Area 1

Thermoplastic Composites

Birtha, Laresser, Kloiber, Kobler, Kohl, Marschik, Miron, Wenninger

Thermoplastic Composites

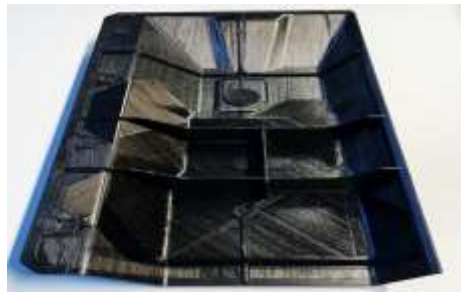
From Fiber and Matrix to Structural Lightweight Components





UD Tape Extrusion → Tape Laying → Consolidation → Preheating → Forming / Functionalization





Inhalt

- Introduction
- Inline Measurement Systems
- Material Characterization
- Lab-Scale Equipment
- Process and Component Optimization
- Simulation

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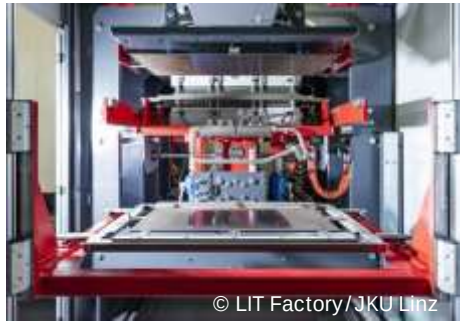
Thermoplastic Composites



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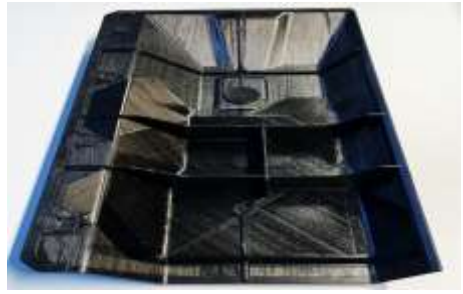
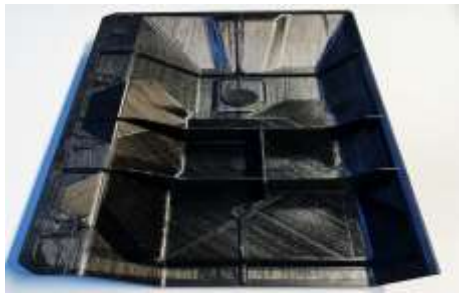


From Continuous Fibers and Matrix to Structural Lightweight Components

Materials







Fiber, Matrix → UD Tape → Layup → Stack → Component

- **Polymers**: PP, PC, LM-PAEK
- **Fibers**: GF, CF
- **Overmolding**: PC and PEEK (short fiber reinforced)
- **Semi-Finished Parts**: Organosheets, Honeycombs

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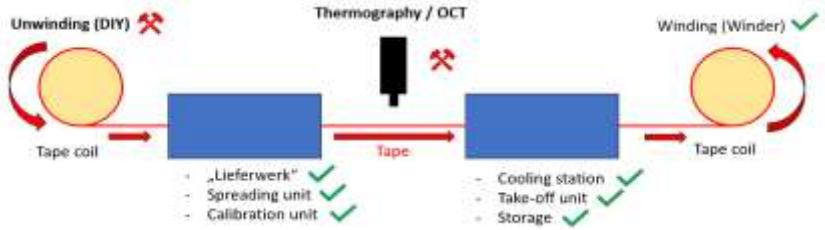
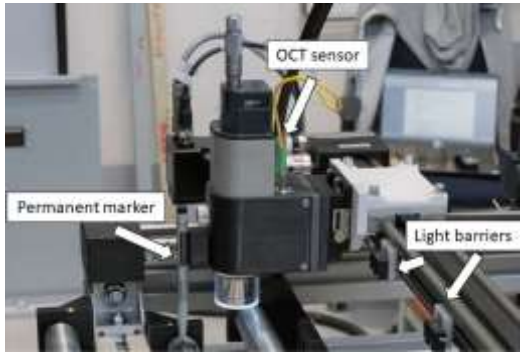
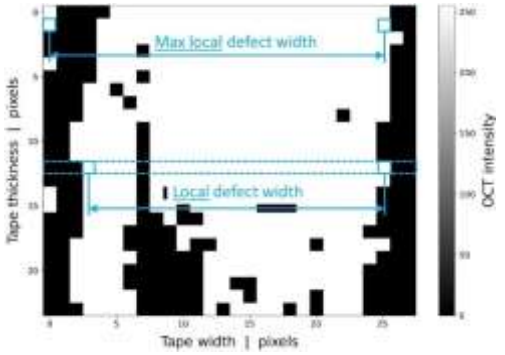
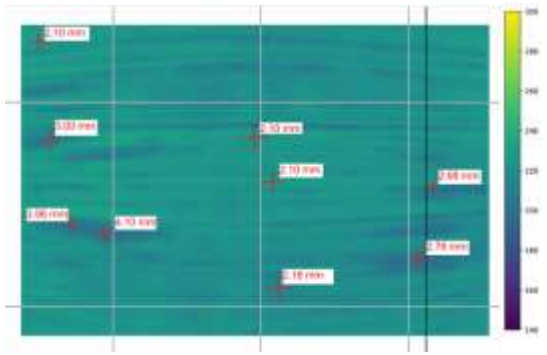
Inline Measurement Systems







