabrics is demonstrated by Poppe et al. [5] by means of a modified bias extension test (IBET). Beyond that, FE-based forming simulations are performed to access the process relevance of infiltration-dependent shear behavior. The predicted numerical results indicate an important impact of the infiltration on the shear angle distribution during draping. However, the interactions resulting from a wet forming process have not yet been researched experimentally. In order to evaluate and suitably design the draping process in the infiltrated and dry state, 48 grippers are mounted on a surrounding frame (clamping frame) which in turn enables introducing and possible recording of the restraining local material draw-in while forming. Moreover, the new test bench facilitates a suitable validation of the viscous forming behavior for the development of process simulation methods [5,9].
In this study, first viscous forming tests are performed with the clamping frame, which so far enables determination of the final material draw-in. Additionally, an optical evaluation method is presented to determine the local shear angle after forming. Subsequently, a first validation of the numerical model published by Poppe et al. [5] is presented, which indicates further promising enhancements for the new test bench. Prospectively, the test bench's modular design enables performance assessments of different blank holder concepts for optimization of forming results. These identified concepts can in turn be used to develop clamping concepts for press tools on a large series scale.

## Experimental Set-Up and Trial Execution

**Test bench set-up.** For this study, a modular draping station as seen in Figure 2 (a) is developed. This draping station consists of an aluminum table and a base frame. On the table, the developed clamping frame can be transferred between the 'forming' position under the base frame and the 'loading' platform outside the base frame. The clamping frame is shown in Figure 2 (b). It contains 48 grippers arranged in a rectangle, on separate slide rails.

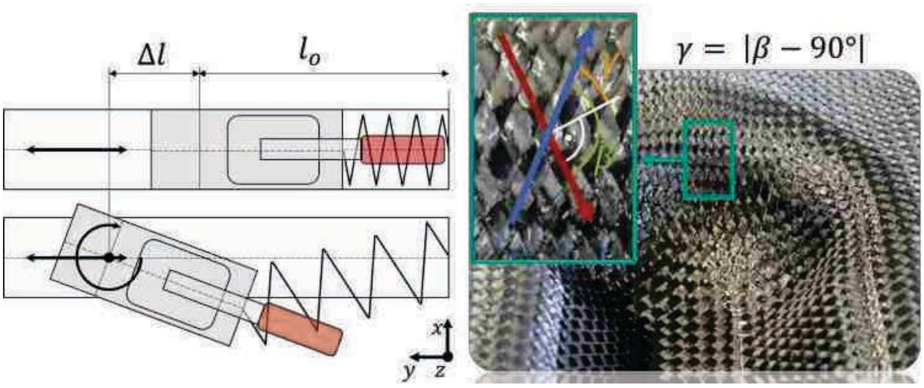


(a) (b)

Figure 2: Modular draping station (a) and clamping frame including 48 separate grippers (b).

The design of the grippers enables slight vertical rotation. The kinematic of the grippers is shown in Figure 3 (a). The restraining forces of the grippers are induced by exchangeable springs. A generic Double Dome geometry is used in this study. For the movement of the punch, a pneumatic cylinder from Festo AG & Co. KG is used. The pneumatic cylinder is connected to the punch via an adapter plate and mounted on the recirculating linear rail guide of a traverse via an aluminium profile. The stroke of 400 mm enables good accessibility to the clamping frame in the forming position.

