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Development of Characterization and Simulation Methods for Carbon Fiber Sheet Molding Compounds

Leibniz-Institut für Verbundwerkstoffe

D. Schommer, M. Duhovic, T. Hoffmann, F. Gortner, D. May, J. Hausmann, P. Mitschang, K. Schladitz, K. Steiner

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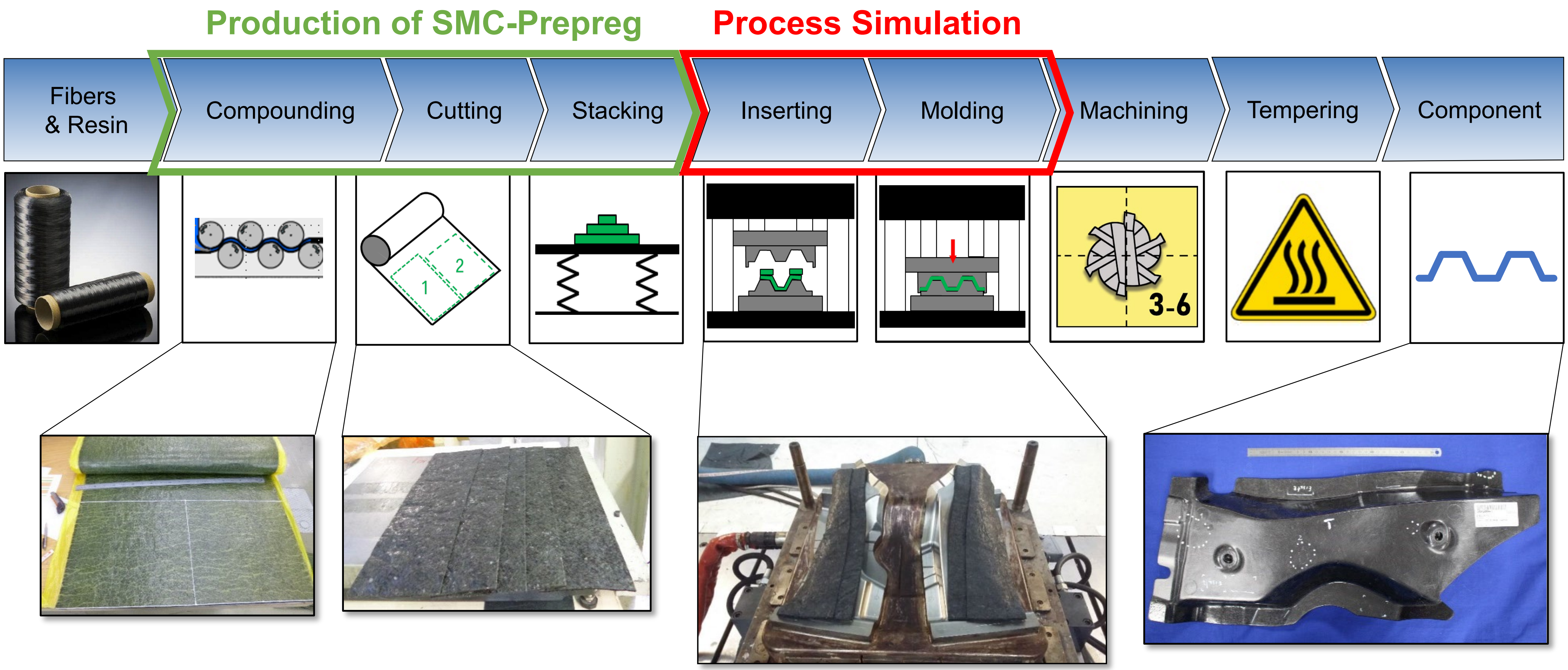
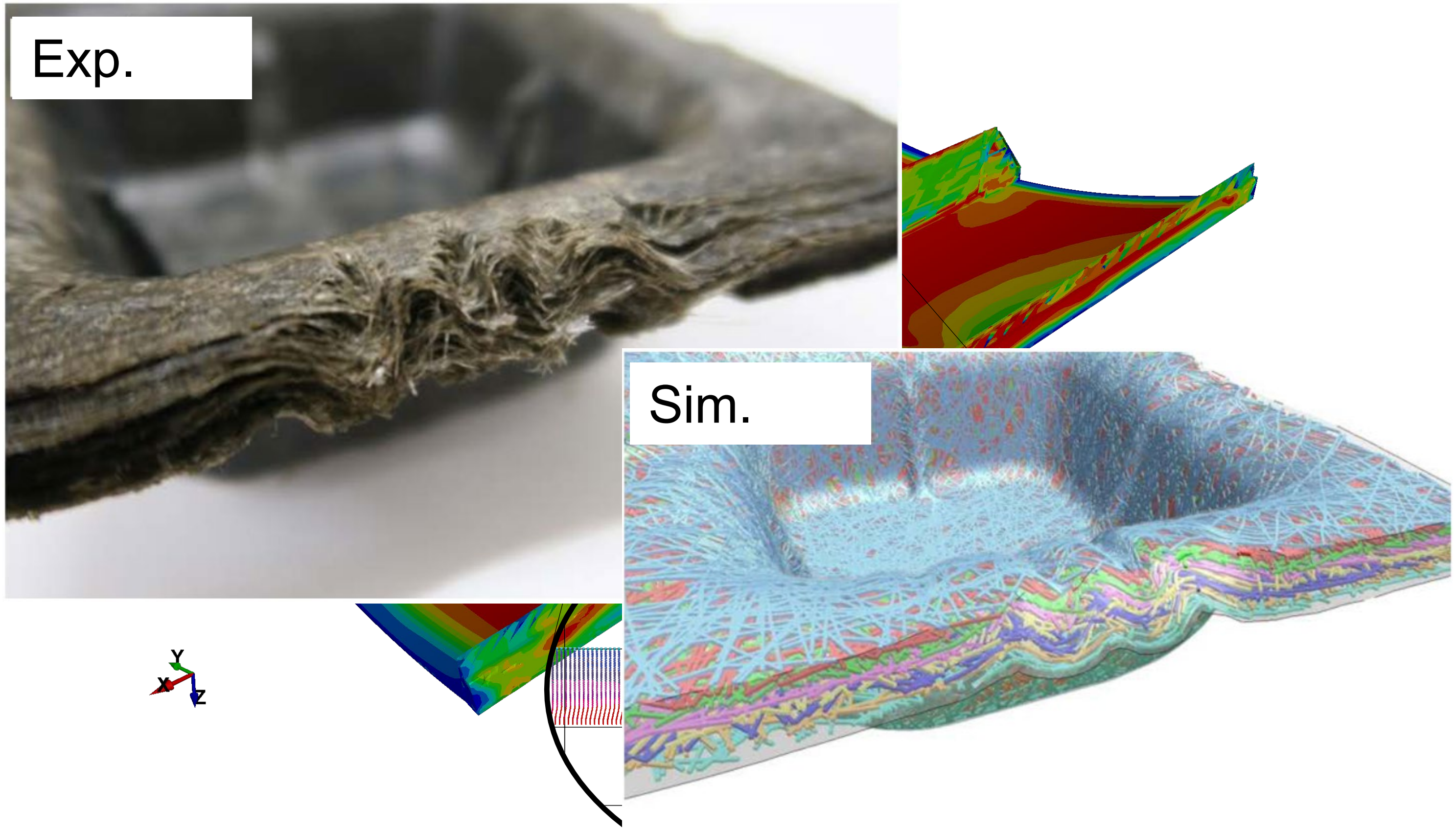
Process Chain for Sheet Molding Compounds



Romanenko V, Duhovic M, et al. Advanced process simulation of compression molded carbon fiber sheet molding compound (C-SMC) parts in automotive series applications. Compos Part A Appl Sci Manuf 2022;157:106924. https://doi.org/10.1016/j.compositesa.2022.106924.

Process Simulation of Compression Molding



Goal: Prediction of fiber orientation

- Flow/filling behavior
- Manufacturing defects/failure behavior
- Warpage
- Structural behavior

Solutions:

- Continuum mechanics material models
- Direct fiber simulation

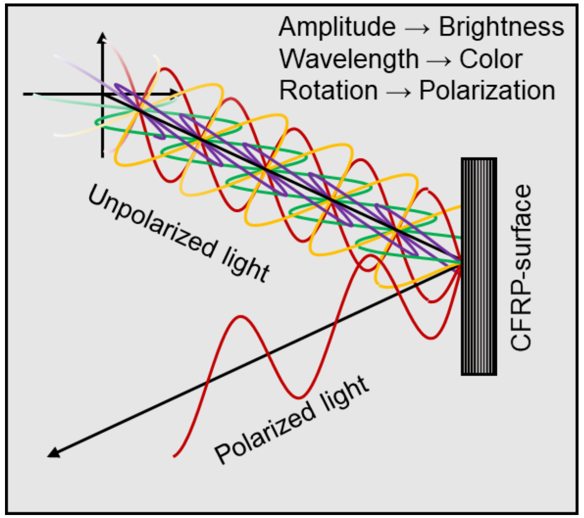
Similarities:

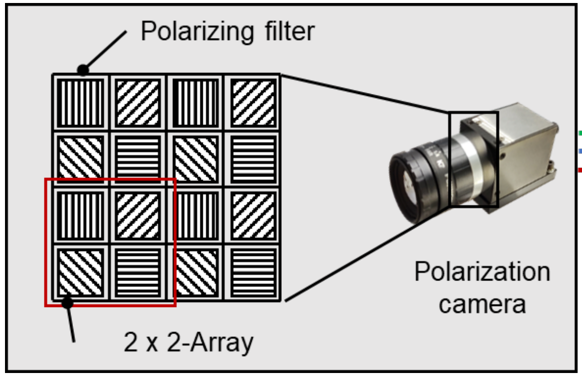
- Initial fiber orientation influences process simulation result!

Hayashi S, Chen H, Hu W. Development of New Simulation Technology for Compression Molding of Long Fiber Reinforced Plastics using LS-DYNA®. 15th International LS-DYNA® Users Conference https://www.dynalook.com/conferences/15th-international-ls-dyna-conference/composites/development-of-new-simulation-technology-for-compression-molding-of-long-fiber-reinforced-plastics-using-ls-dyna-r

Fiber orientation: Semi-finished product

Carbon fibers polarize ambient light!



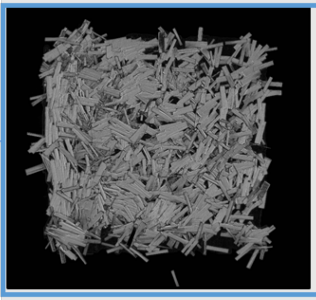


Components

Complex example: random chopped fibers

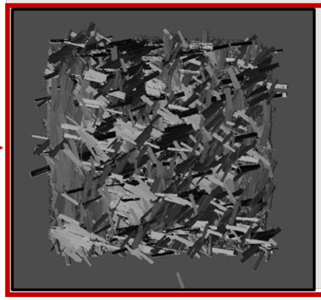
- Intensity

0 Color brightness → 255



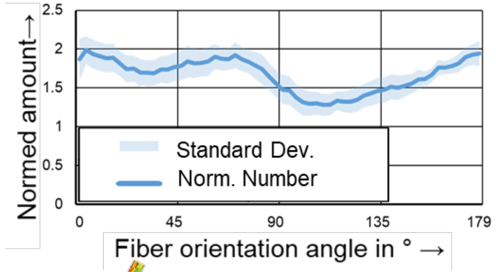
- DOLP (Degree of Linear Polarization)

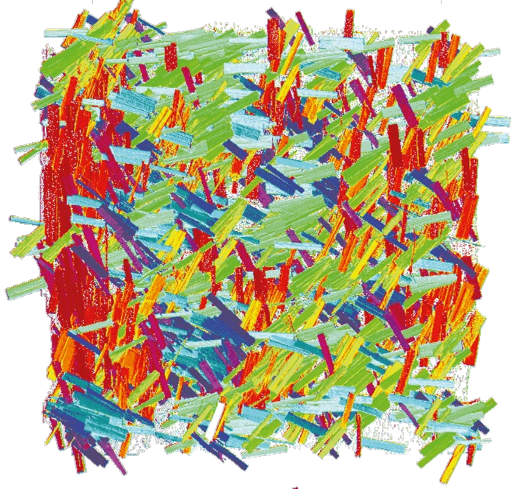
0 DOLP → 1



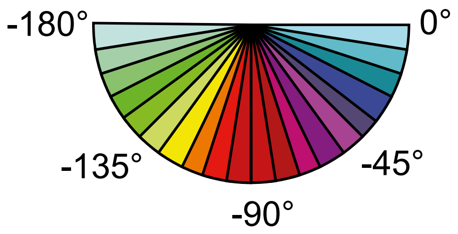
- AOP (Angle of Polarization)

0 AOP in ° → 179





Fiber Orientation Angle



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In-Situ Measurement of Fiber Orientation

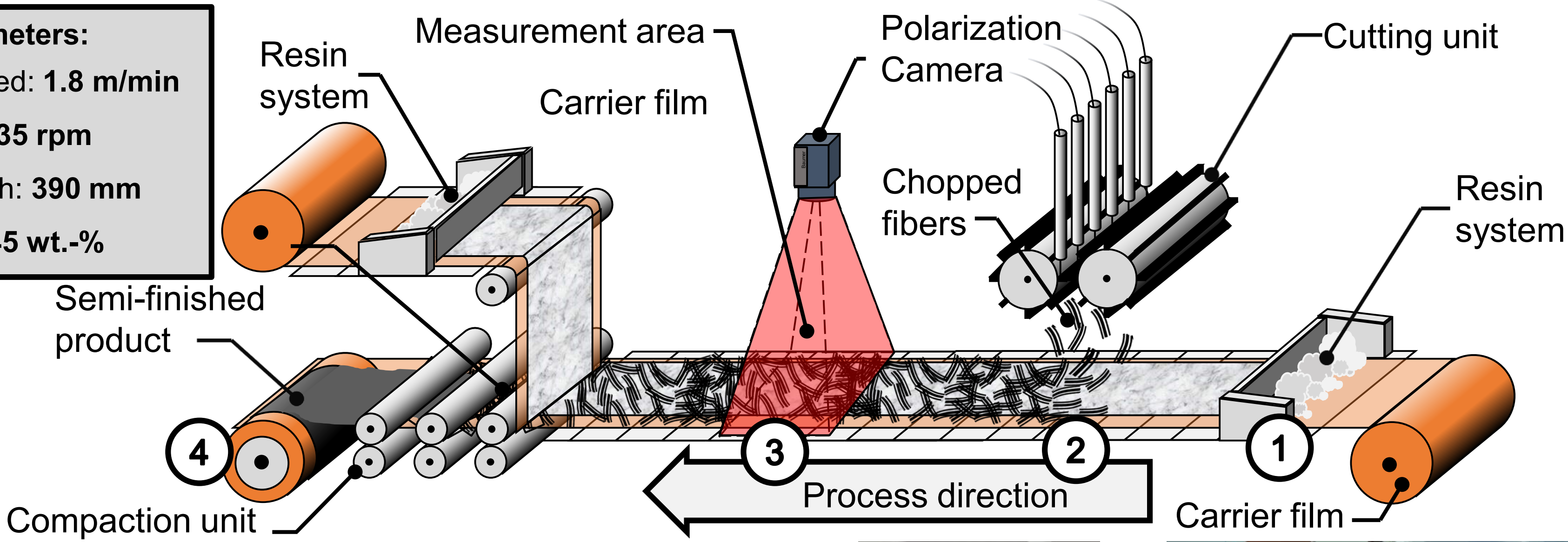
Process parameters:

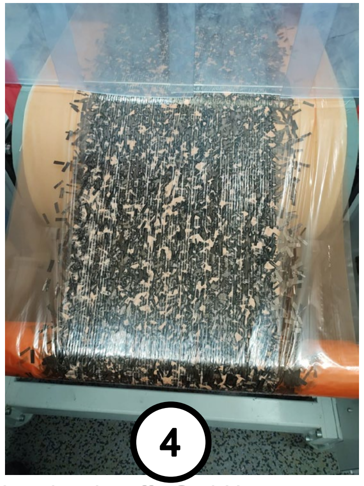
Production speed: **1.8 m/min**

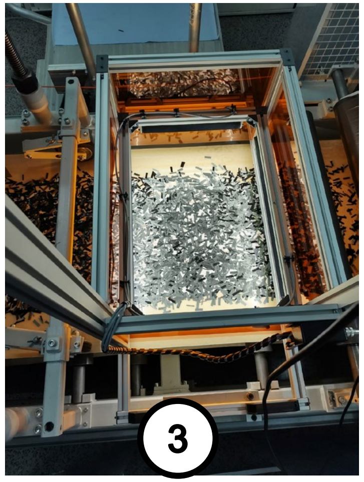
Cutting speed: **35 rpm**

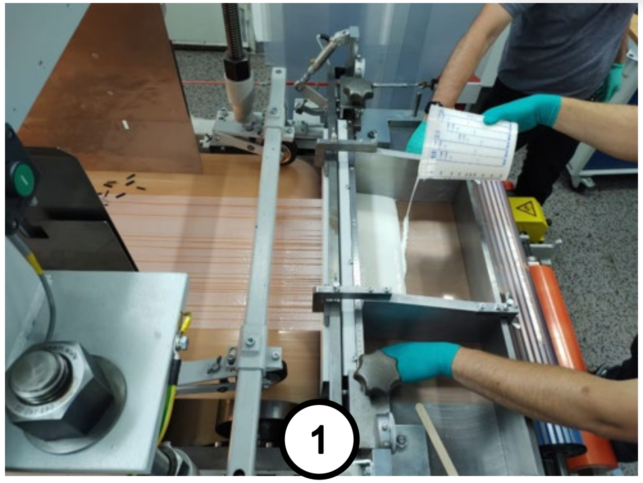
Production width: **390 mm**

Fiber content: **45 wt.-%**









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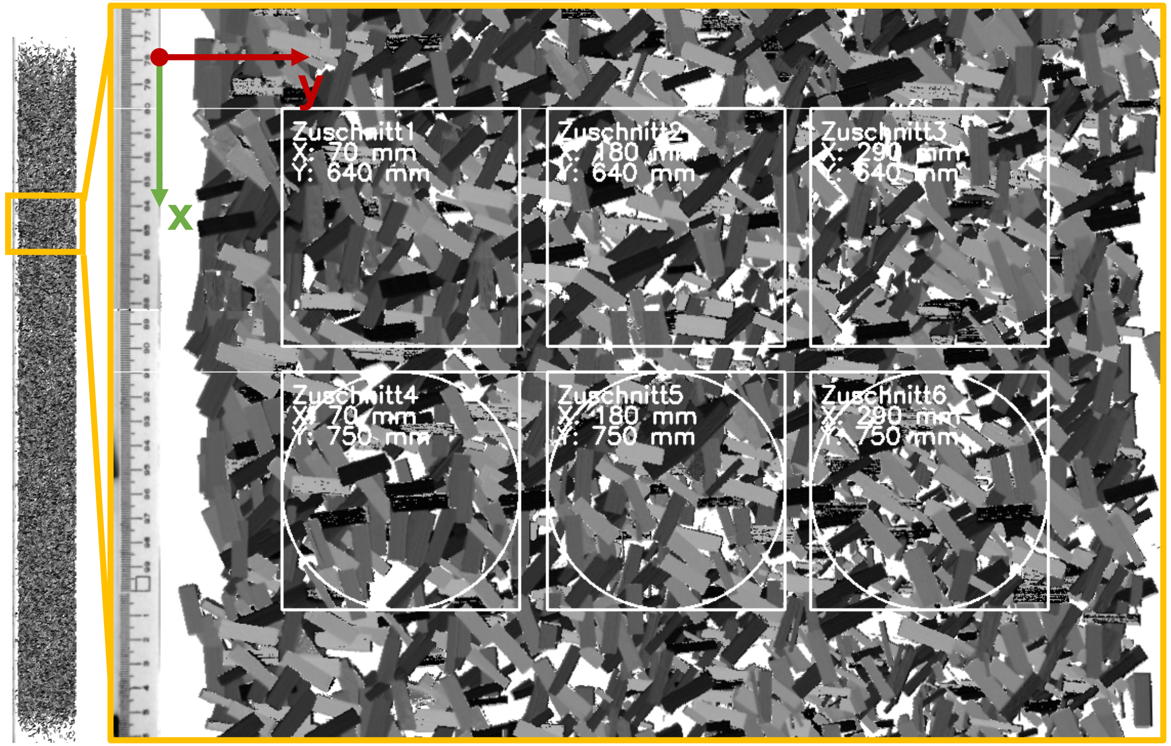
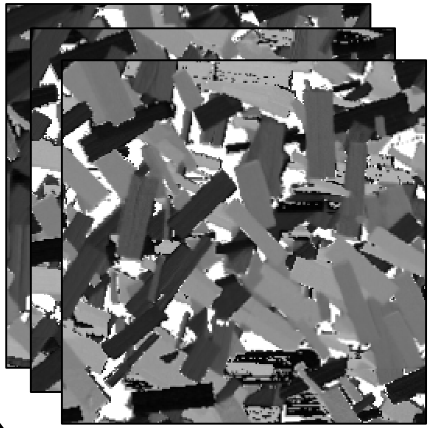
In-Situ Measurement of Fiber Orientation

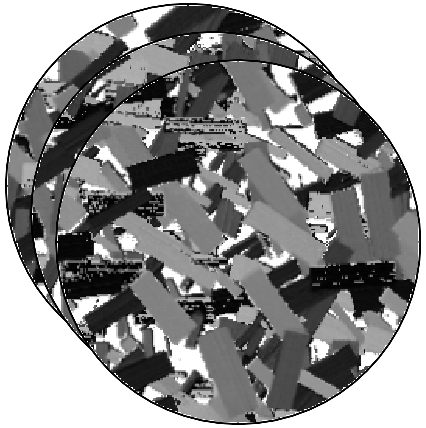
Digital semi-finished product

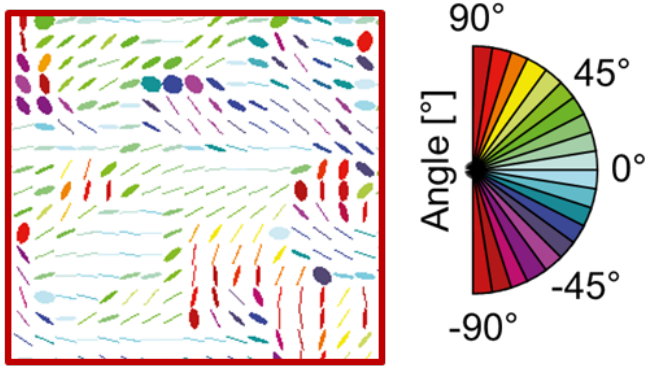
Cutting plan



Digital cut-outs

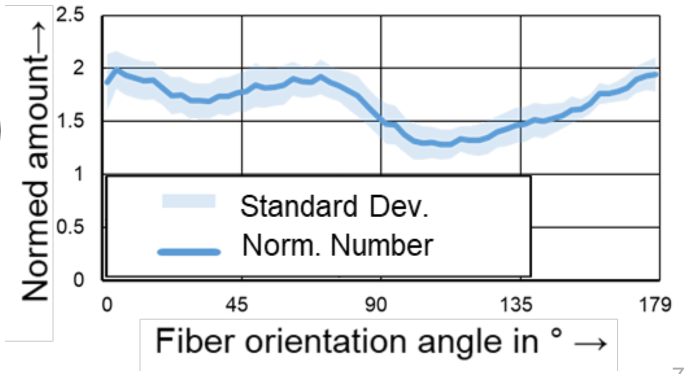






Fiber Orientation Tensors as .csv

Fiber Orientation Angles as .csv



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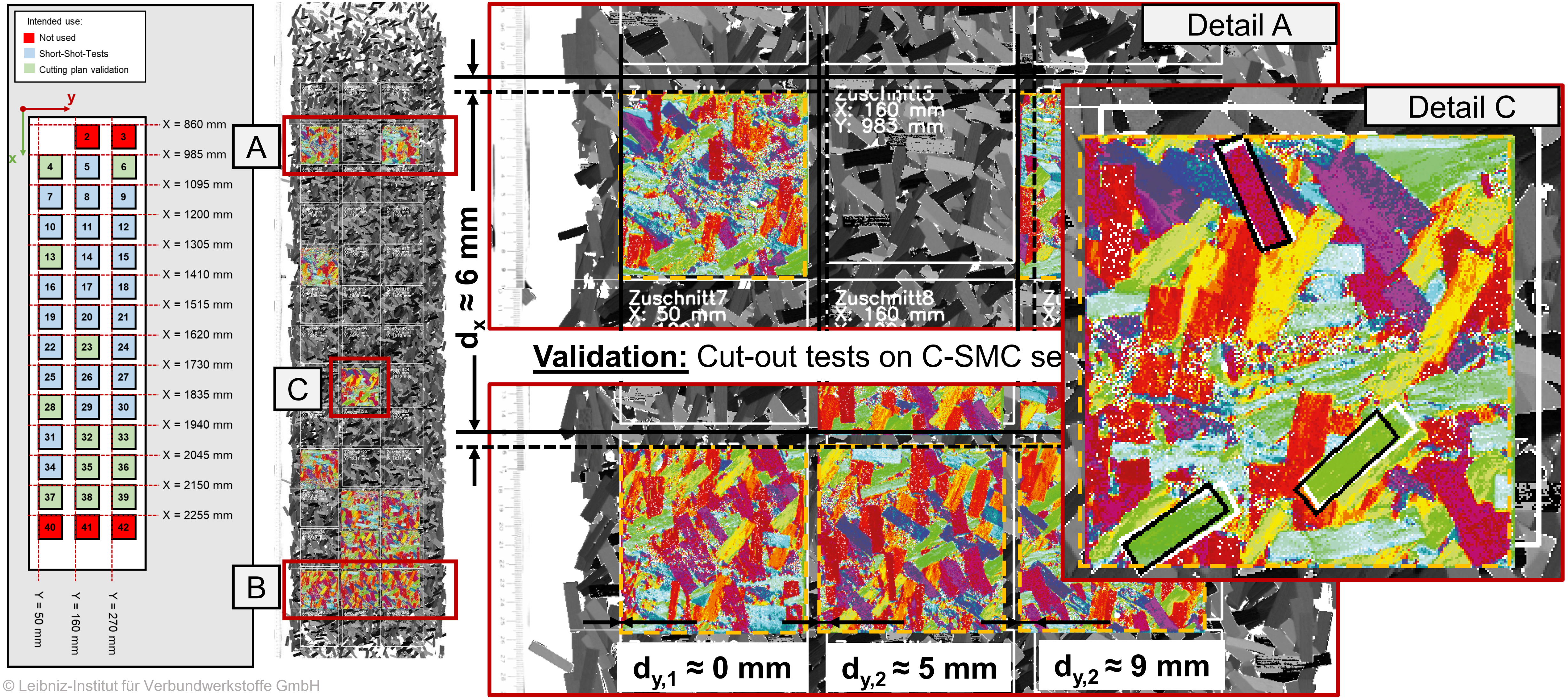
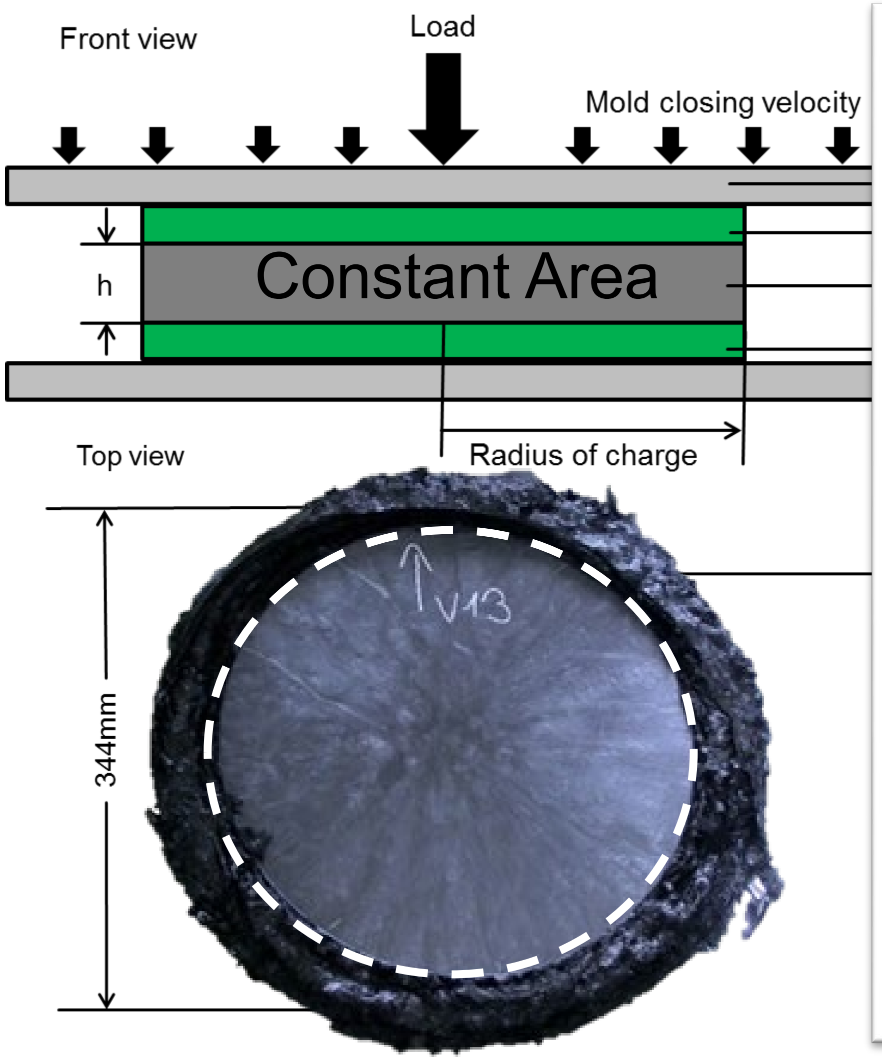
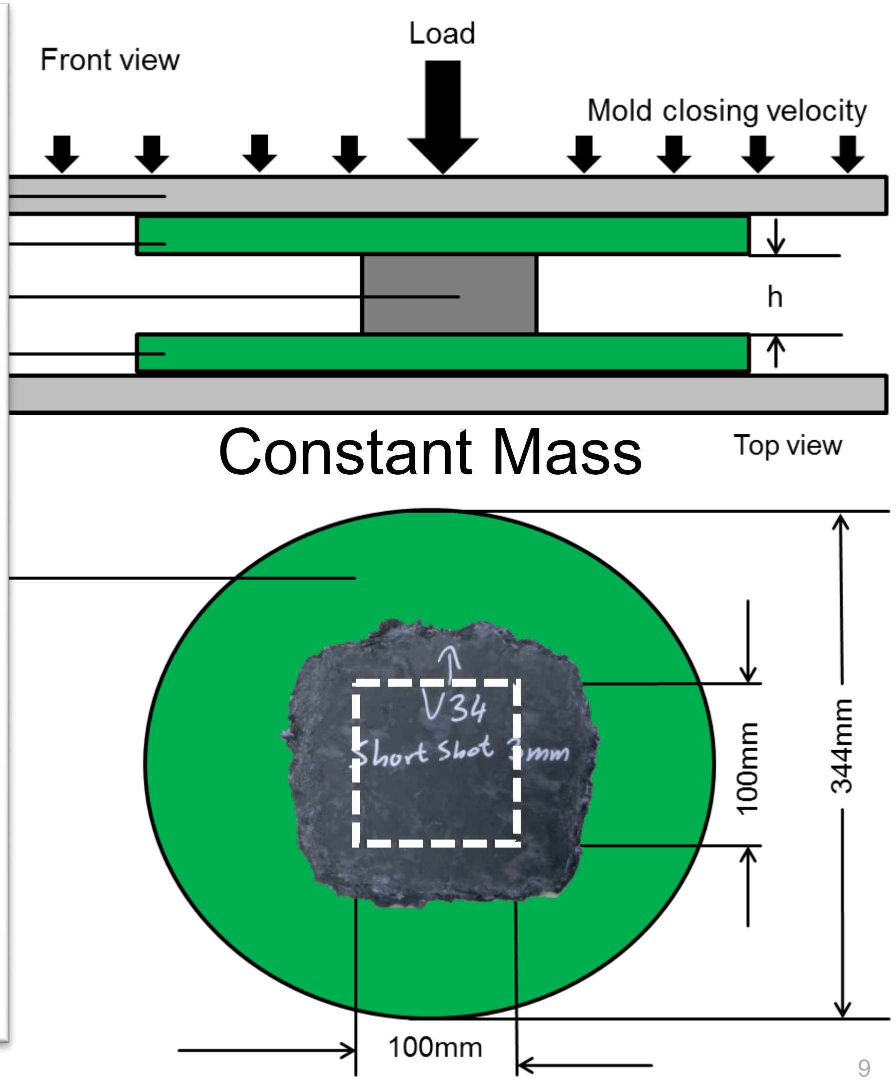
In-Situ Measurement of Fiber Orientation