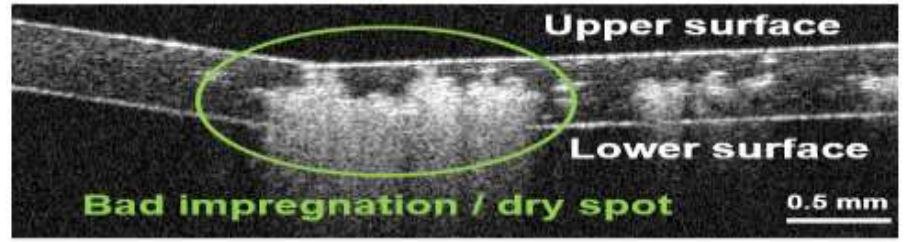


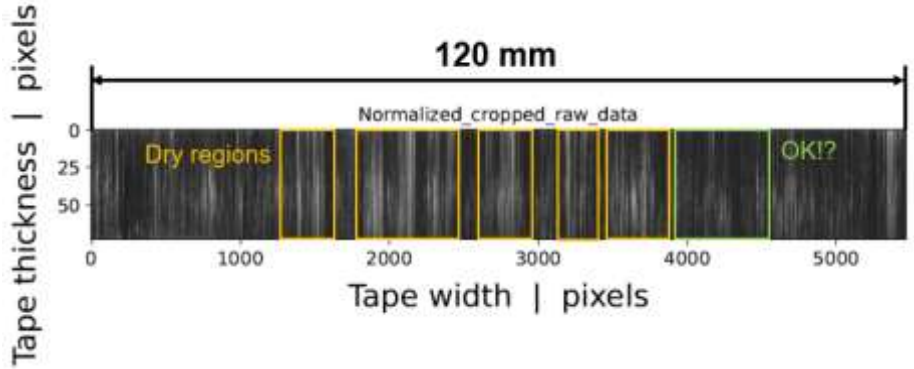
UD Tape Extrusion → Tape Laying → Consolidation → Preheating → Forming / Functionalization

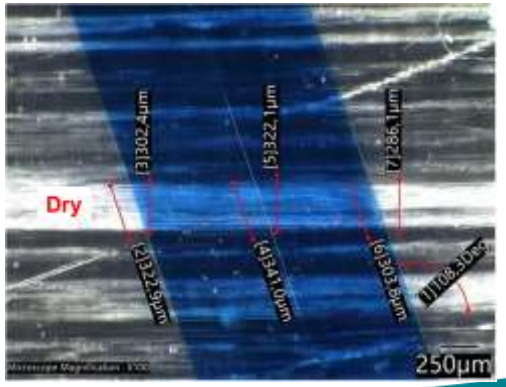
- Optical Coherence Tomography (UD Tape Extrusion)
- Active Thermography (UD Tape Extrusion)
- Optical Camera (UD Tape Extrusion)
- Passive Thermography (Consolidation, Preheating)