**Material and trial execution.** The study examined a carbon fiber plain woven fabric with a filament yarn consisting of T700-12K-50C Toray fibers and a basis weight of $300\ \pm (10)\ g/mm^2$ from Sigmatex (GB). The roving width is $5.0\ \pm 0.5\ mm$ with initial spaces of $2.0\ \pm 0.3\ mm$. The semi-finished fiber product, which is supplied as a fiber roll, was cut to match the clamping frame dimensions ($770\ \times\ 570\ mm2$) and the desired fiber orientation (± 45°). After cutting, one ply is fixed in the clamping frame in 'loading' position. The clamping frame is then moved into the tool ('forming' position). Once in 'forming' position, silicone oil of defined viscosity is applied for fabric infiltration. After 30 seconds infiltration time, the punch is pneumatically actuated. As soon as the punch has completely formed the fabric, the traversed distance $\Delta l$ (fiber feed, cf. Figure 3 (left)) of the individual grippers is recorded. Before punch retraction, the grippers are opened to avoid inadmissible spring-back of the textile. Validation of the forming result is based on the measured fiber feed $\Delta l$ and on optical investigation of the forming results (shear angle). For this purpose, a camera system is installed for photographic documentation of the fabric deformation state. Since the Double Dome is a double-symmetric geometry, camera shots are taken from only one side. An evaluation region is defined which covers the zone of highest shear deformation (cf. Figure 3 (right)). From this region, shear angles are extracted at 15 positions using an in-house written Matlab© tool. To account for the perspective distortion, a geometric correction factor is used for post-processing.
For the execution of the wet forming trials, three different infiltration states are investigated. In addition to the dry state, silicone oils with viscosities of $20\ mPas$ and $250\ mPa$s are used as resin replacement systems [4, 5]. To evaluate the effect of the retention forces, two different spring configurations are applied during the test. In the first constellation, weak springs with a stiffness of $R_{\text{weak}} = 0.016\ N/mm$ are applied at all 48 gripper positions. The second configuration makes use of stronger springs $R_{\text{strong}} = 0.48\ N/mm$ at all 48 grippers. As initial fiber orientation of the fabric ± 45° is used. The penetration speed (approx. $60\ mm/s$), the penetration force of the punch ($454\ N$) as well as the quantity of the resin replacement medium ($60\ ml$) are kept constant. In order to increase the statistical significance, each trial is repeated three times.



(a) (b)

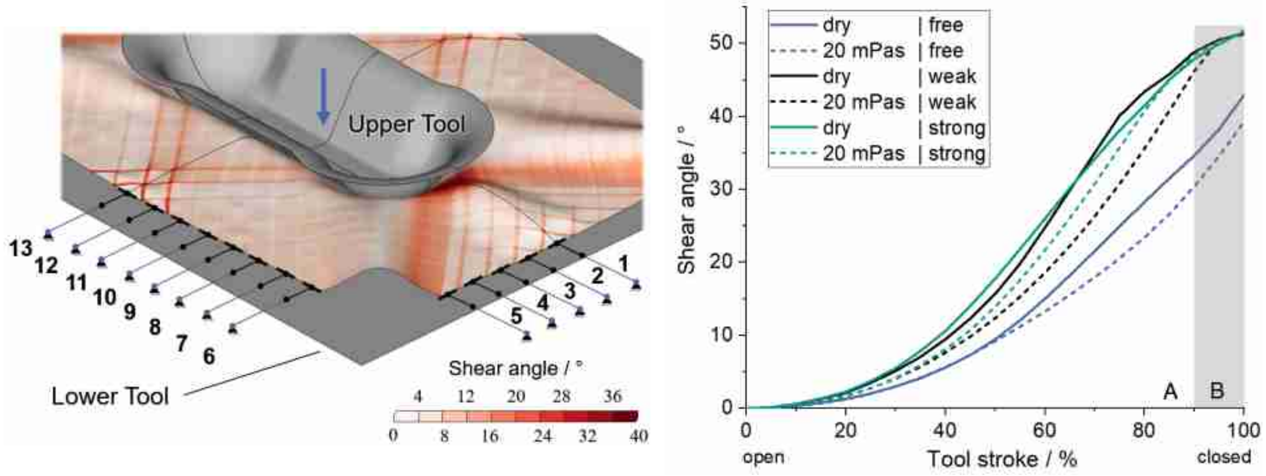
Figure 3: Gripper kinematic and determination of the traverse position $\Delta l$ (a) and determination of the resulting shear angle $\gamma$ (b).

## Numerical Part.

In the following, the applied macroscopic FE forming simulation approach is presented along with the virtual representation of the above outlined test bench including the Double Dome geometry and the modular clamping frame.