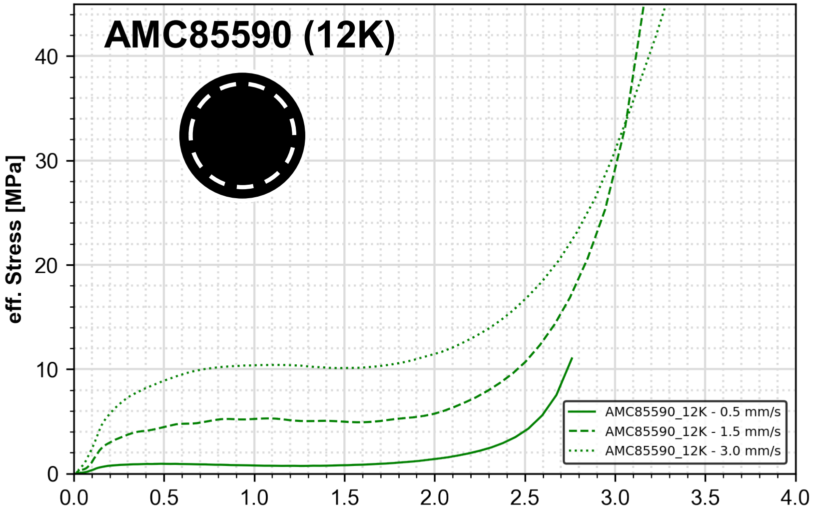


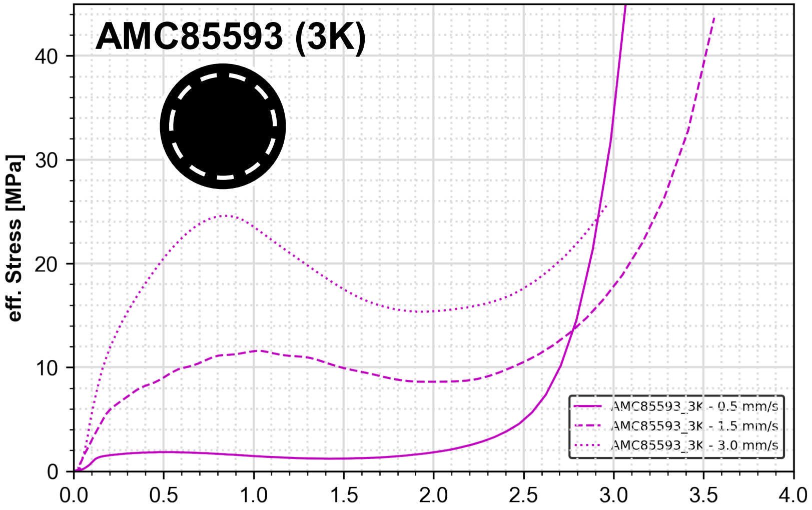
Flow/filling characterization





Flow/filling characterization: Constant area



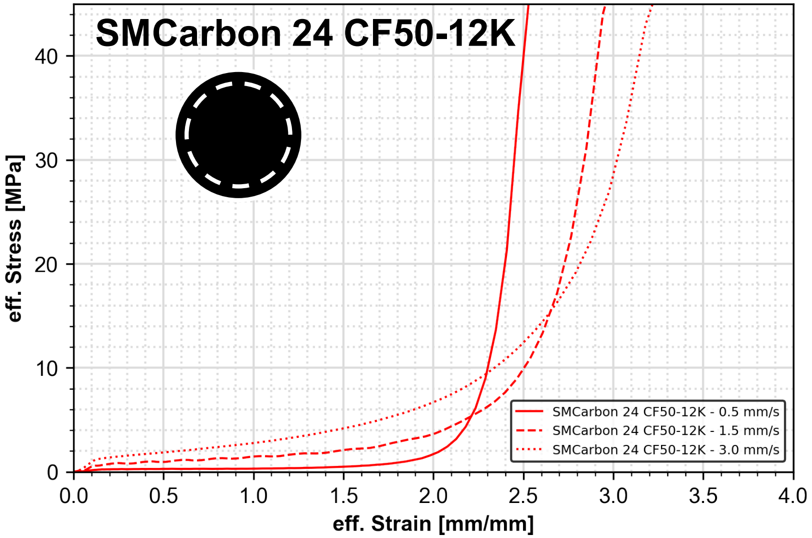


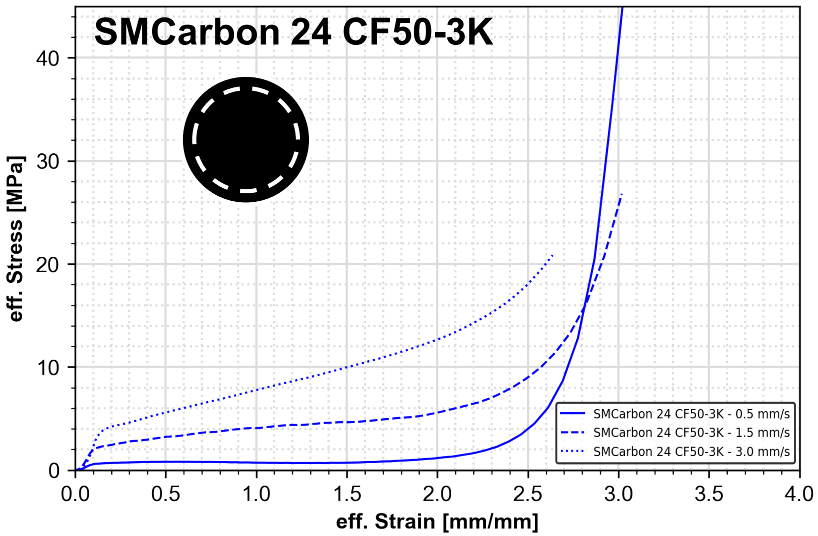
Differences:

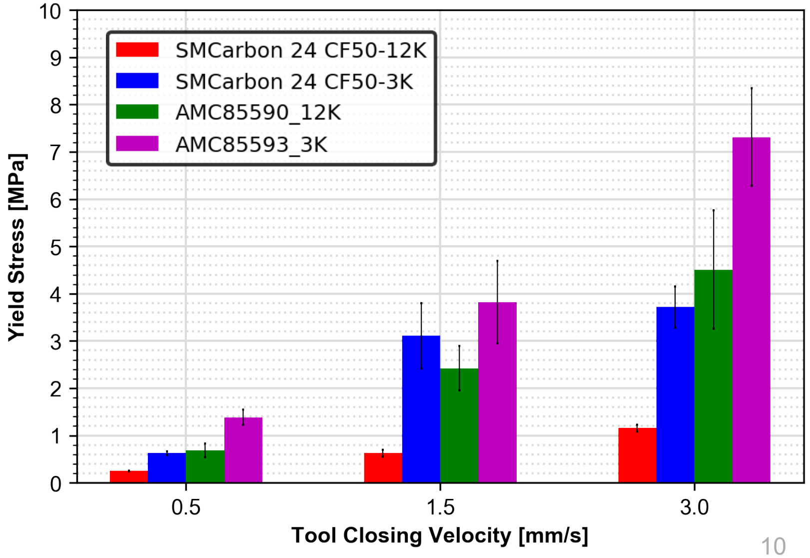
- Two manufacturers (Quantum, Polynt)
- 12K und 3K filaments

Similarities:

- Vinylester based
- Fiber content approx. 50 wt%
- Fiber length: 1 inch

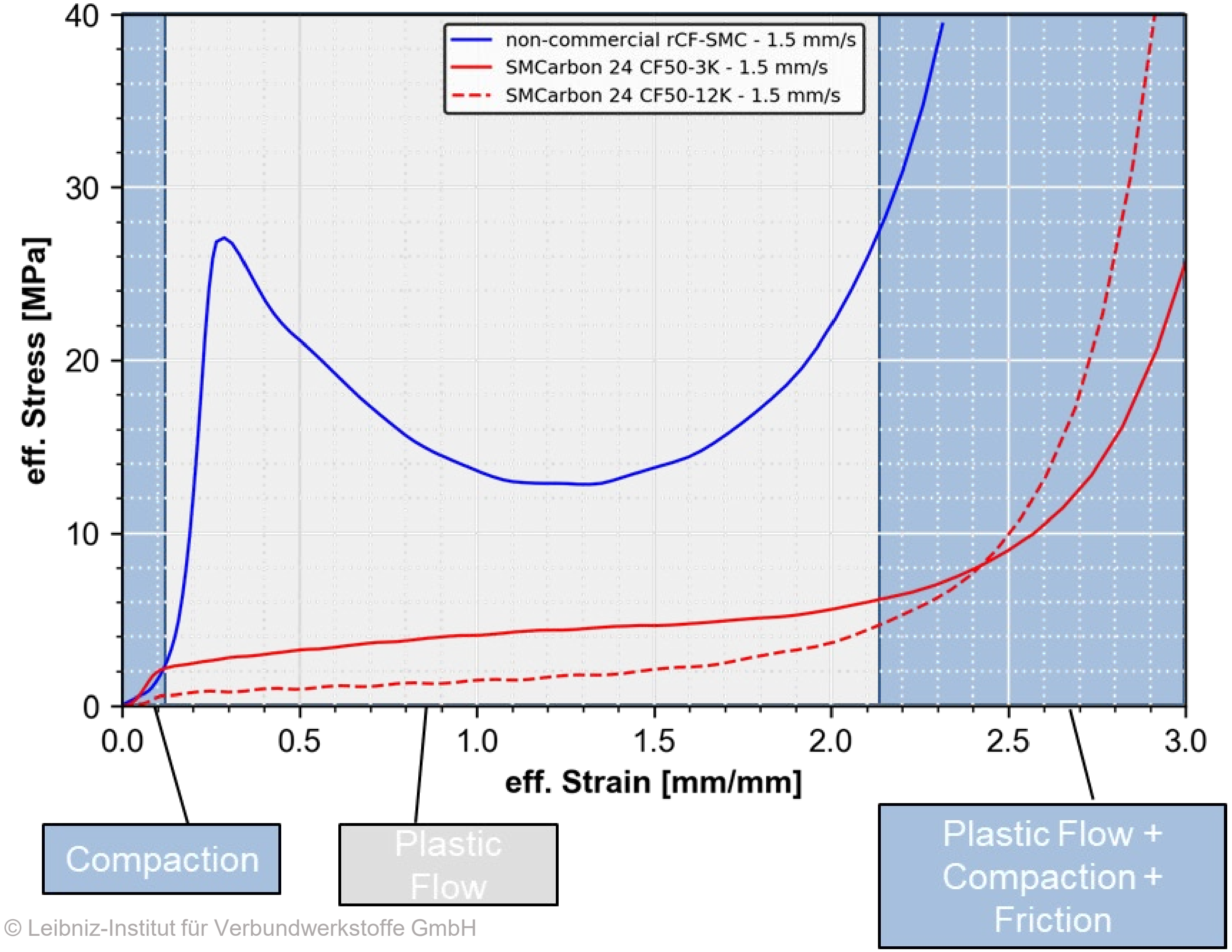




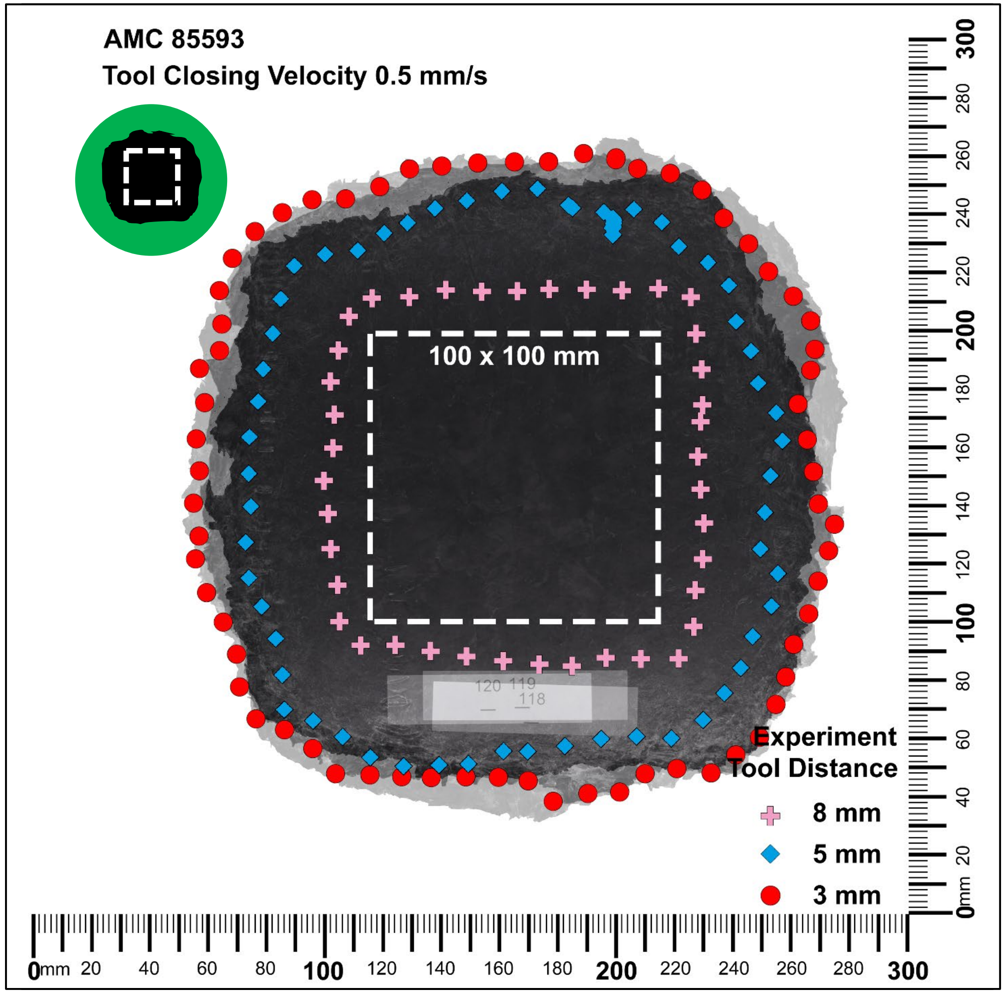


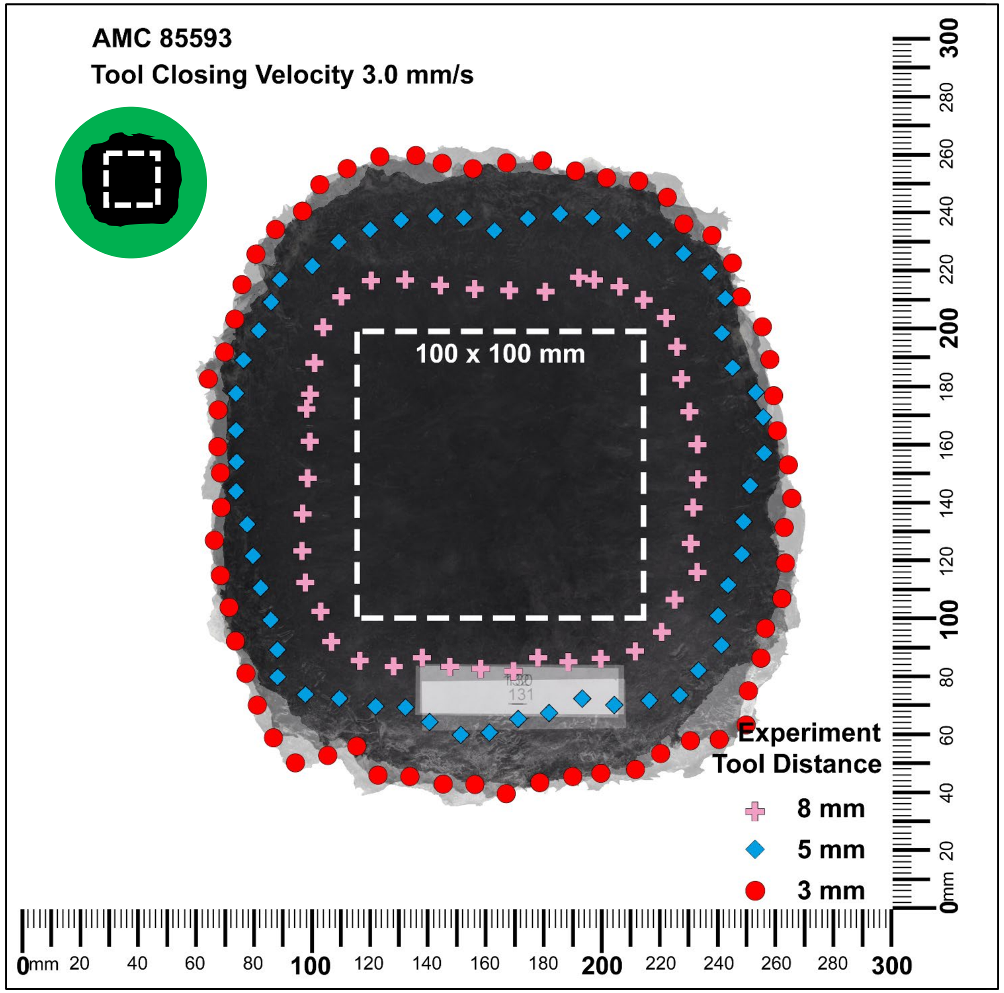
Flow/filling characterization: Constant area

Typical C-SMC material shows a compaction phase follows by a flow phase during compression molding



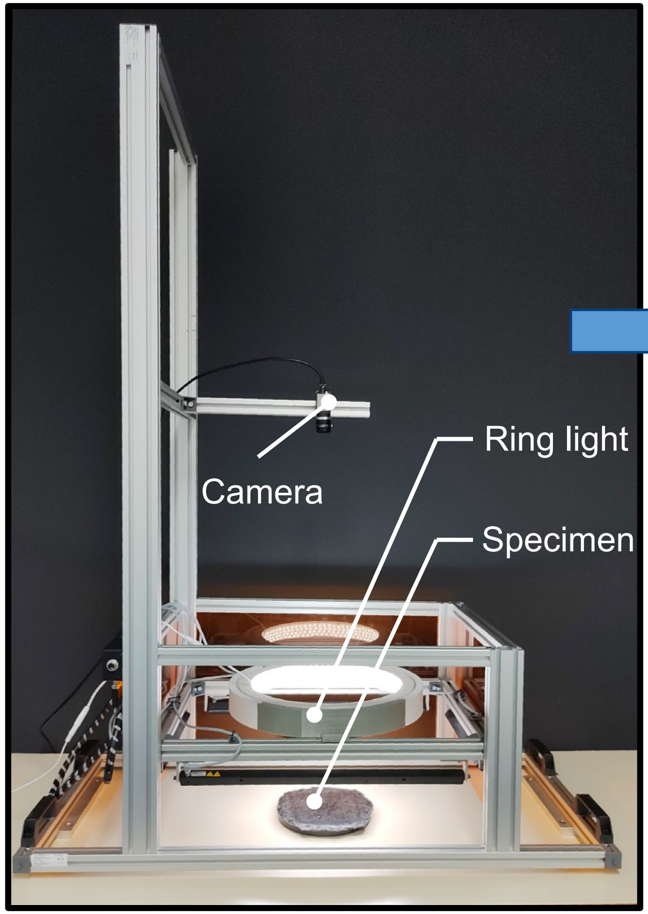
Flow/filling characterization: Constant mass





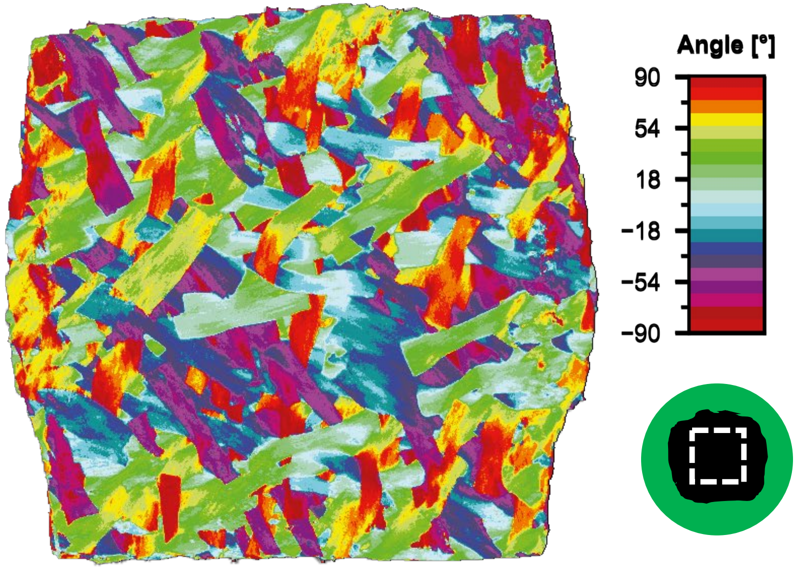
Fiber orientation: Pressed specimens

Optical measurement of surface fiber orientation



Polarization image data

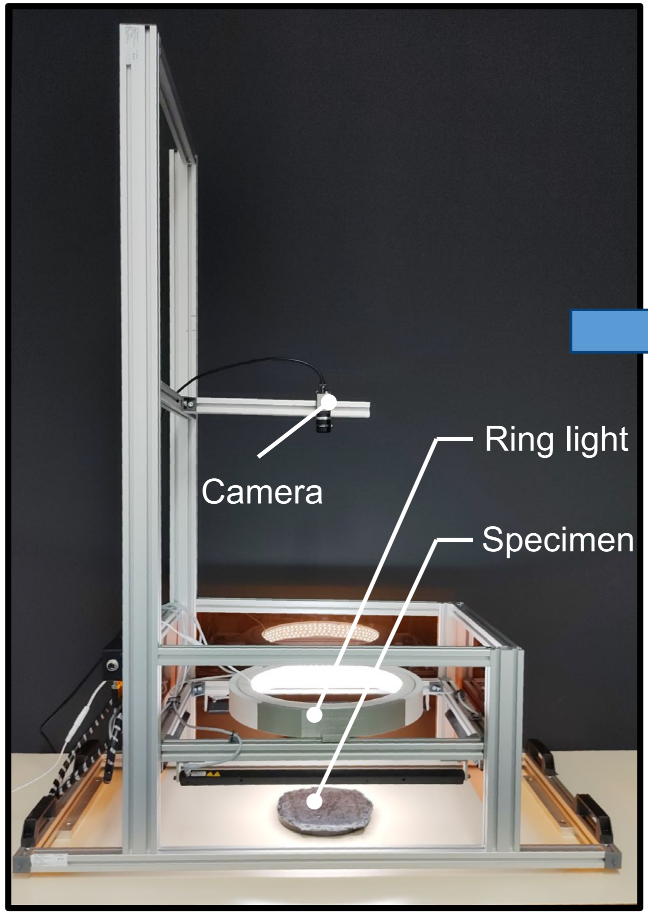
→ Greyscale shows fiber orientation angle in range from -90° to 90° to picture horizontal



→ Colored for better visibility

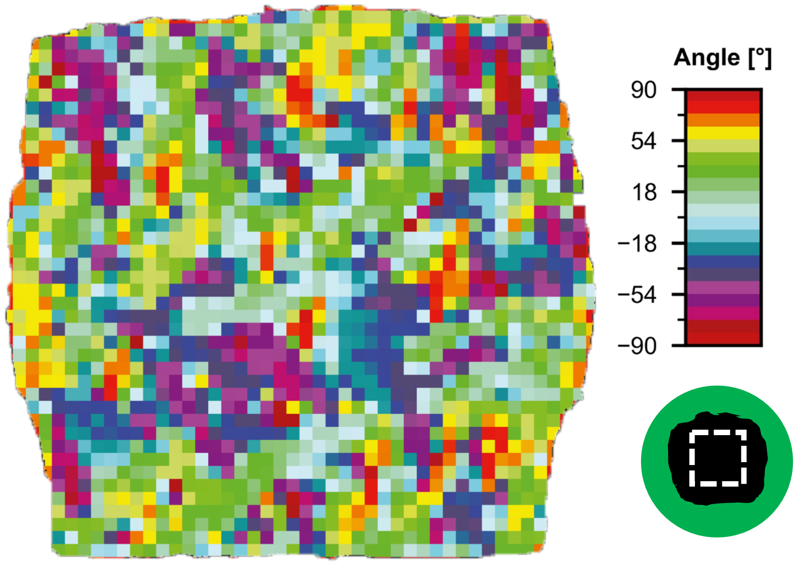
Fiber orientation: Pressed specimens

Optical measurement of surface fiber orientation



Polarization image data

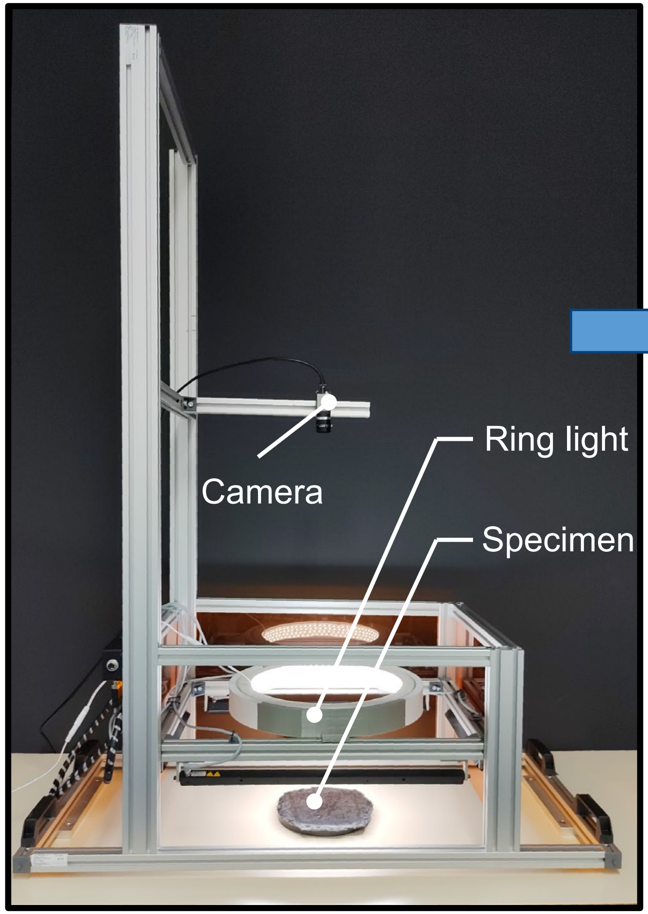
→ Place grid over specimen for reducing data and comparison with simulation