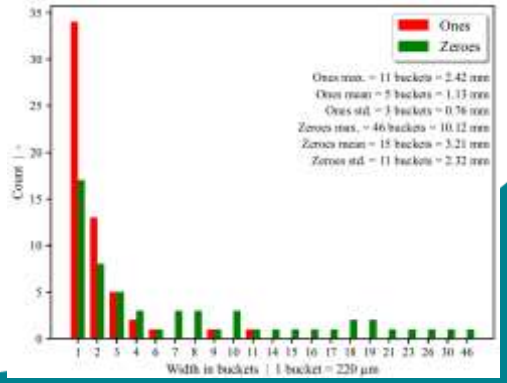
Optical Coherence Tomography (OCT)

- **Goals**
  - Detection of defects in glass-fiber-reinforced UD tapes
  - Robust and fast evaluation methodology
- **Main Results**
  - Inline measurement approach based on OCT
  - Full-cross sectional analysis of quality attributes
  - Objective evaluation of defects using statistics
  - Digital fingerprint of tape quality
- **Impact**
  - Deeper understanding of tape production
  - Improved process and quality control
  - Reduction of waste and saving of resources



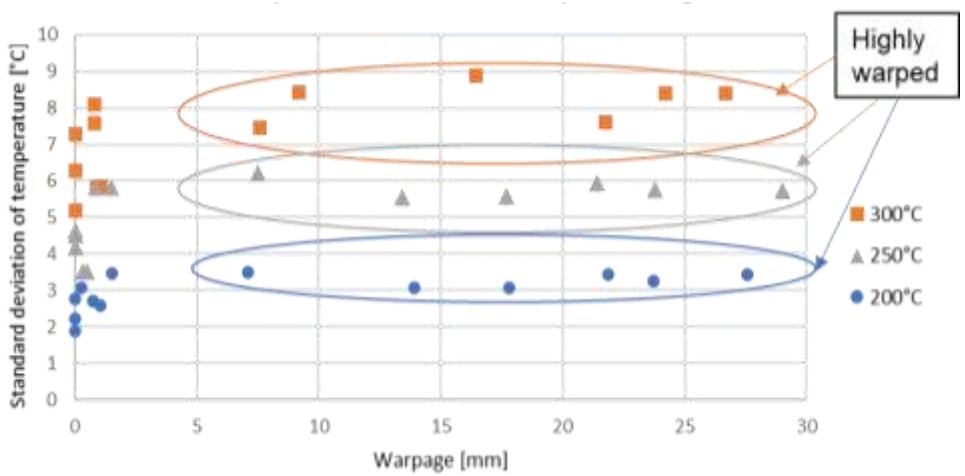


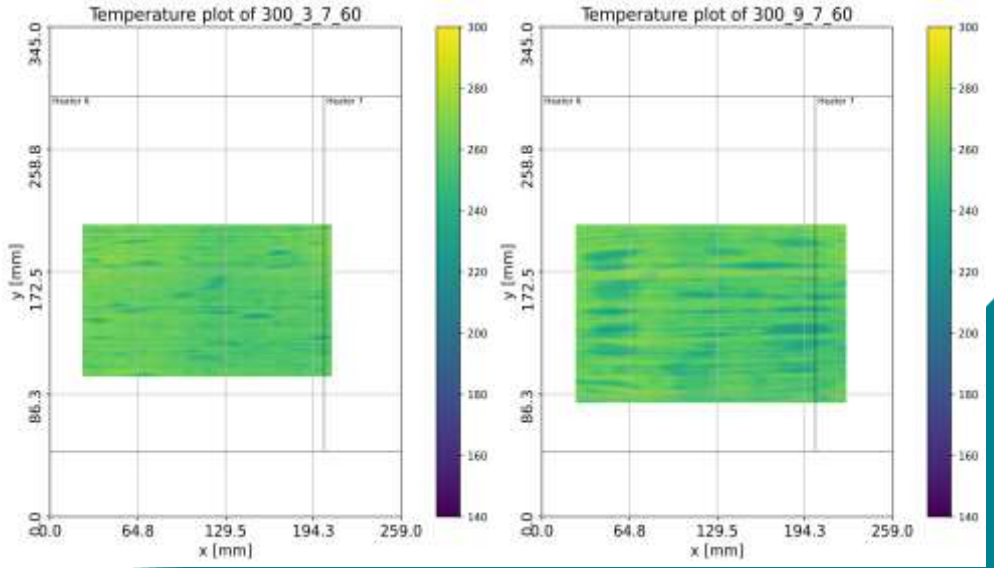




Passive Thermography (PT)