**Numerical model**. FE forming simulation is based on constitutive modelling of the relevant interactions during forming. The forming mechanisms are normally categorized according to intra-ply and interface mechanisms [10]. Intra-ply mechanisms, namely membrane and bending behavior, are implemented by means of user subroutines within the commercially available FE solver ABAQUS. Membrane behavior is accounted for by a hyperviscoelastic material model parametrized with dry and infiltrated specimens via a modified (infiltrated) bias extension test (IBET) [5]. Furthermore, bending behavior is implemented by means of a hypoviscoelastic constitutive model, which properly accounts for fiber reorientation during forming [10]. To model the decoupled membrane and bending behavior, superimposed membrane and shell elements are applied to represent the single layer of the stacked laminate. An ABAQUS built-in contact formulation is used to account for the interface mechanisms between tool and ply. Constitutive models for intra-ply behavior in this study are parametrized for the applied material as used in the experiment including the same viscosities for the fluid. A constant coefficient of friction $\boldsymbol{\mu = 0.2}$ is implemented for all simulations [4].

**Simulation setup**. A virtual representation of the above outlined test bench (cf. Figure 2) in conjunction with the introduced numerical model according to Figure 4 (a) is set up and applied in the following. Forming simulations with single plies are conducted with and without grippers. Whereas the tools are modelled as rigid surfaces, grippers are implemented by means of suitable combinations of kinematic constrains, springs (blue lines) and boundary conditions according to Figure 3 (a) and Figure 4 (a). Friction of the sleds is neglected in this first simulation approach. A constant closing speed of 60 $mm/s$ is applied to the upper tool by means of a linear displacement boundary condition. Gravity is taken into account. An explicit time integration schema is used to handle the large contact areas between tool and ply. Springs with equal stiffness are used in this first approach for all grippers. Exploiting the double-symmetry (geometry, grippers and fabric orientation), only a quarter model is implemented.



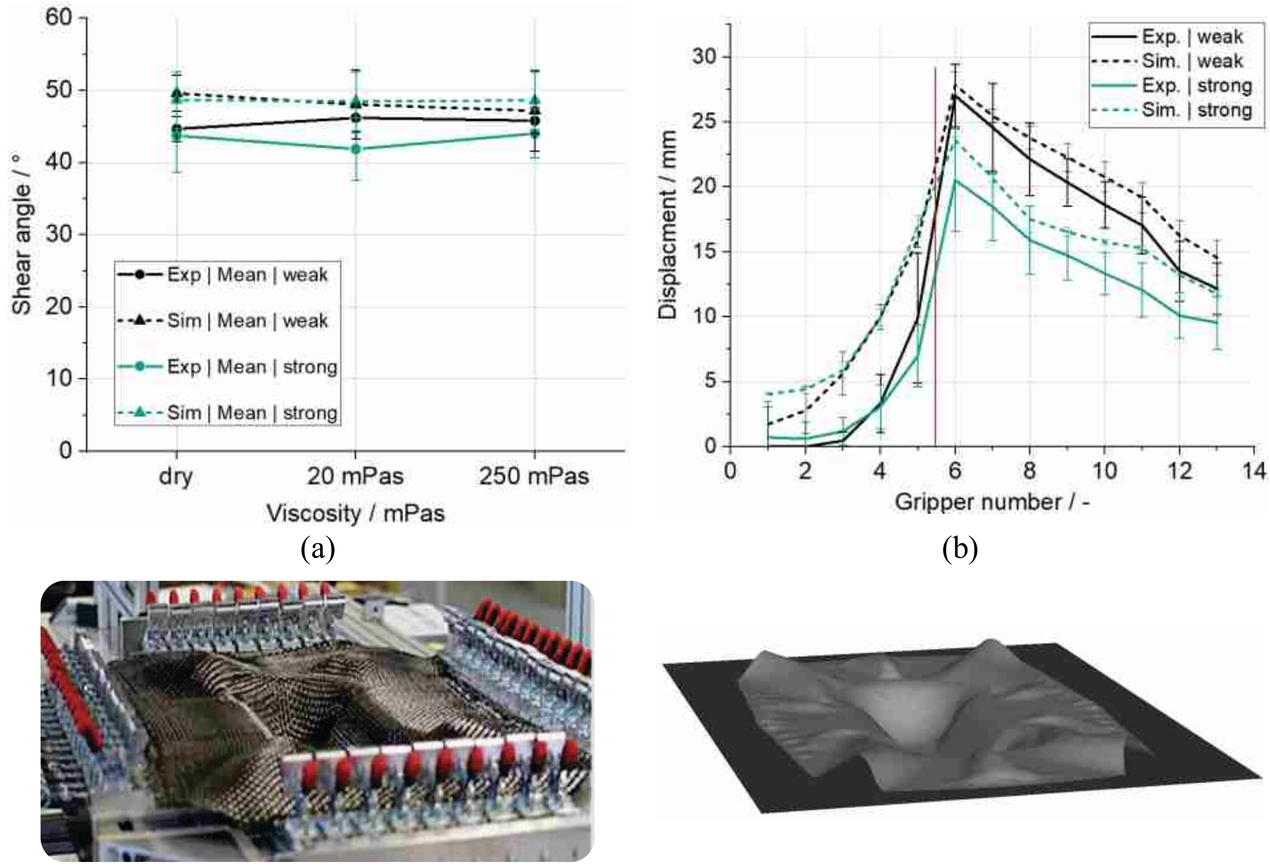
(a) (b)