→ Grid resolution corresponds to element size in later simulation

Fiber orientation: Pressed specimens

Optical measurement of surface fiber orientation



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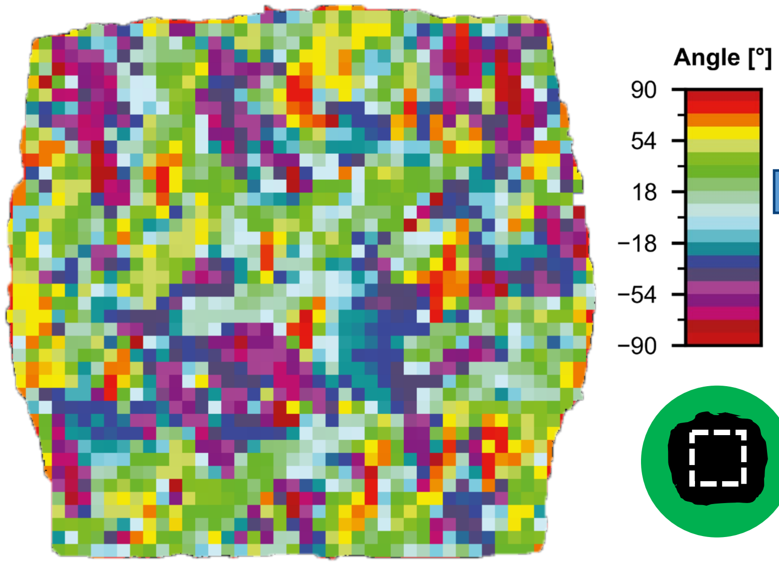
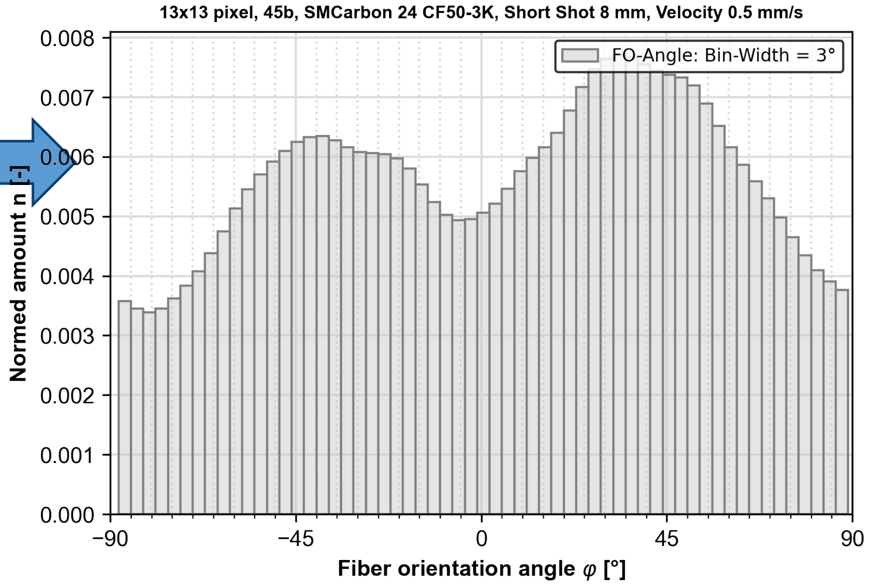


→ Grid resolution corresponds to element size in later simulation

Analysis

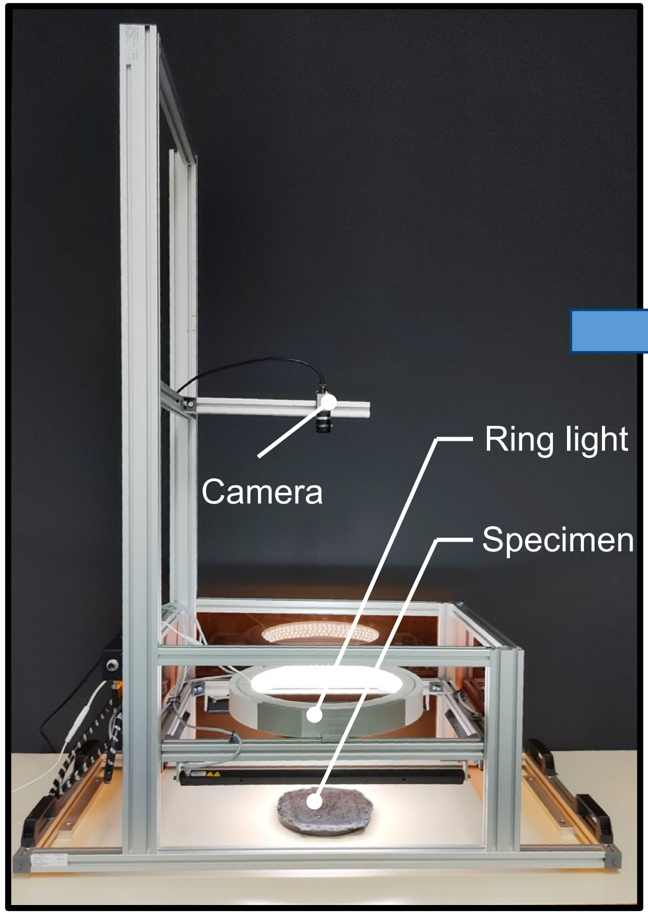
→ FO is visualized as histogram with Gaussian fit

python



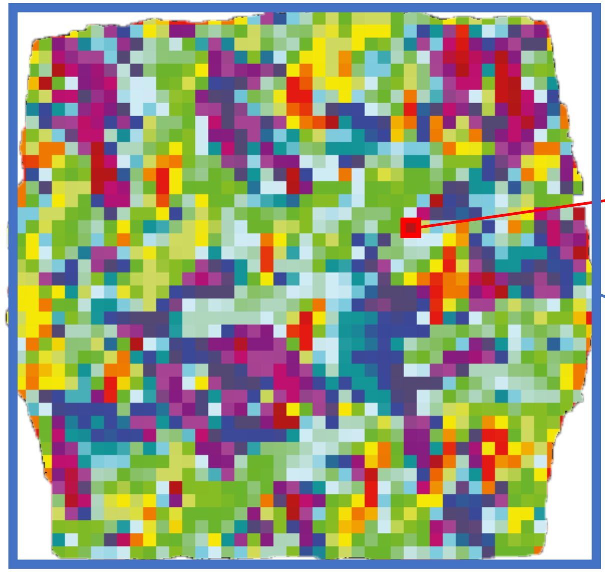
Fiber orientation: Pressed specimens

Optical measurement of surface fiber orientation



Polarization image data

→ Calculation of fiber orientation tensor for each grid cell



Analysis

python

→ FOT information for each grid cell, for example

0.685	0.465	0.000
	0.315	0.000
		0.000

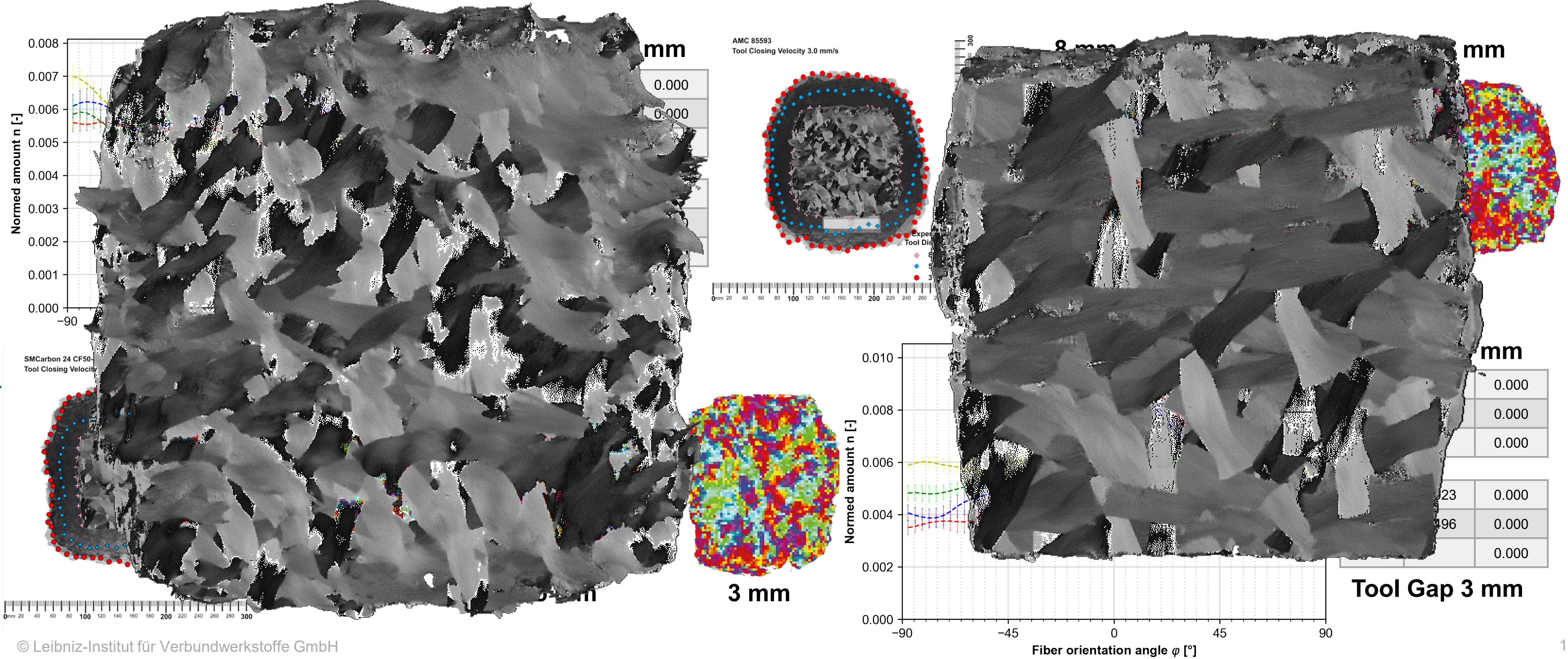
→ Average FOT for specimen

0.456	-0.043	0.000
	0.544	0.000
		0.000

→ An in-plane fiber orientation is assumed
→ All z-components of FOT are zero

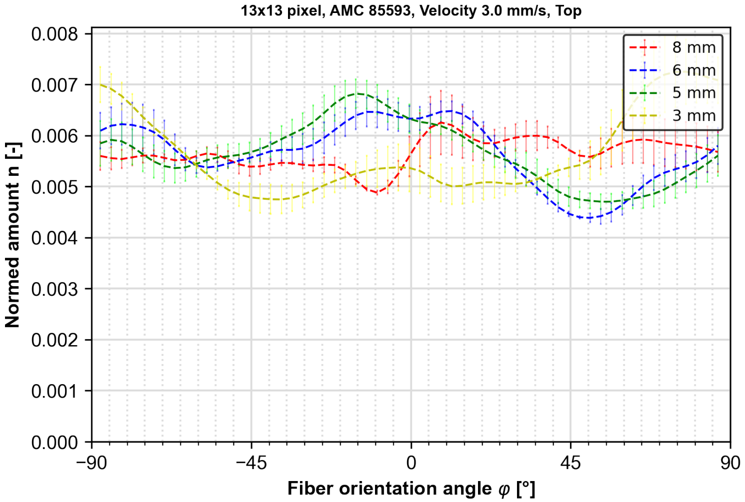
Fiber orientation: Pressed specimens

Histograms and average FOT information of short shot specimens for press closing velocity of 3.0 mm/s



Fiber orientation: Pressed specimens

Histograms and average FOT information of short shot specimens for press closing velocity of 3.0 mm/s

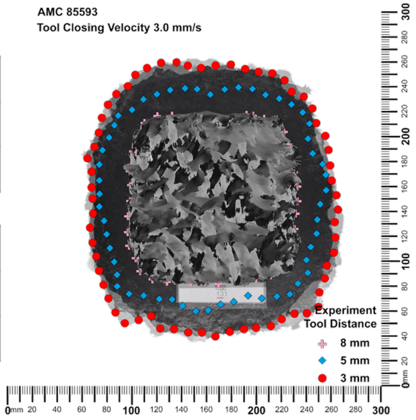


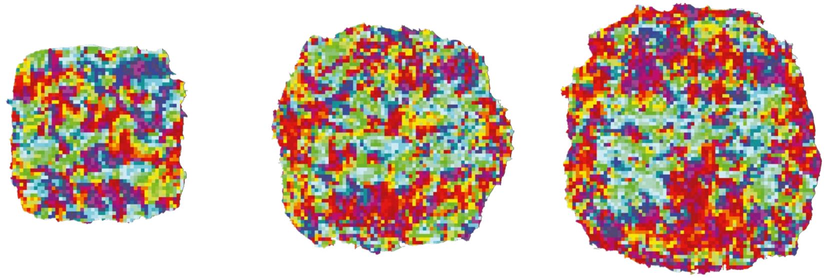
Tool Gap 8 mm

0.498	-0.012	0.000
	0.502	0.000
		0.000

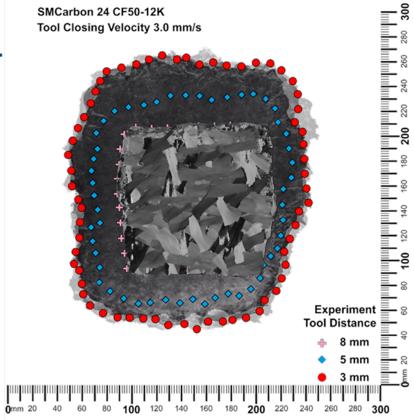
0.458	-0.014	0.000
	0.542	0.000
		0.000

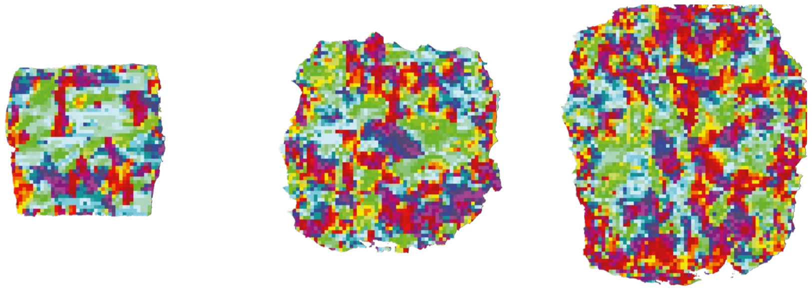
Tool Gap 3 mm



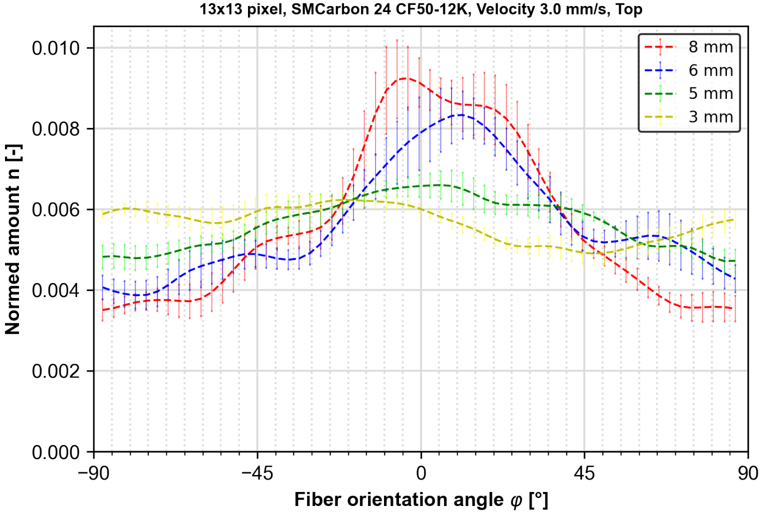


8 mm | 5 mm | 3 mm





8 mm | 5 mm | 3 mm



Tool Gap 8 mm

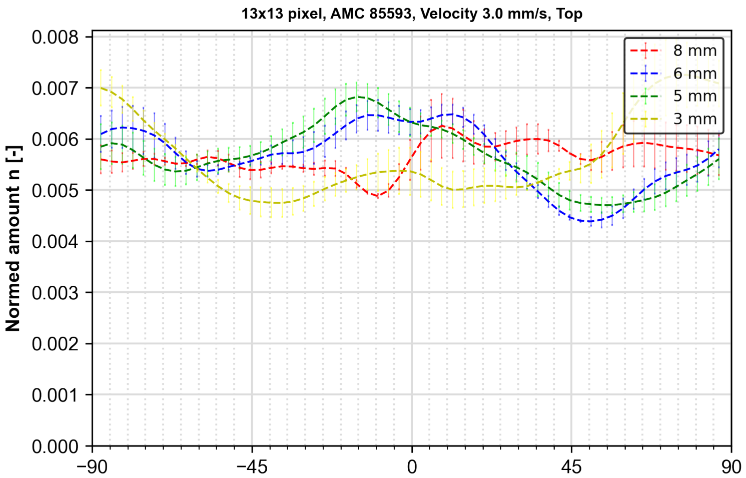
0.621	-0.021	0.000
	0.379	0.000
		0.000

0.504	0.023	0.000
	0.496	0.000
		0.000

Tool Gap 3 mm

Fiber orientation: Pressed specimens

Histograms and average FOT information of short shot specimens for press closing velocity of 3.0 mm/s