- **Goal**
  - Measurement of temperature homogeneity of preheated composite parts (before forming)
  - Influence of preheating process on final part quality
- **Main Results**
  - Inline measurement approach based on PT
  - Python script for statistical analysis of thermograms
  - Correlation of temperature field to level of warpage and residual stresses (deconsolidation)
- **Impact**
  - Improved process and quality control
  - Deeper understanding of the preheating process and its effects on final part quality





Publications

- M. Wenninger, C. Marschik, K. Felbermayer, B. Heise, G. Steinbichler, Optical Coherence Tomography – A New Method for Evaluating the Quality of Thermoplastic Glass-Fiber-Reinforced Unidirectional Tapes, AIP Conf. Proc. 2884, 050008, **2023**, DOI: 10.1063/5.0168192
- J. Birtha, E. Kobler, C. Marschik, K. Straka, G. Steinbichler, S. Schlecht, P. Zwicklhuber, Inline Quality Measurement of Preheated Thermoplastic Composite Parts Using Passive Thermography, xxx (minor revision)
- M. Wenninger, C. Marschik, M. Schnaitter, G. Hochleitner, G.R. Berger-Weber, G. Steinbichler, Using Optical Coherence Tomography to Evaluate the Optimal Settings for Inline Detection of Defects in Glass-Fiber-Reinforced Unidirectional Thermoplastic Tapes, xxx
- M. Wenninger, C. Marschik, K. Felbermayer, B. Heise, T. Kranzl, G. Steinbichler, A Novel Measurement Approach based on Optical Coherence Tomography for Inline Quality Assessment of Thermoplastic Glass-Fiber Reinforced Unidirectional Tapes, J. Therm. Comp., **2023**, 36, 3943-3965, DOI: 10.1177/08927057221143371
- M. Wenninger, K. Kloiber, C. Marschik, G. Hochleitner, G.R. Berger-Weber, G. Steinbichler, Applying Optical Coherence Tomography to Inline Quality Monitoring of Unidirectional Glass-Fiber-Reinforced Thermoplastic Tapes, xxx
- M. Wenninger, PhD Thesis, Johannes Kepler University Linz, **2023**

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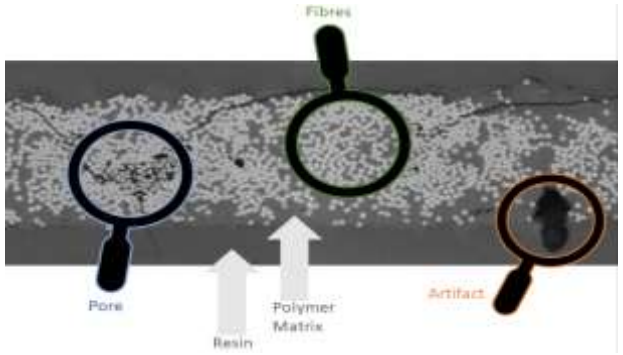
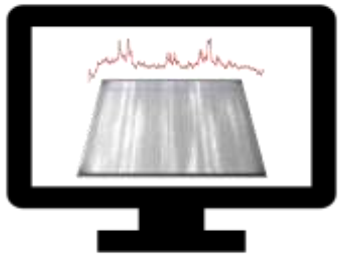
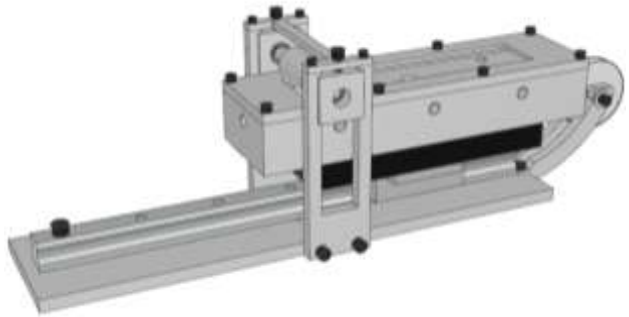
Material Characterization