Figure 4: (a) Simulation model in ABAQUS comprising numbered gripper positions; (b) Simulation results: averaged shear angles in evaluation zone (cf. Fig. 3 (b)) during single ply forming simulations for three gripper configurations (free, weak springs, strong springs) and two infiltration states (dry, 20mPas) with initial fiber orientation of ±45 degree.

The numerical studies reveal that the effect of viscosity mainly concerns the shear angle distribution during forming, indicated by Region A in Figure 4 (b). The numerical setup without grippers (free), predicts an impact of viscosity on the shear angle distribution, even for the final shape (Region B). In contrast to that, numerical setups with grippers limit the impact to Region A. This seems reasonable in this case, since the final shape of the ply is almost only kinematically constrained, when grippers are present within the simulation. Therefore, in the course of test bench development, the final shape (Region B) enables a first evaluation of the overall design idea by comparison of experimental results among one another and between experimental and simulation results to validate the simulation approach.

## Comparison and Discussion of Experimental and Numerical Results

Direct comparison of the experimental gripper displacements among the four symmetric zones of the test bench prove reliability of the measured data. Thus, the experimental results are averaged with regard to the double symmetric setup. Furthermore, the experimental results show that the impact of infiltration on the final deformation state (cf. Region B, Figure 4 (b)) is negligible compared to the uncertainty of the measured shear angles (cf. Figure 5 (a)) similar to the prediction of the numerical model. Moreover, the comparison of the maximal measured shear angles within the evaluated main deformation zone provides a good agreement between experiment and simulation. Again, simulation provides systematically higher values. For improved clarity, values of all viscosities are averaged within Figure 5 (b), where a comparison between the experimental and numerical results regarding the final gripper displacements is presented. Whereas the overall displacement profile shows a good agreement, simulation results are systematically higher than the experimental values. A systematic deviation is introduced by increasing gripper tensions, comparably predicted by experiment and simulation. Furthermore, potential friction within the sleds could locally increase the gripper forces during the experiments, thus experimental displacements are systematically lower.



(a)

(b)

(c)

(d)

Figure 5: Comparison between experimental and numerical results of the formed woven fabric with initial fibre orientation of ±45 degree; (a) Impact of viscosity on the final average shear angle (Region B); (b) Differences regarding the final gripper displacement profile for both spring stiffness's; (c,d) Comparison: experimental and numerical result of the overall shape.

Finally, the overall shape of the deformed parts in both experiment and simulation are comparable according to Figure 5 (c, d). The outlined differences between experiment and simulation mainly origin from two effects. First, mesoscopic draping effects, namely relative slippage and wrinkling of the rovings, are observed to some degree during the experiments, but cannot be accounted for by the macroscopic approach. Second, friction within the sleds, which leads to increased gripper tensions, is neglected in the simulation. This leads to the prediction of increased local deformations (e.g. shear angles) compared to the experiments.