Tool Gap 8 mm

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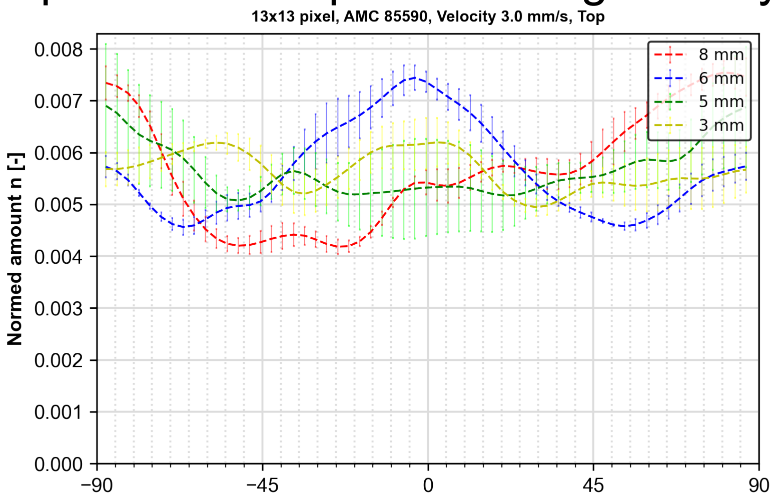
		0.000

Tool Gap 3 mm

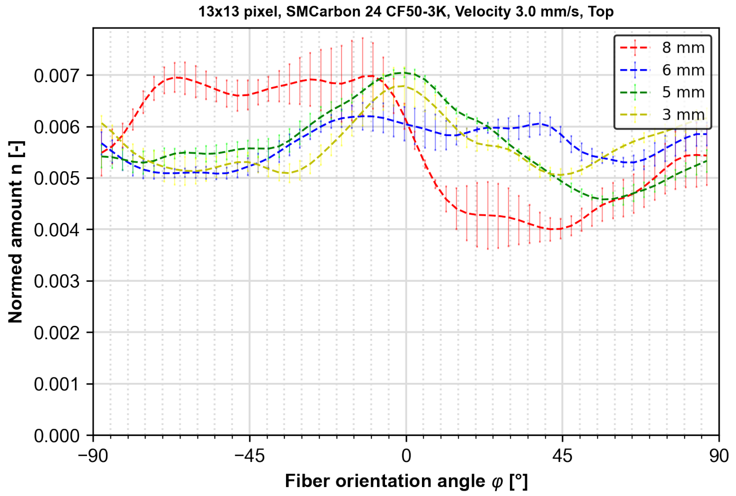


Tool Gap 8 mm

0.456	-0.043	0.000
	0.544	0.000
		0.000

0.501	0.012	0.000
	0.499	0.000
		0.000

Tool Gap 3 mm

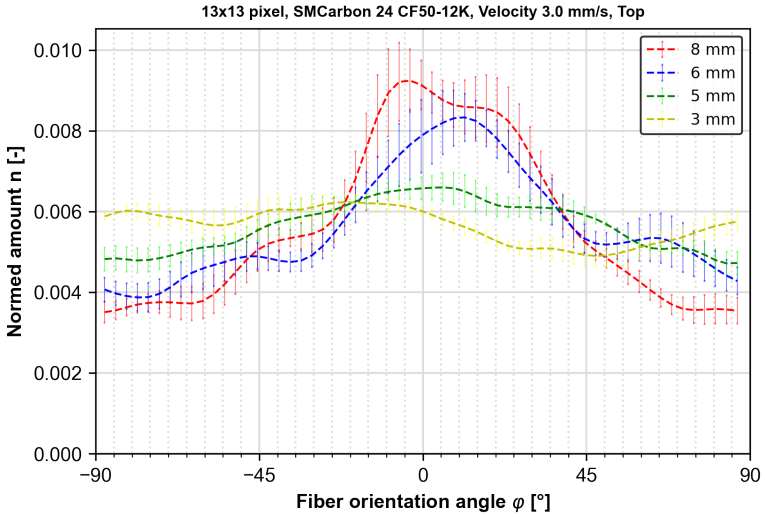


Tool Gap 8 mm

0.502	0.067	0.000
	0.498	0.000
		0.000

0.510	-0.005	0.000
	0.490	0.000
		0.000

Tool Gap 3 mm



Tool Gap 8 mm

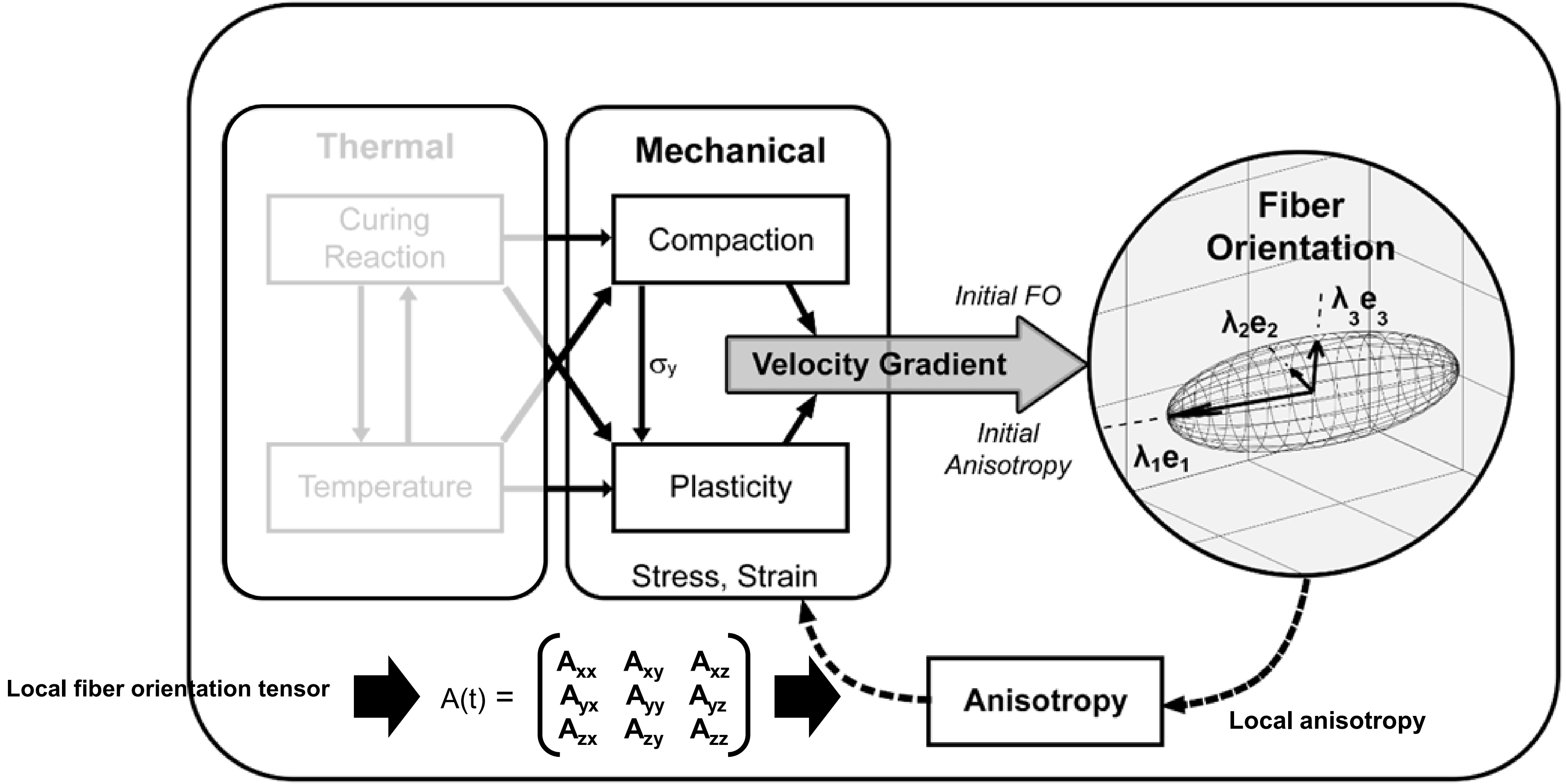
0.621	-0.021	0.000
	0.379	0.000
		0.000

0.504	0.023	0.000
	0.496	0.000
		0.000

Tool Gap 3 mm

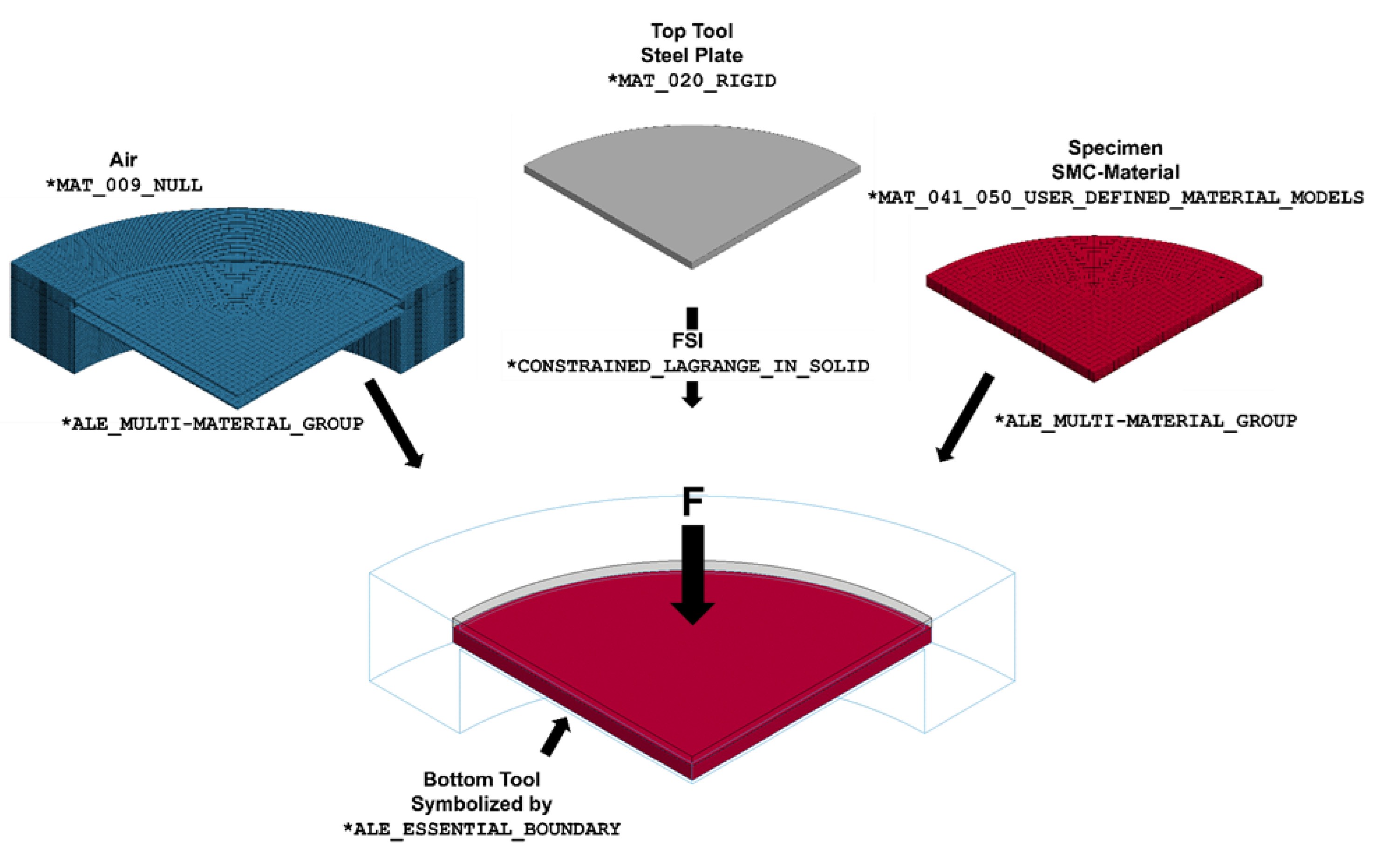
Material model structure

Development of a material model that takes into account the basic effects, uses mathematical formulations that are as simple as possible and is built upon a modular principle, whereby each block represents specific aspect of material behavior.



Simulation method

Arbitrary-Lagrangian-Eulerian (ALE) – Suitable for the representation of bodies that combine the properties of fluids and solids.



Calculation in two steps:

1. **Lagrangian step:**
   Calculation of deformation in a Lagrangian formulation
2. **Advection step:**
   Remapping of element state variables back onto the reference mesh.

Main difference to Eulerian method: ALE allows a movement and deformation of reference mesh.