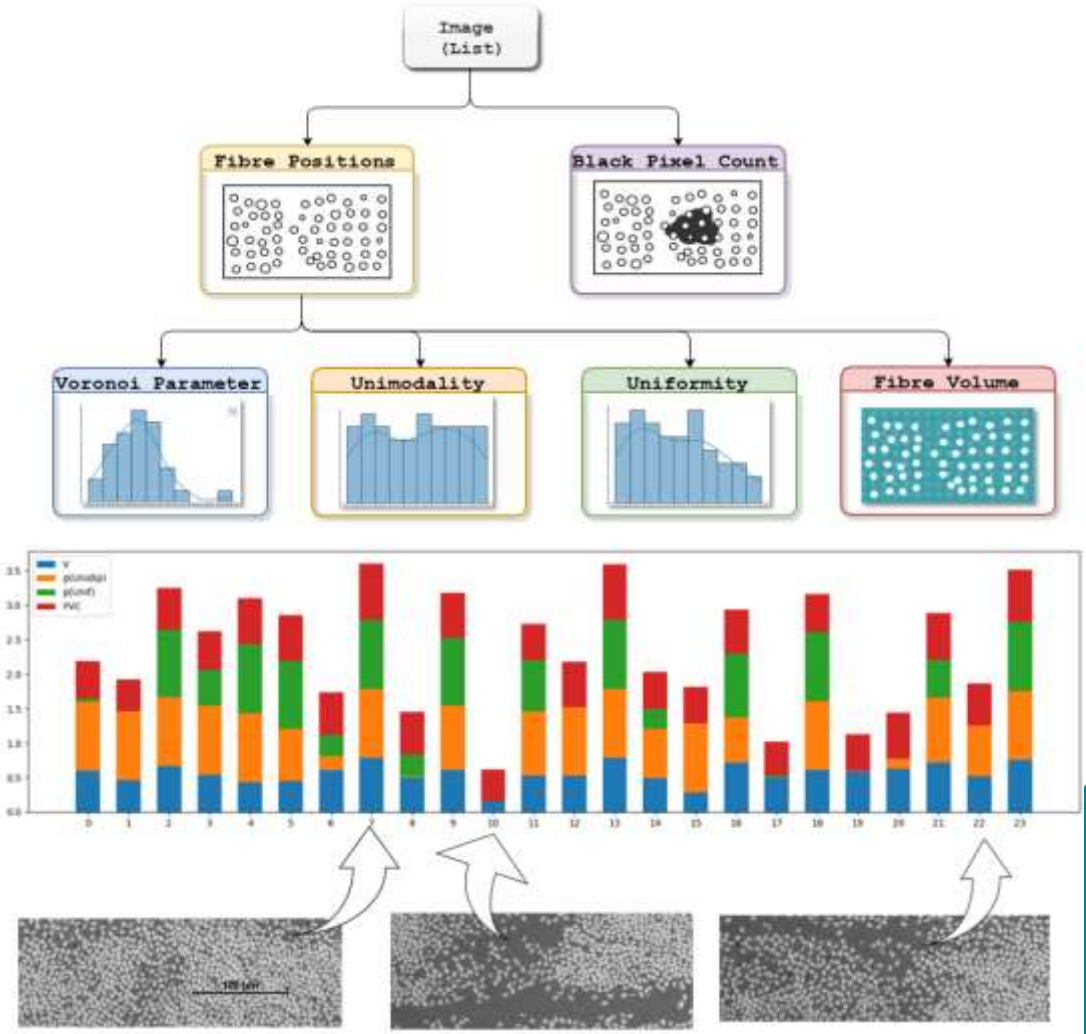


Fiber, Matrix → UD Tape → Layup → Stack → Component

- Automated Quality Assessment of UD Tapes using Microscopy and Computer Vision
- Surface Quality Analysis of Composites using a Photobox and Statistics
- High-Temperature Characterization of UD Tapes and Stacks
- Standardized Testing of Composite Materials