## Conclusion and Outlook

The present work introduces a modular draping test bench, which enables targeted restraining of the local material draw-in due to grippers mounted on a surrounding frame in wet compression molding (WCM). Initial experimental tests with dry and infiltrated woven fabrics prove reliability of the overall design. Moreover, first virtual tests are in good agreement with the experimental results. However, to enable a deeper investigation of the viscous draping behavior, further improvements have to be implemented, in particular inline measurement of the gripper displacements during forming and differently distributed stiffness of the gripper springs. Consequently, viscous forming behavior can be investigated along with the development and comparison of different blank holder systems and tool concepts in the near future. Beyond that, the modular design enables directed optimization and manipulation of different blank holder systems for single- and multi-ply configurations, which will also be in scope of future efforts.

## Acknowledgment

The authors thank the German State Ministry for Science, Research and Art of Baden-Württemberg (MWK) for the funding of the project *Forschungsbrücke KIT – University Stuttgart,* for which the presented work is carried out. Additionally, the authors would like to thank their project partners at Stuttgart University, Institute for Aircraft Design (IFB) under leadership of Prof. Middendorf for the collaboration. The work is also part of the Young Investigator Group (YIG) "Tailored Composite Materials for Lightweight Vehicles", generously funded by the Vector Stiftung.

## References

[1] Henning F, Kärger L, Dörr D, Schirmaier F J, Seuffert J, Bernath A: Fast processing and continuous simulation of automotive structural composite components, Composites Science and Technology 171: 261-279, 2019.
[2] Bergmann J, Dörmann H, Lange R: Interpreting process data of wet pressing process. Part 1: Theoretical approach, Part 2: Verication with real values. Journal of Composite Materials 50 (17): 2399-2407 & 2409-2419, 2016.
[3] Stanglmaier, S. J.: Empirische Charakterisierung und Modellierung des Imprägnierprozesses lokal verstärkter Kohlenstofffaserhalbzeuge im RTM- und Nasspress-Verfahren für die Großserie. Karlsruhe, Karlsruher Institut für Technologie (KIT). Dissertation. 2017.
[4] Hüttl, J., Poppe, C., Albrecht, F., Lorenz, F., Thoma, B., Kärger, L., Middendorf P., Henning, F., "Investigations on friction behaviour and forming simulation of plain woven fabrics for wet compression moulding", conference contribution, Proceedings SAMPE Europe, Stuttgart, Germany (2017)
[5] Poppe, C., Dörr, D., Henning, F., Kärger, L.: Experimental and numerical investigation of the shear behavior of infiltrated woven fabrics, Composite Part A, Vol 14, 327 -337, 2018 https://doi.org/10.1016/j.compositesa.2018.08.018
[6] Bockelmann, P.: Process Control in Compression Molding of Composites. München, Technische Universität München, Fakultät für Maschinenwesen, Lehrstuhl für Carbon Composites. Dissertation. 2017.
[7] Heudorfer, K., Carosella, C., Middendorf, P.: Compression Wet Moulding as alternative to RTM. 25. Stuttgarter Kunststoffkolloquium, Germany (2017)
[8] Khan, M. A., Mabrouki, T.; Vidal-Sallé, E., Boisse, P.: Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark. In: Journal of Materials Processing Technology 210 (2010), Nr. 2, S. 378–388
[9] Poppe C, Dominik D, Kärger L, Henning F, "A 2D modeling approach for fluid propagation during FE-forming simulation of continuously reinforced composites in wet compression molding" Proceedings of the ESAFORM2018, Palermo/Italy, 2018 10.1063/1.5034823
[10] Dörr, D., Schirmaier, F., Henning, F., Kärger, L., "A viscoelastic approach for modeling bending behavior in finite element forming simulation of continuously fiber reinforced composites", Composites Part A, Vol. 94, pp. 113-123 doi:10.1016/j.compositesa.2016.11.027 (2017)

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doi: 10.5445/IR/1000098668

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2019. Key engineering materials, 809, 35–40.
doi:10.4028/www.scientific.net/KEM.809.35