Fiber orientation model

Folgar-Tucker-Equation

Based on the equation by Jeffery (1922):

$$\frac{D}{Dt}p = \hat{M}^T \cdot p - (p^T \cdot \hat{M} \cdot p)p$$

p	=	Orientation vector
$\hat{M}$	=	Effective local velocity gradient

Orientation of an ellipsoid particle in an infinite Newtonian fluid

$$\frac{\boldsymbol{DA}}{\boldsymbol{Dt}} = (\boldsymbol{W} \cdot \boldsymbol{A} - \boldsymbol{A} \cdot \boldsymbol{W}) + \xi(\boldsymbol{D} \cdot \boldsymbol{A} + \boldsymbol{A} \cdot \boldsymbol{D} - 2\mathbb{A}: \boldsymbol{D}) + 2C_i\dot{\gamma}(\boldsymbol{I} - 3\boldsymbol{A})$$

Folgar-Tucker-Equation (1984) Developed for injection molding

A	=	Fiberorientation Tensor 2. Order $\boldsymbol{A} = \langle pp \rangle$
$\mathbb{A}$	=	Fiberorientation Tensor 4. Order
W	=	Vorticity Tensor 2. Order

D	=	Deformation Tensor 2. Order
ξ	=	Geometry Factor 2. Order
I	=	Unit Tensor 2. Order

Fiber orientation model (implemented in LS-DYNA®)

Folgar-Tucker-Model + Maier-Saupe term

$$\frac{\mathbf{DA}}{\mathbf{Dt}} = \mathbf{MA} + \mathbf{M}^{\mathbf{T}}\mathbf{A} - 2\mathbb{A}{:}\mathbf{M} - 6C_i\dot{\gamma}\left(\mathbf{A} - \frac{1}{3}\mathbf{I}\right)$$

$$\mathbf{M} = \lambda\gamma + \frac{1}{2}\left(\nabla u - \nabla u^T\right) + \dot{\gamma}U_0\mathbf{A}$$

$$\lambda = \frac{{r_a}^2 - 1}{{r_a}^2 + 1}$$

$$\dot{\gamma} = \sqrt{\frac{1}{2}\gamma : \gamma}$$

$$\gamma = \frac{1}{2}\left(\nabla u + \nabla u^T\right)$$

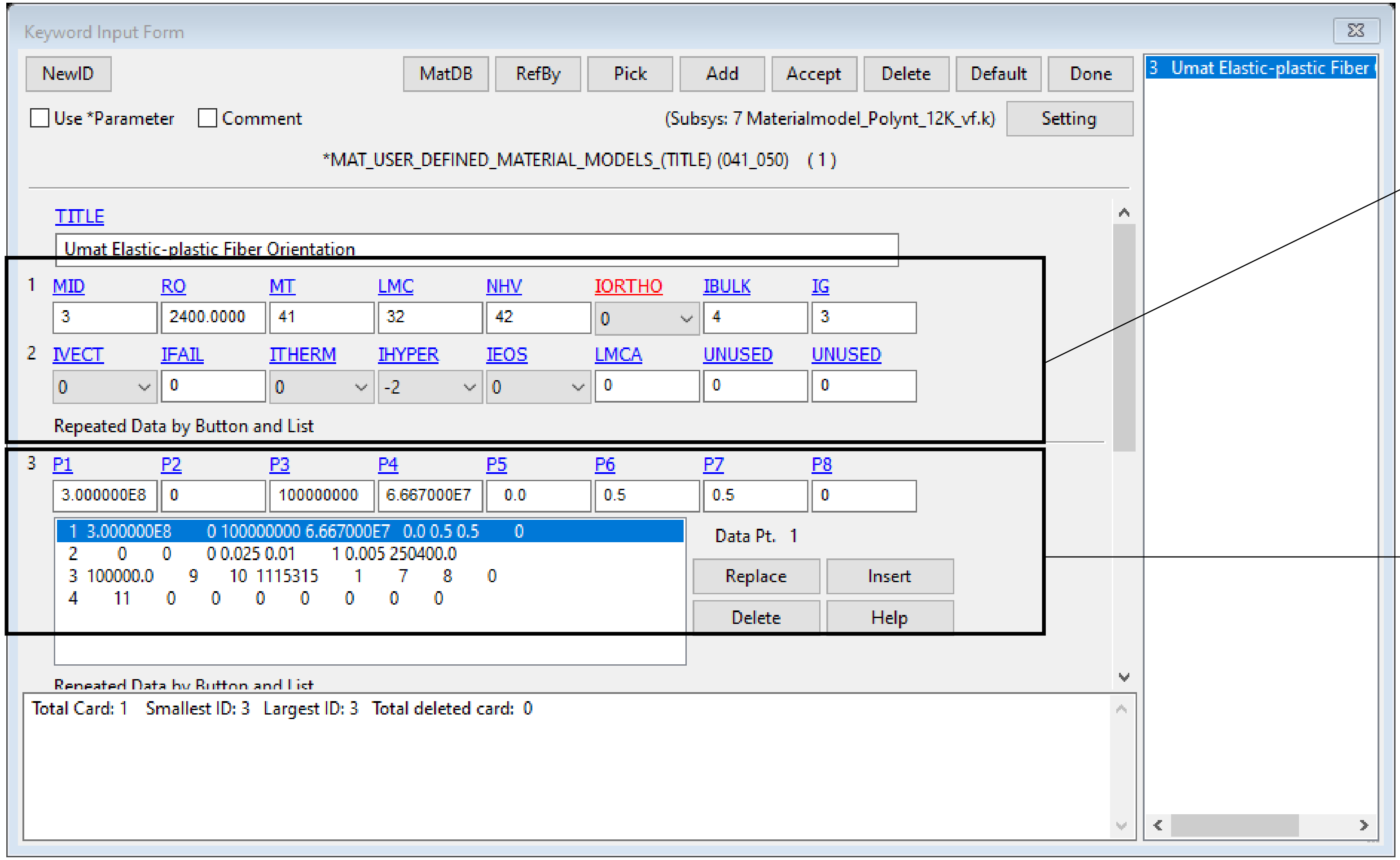
Fraunhofer ITWM

A	=	Fiber orientation tensor 2. order $\boldsymbol{A} = \langle pp \rangle$
$\mathbb{A}$	=	Fiber orientation tensor 4. order
M	=	Maier-Saupe term
∇u	=	Velocity gradient
U_0	=	Maier-Saupe potential
I	=	Unity tensor 2. order
r_a	=	Fiber Geometry factor

Latz, A.; Strautins, U.; Niedziela, D.: Comparative numerical study of two concentrated fiber suspension models. J. Non-Newtonian Fluid Mech. 165, pp. 764-781 (2010).

Model input parameters

Material card for user-defined material model implemented in LS-DYNA.



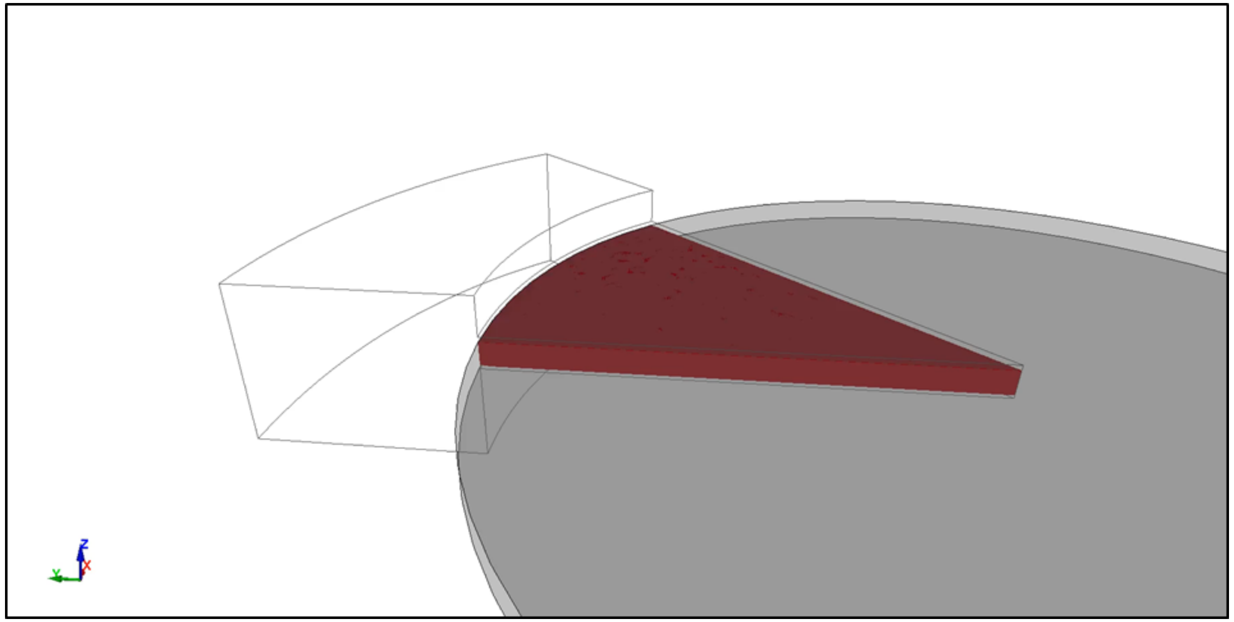
RO: Combined density of matrix and fibers
MT: User Material ID
LMC: No. of material constants to be defined
NHV: No. of history variables constants to be output

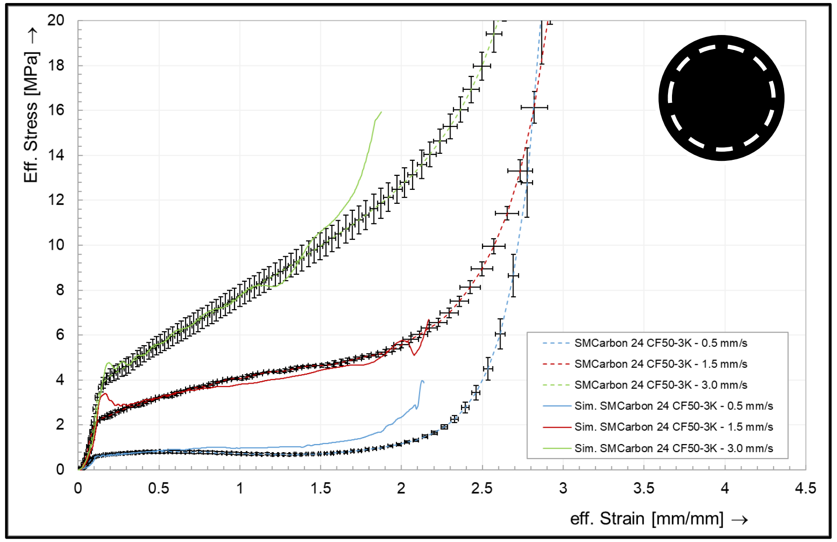
P1-P8: The first 8 (of 26) user defined material parameters
Cm(1)-Cm(26): Tensile modulus, Poisson's ratio, shear modulus, compression modulus, A_{xx}, A_{yy}, A_{zz}, A_{zy}, A_{xz}, A_{zy}, fiber length, fiber diameter, Maier-Saupe Potential, fiber interaction coefficient…etc.

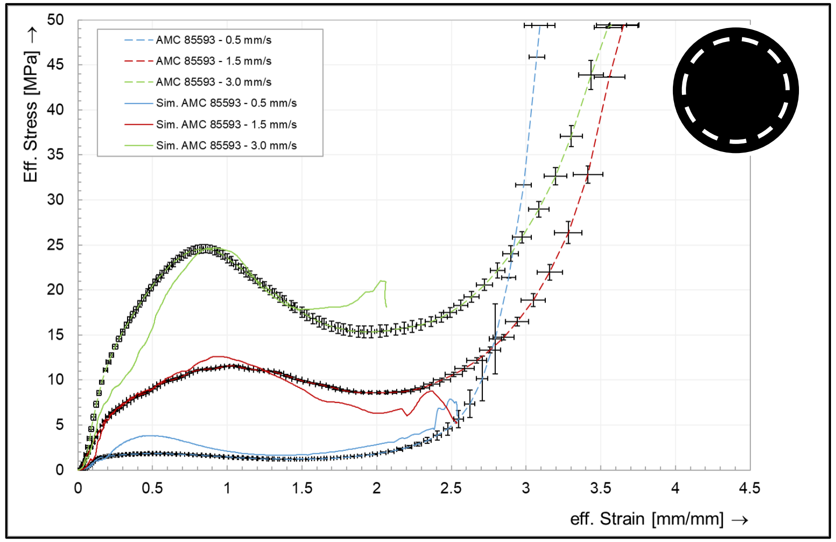
Material model validation

Validation and evaluation of the accuracy of the material model carried out via post-simulation of the characterization tests.

Material model calibration





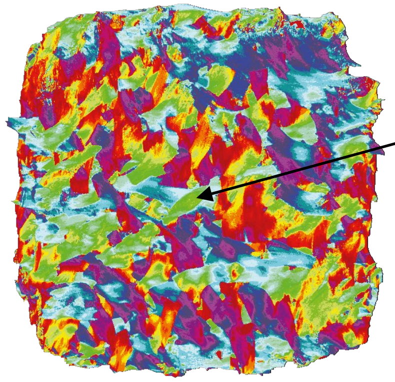


Does the Folgar-Tucker FO model work for C-SMCs?

Question: How well does the Folgar-Tucker model describe the fiber orientation behavior of C-SMCs?

Main differences between polarization camera image and simulation result:

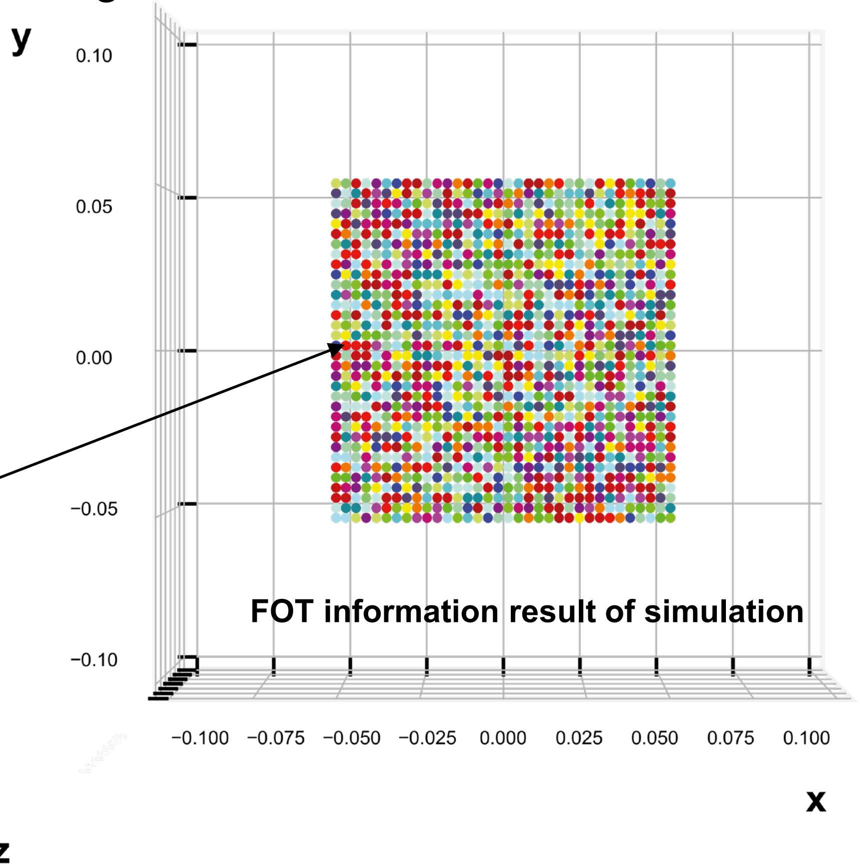
→ Short Shot with tool gap of 8 mm:



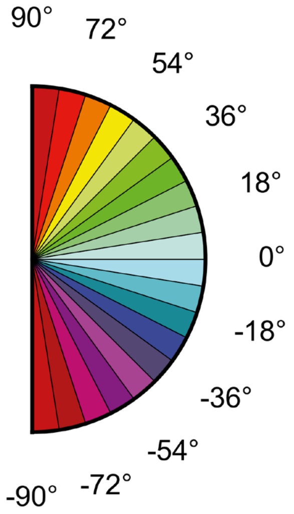
Polarization camera image

Long fiber reinforcement formed by yarn cuttings
⇒ Grid cells in analyses **are** connected
⇒ FOT in grid cells are influenced **by** each other

Every element in simulation model describes one fiber distribution (FOT)
⇒ Elements in simulation **are not** directly connected
⇒ FOT in elements **are not** influencing each other



FOT information result of simulation

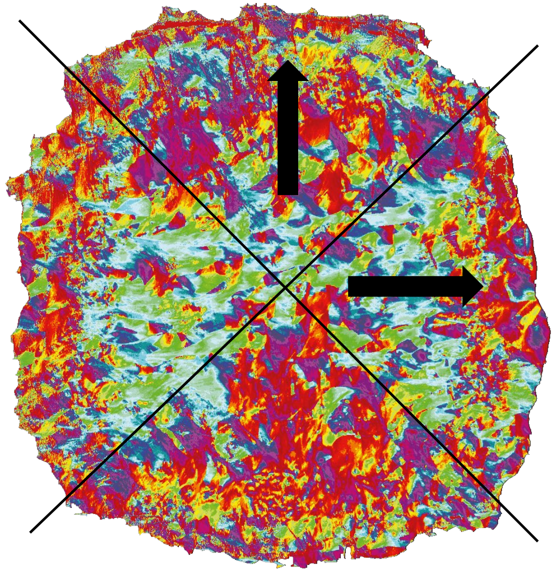


Does the Folgar-Tucker FO model work for C-SMCs?