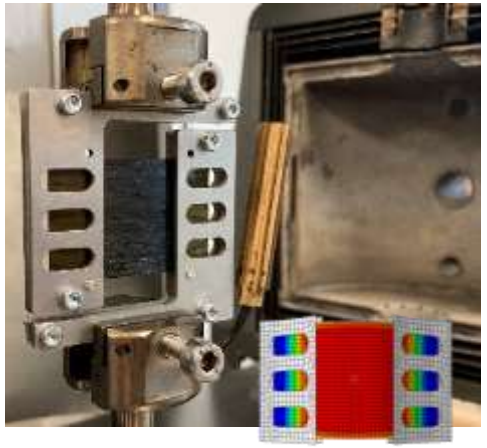
Automated Analysis of UD Tapes

- **Goal**
  - Automated evaluation of critical quality attributes (CQA) of fibre distribution, volume content, and porosity in UD tapes using microscopy images
- **Main Results**
  - Set of robust and explainable parameters that characterize CQA of UD tapes
  - Framework for tailored analysis of different image acquisition scenarios
- **Impact**
  - Quantifiable and objective quality attributes
  - Ground truth for the alignment and calibration of inline quality measurement systems



High-Temperature Material Characterization

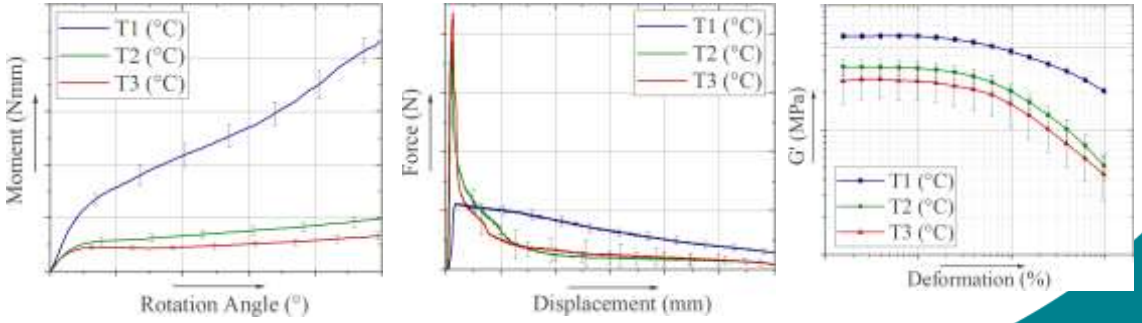
- **Goal**
  - Measurement of material data under process relevant conditions
- **Main Results and Impact**
  - Advanced test methods for the characterization of UD tapes and stacks subject to primary deformation mechanisms
    - Bending
    - Shear
    - Ply/ply and tool/ply slippage
  - Temperature- and velocity-dependent material data for model calibration and process simulation
  - Efficient workflow for the characterization of novel high-performance material systems up to 400°C



ROTATION BENDING TEST

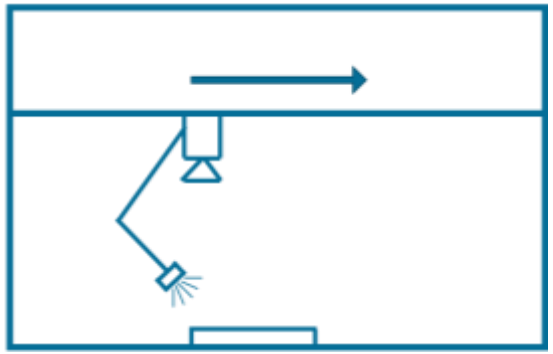
PULL-THROUGH OR PULL-OUT TEST

TORSION BAR TEST

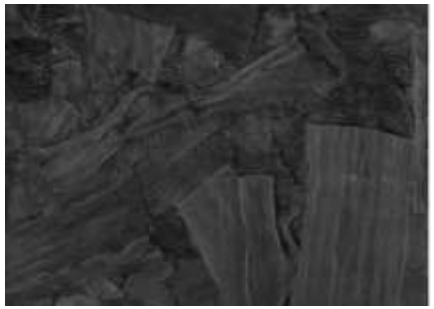


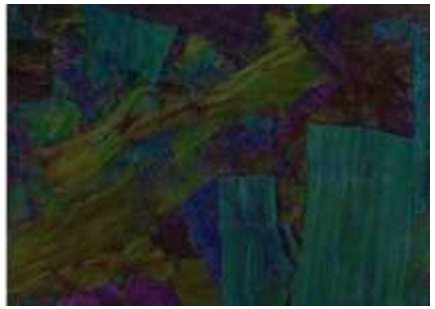
Thermoplastic composite material data within the processing temperature range