Question: How well does the Folgar-Tucker model describe the fiber orientation behavior of C-SMCs?

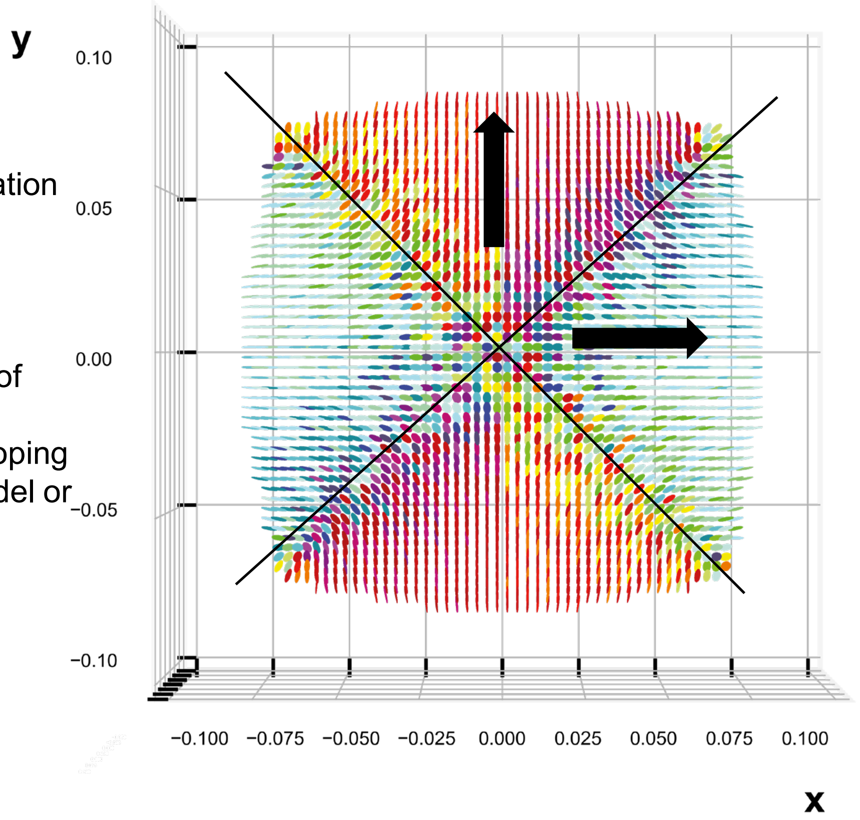
Is the tendency correct?

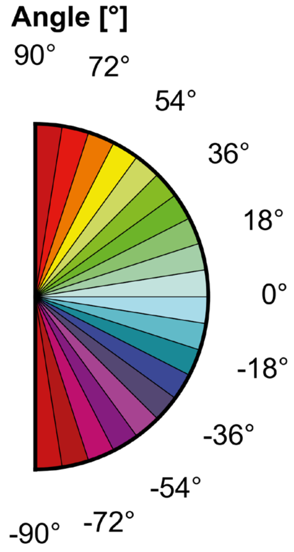
→ Short Shot with tool gap of 3 mm:



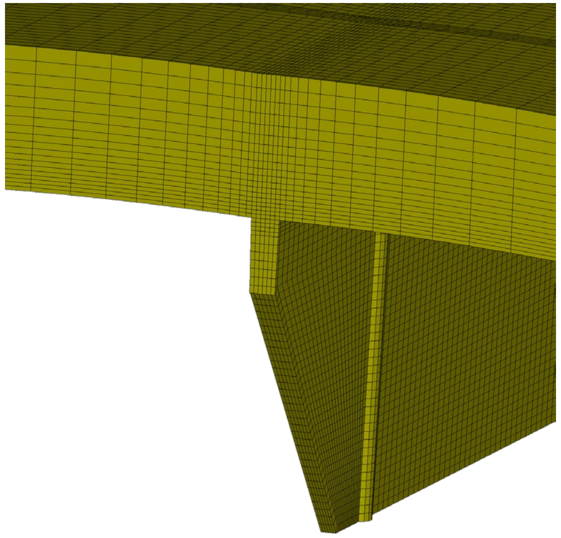
Polarization camera image

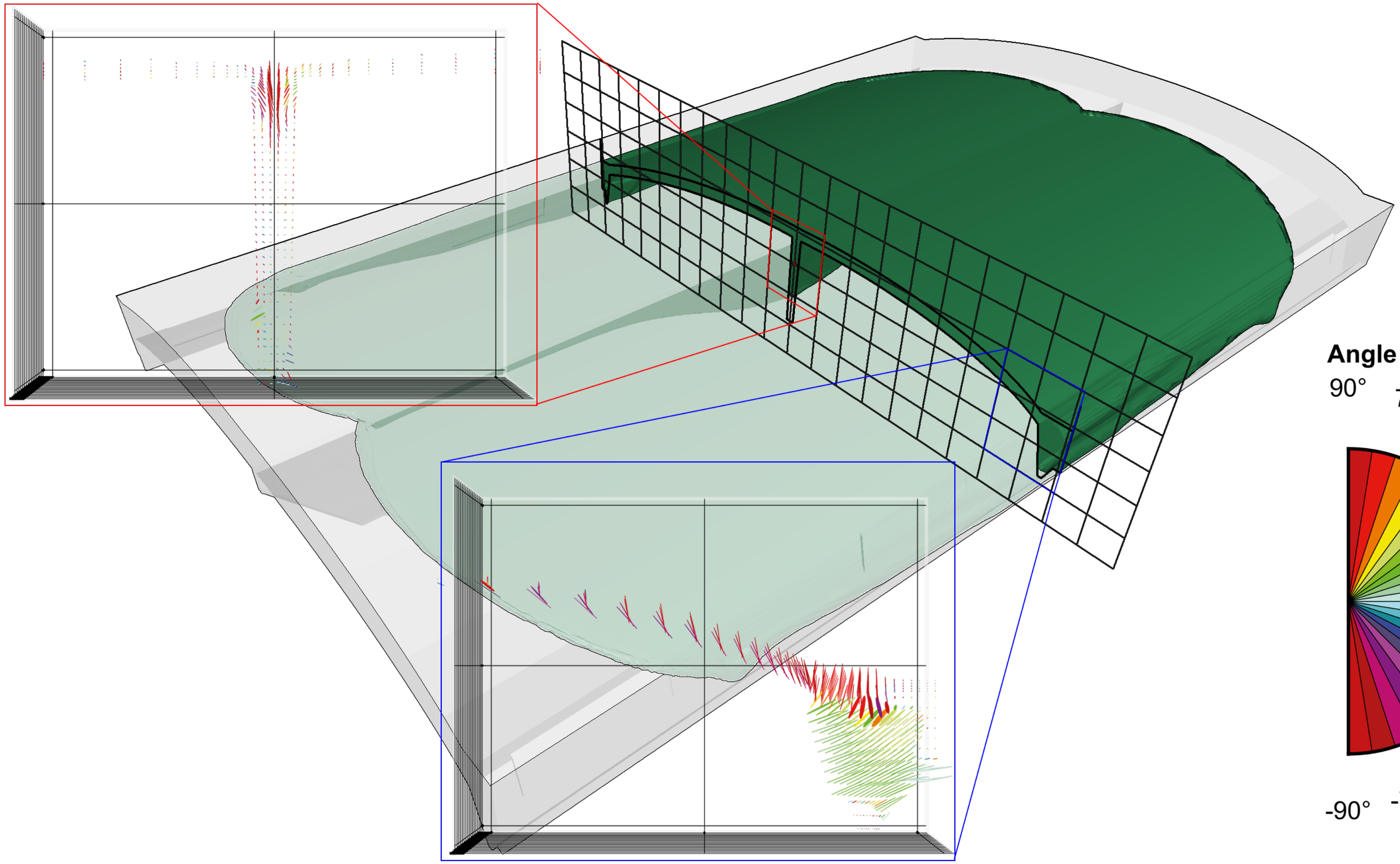
Same orientation tendency in simulation
But: Stronger orientation behavior
Reason: No resistance against movement caused by neighboring elements
Can be influenced by: Calibration of material parameter
Can be optimized by: Using/developing a more suitable fiber orientation model or fiber interaction model

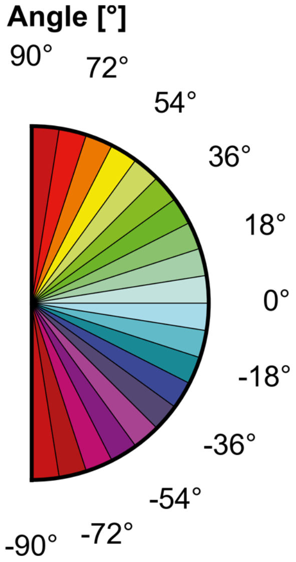


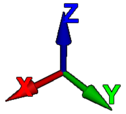


Application Demo: Automotive rear spoiler









Conclusions

Several innovative methods have been developed for the material and process characterization of C-SMC materials focusing on fiber orientation and flow behavior.

- Fiber orientation: Semi-finished product (Polarization imaging)
- Flow/filling characterization (Press rheometry constant area and constant mass)
- Fiber orientation: Pressed specimens (Polarization imaging)

A non-linear elastic piecewise plastic material model with fiber orientation back-coupling based on the Folgar-Tucker-Model + Maier-Saupe term has been implemented in LS-DYNA as a user-defined material model.

- Initial qualitative validations show great results!

Acknowledgements

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Fraunhofer ITWM

HIGH PERFORMANCE CENTER SIMULATION- AND SOFTWARE-BASED INNOVATION

The polarization hardware used within this project has been developed with the help of the Electronic Imaging Department of the Fraunhofer Institute for Integrated Circuits (IIS).

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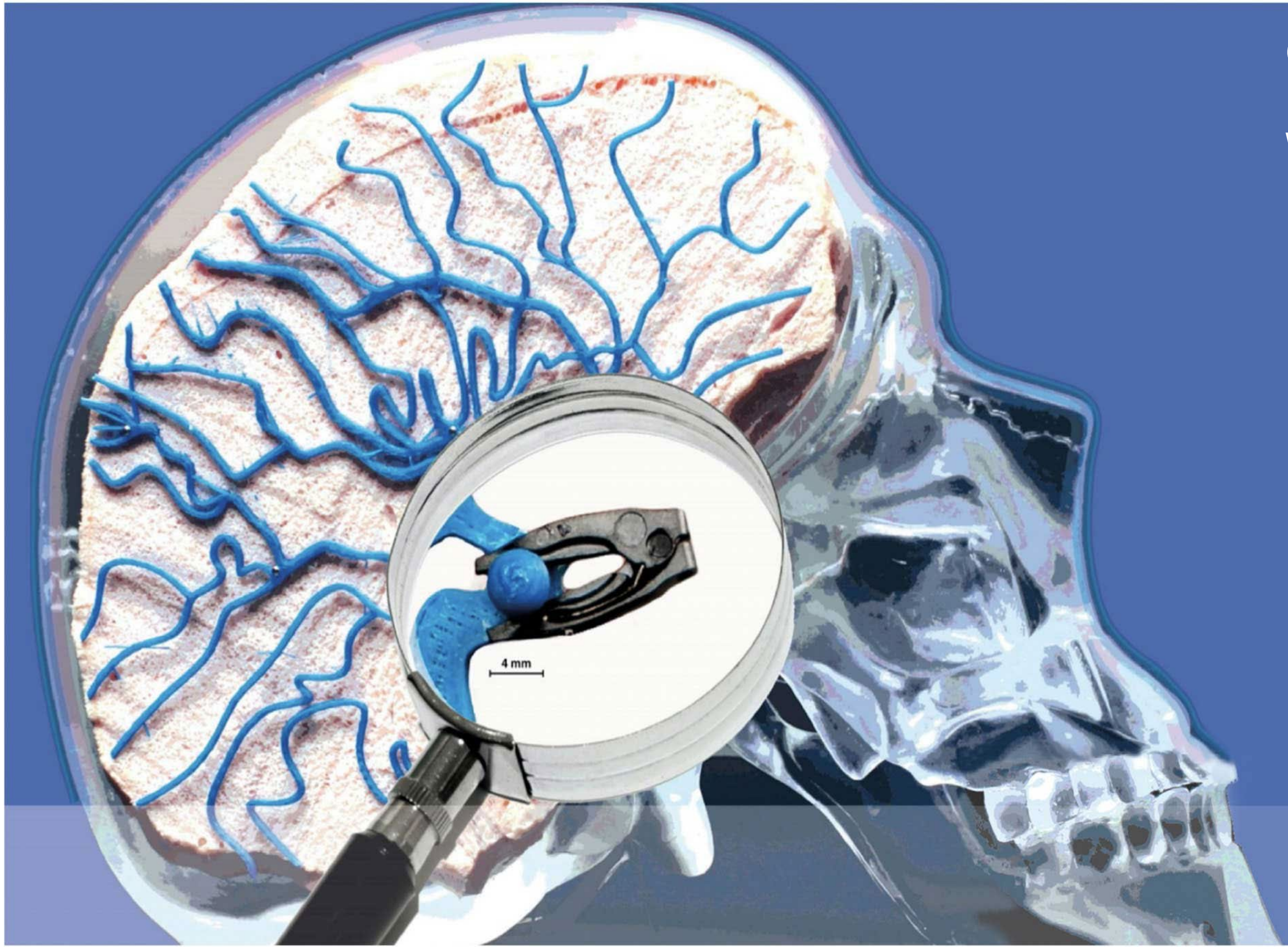
Thank you for your attention!



Contact: Dr. Miro Duhovic
Email: miro.duhovic@ivw.uni-kl.de
Website: www.ivw.uni-kl.de
Phone: +49 (0)631 2017 - 363

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