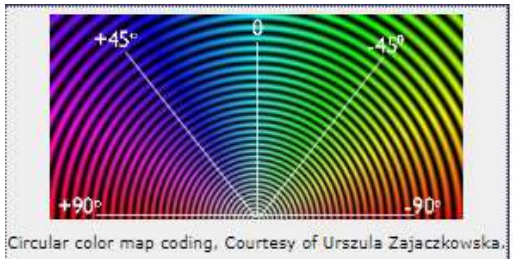
Surface Quality Analysis



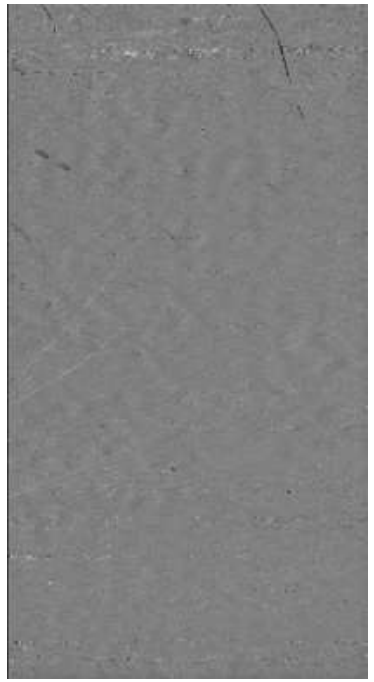
- **Goal**
  - Measurement of surface quality of flat composite parts
- **Main Results and Impact**
  - Custom-built optical measurement system for large surface scans (photobox)
  - Detection of surface defects and fibers using statistics (e.g., in plane fiber waviness through quantitation of fiber orientation)







Circular color map coding, Courtesy of Urszula Zajaczkowska.



Publications

- A. Kapshammer, M.-C. Miron, L. Dangl, Z. Major, Interface Characterization of Consolidated PP/GF Tapes on PP/GF Mat Materials, Polymers, **2023**, 15(4), 935, DOI: 10.3390/polym15040935
- A. Kapshammer, D. Laresser, M.-C. Miron, F. Baudach, Z. Major, Characterization and Modeling of Ply/Tool and Ply/Ply Slippage Phenomena of Unidirectional Polycarbonate CF Tapes, Polymers, 2023, 15(17), 3520, DOI: 10.3390/polym15173520
- K. Kloiber, M. Voltz, C. Marschik, M. Wenninger, S. Kohl, G. Hochleitner, Automated Quality Assessment of UD Tapes, xxx
- D. Laresser, M.-C. Miron, M. Kracalik, F. Baudach, Z. Major, Analysis of the rotation bending test method and characterization of thermoplastic PC/CF UD tapes at processing temperatures, xxx

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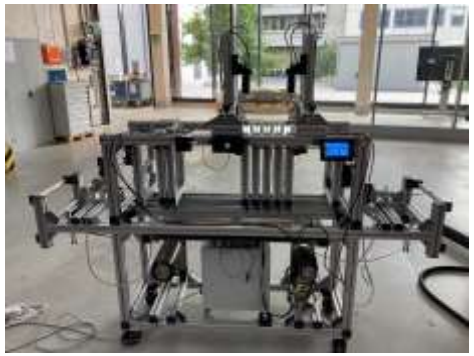
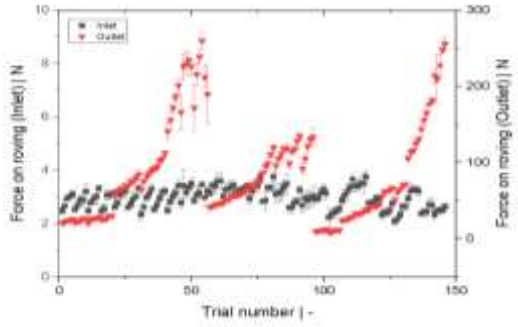
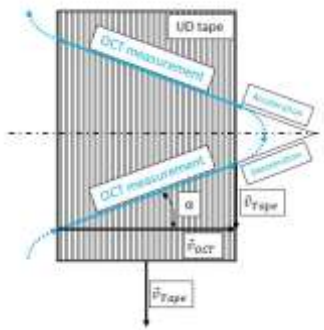
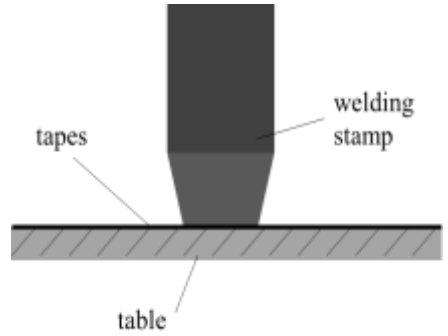
Lab-Scale Equipment









UD Tape Extrusion → Tape Laying → Consolidation → Preheating → Forming / Functionalization

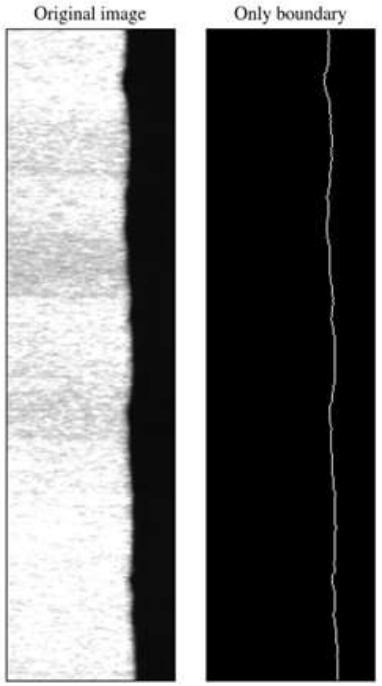
- Fiber Spreading Test Rig
- UD Tape Test Rig
- Lab-Scale Welding Unit
- Lab-Scale Consolidation Unit

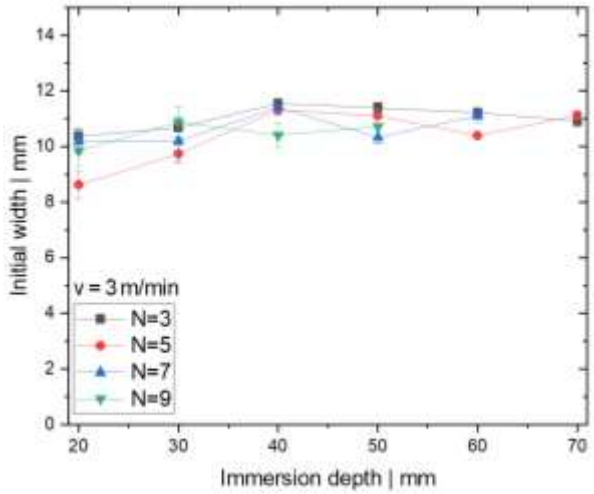
Industrial Scale

- Experiments consume a high amount of energy and materials
- Systematic analyses of process-product relationships are challenging

Fiber Spreading Test Rig

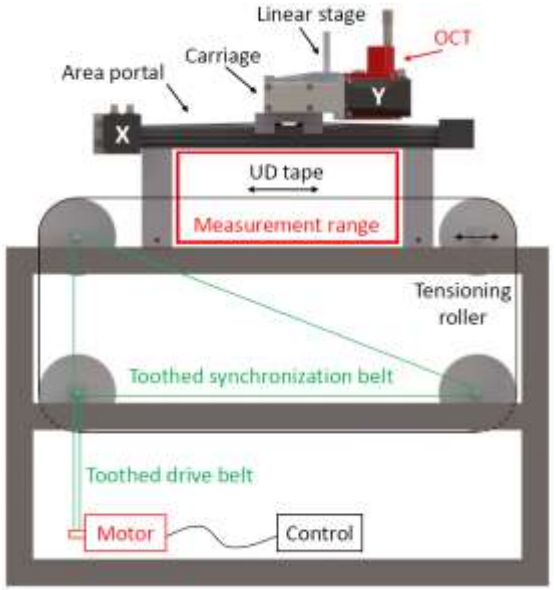
- **Goal**
  - Investigation of mechanical fiber spreading and its main influencing parameters
- **Main Results**
  - Lab-scale test rig for systematic analyses
    - Measurement of fiber spreading behavior and fiber tension
    - Adjustable experimental setup
  - Optimized spreading conditions for different fiber types
- **Impact**
  - Deeper understanding of mechanical fiber spreading
  - Experimental design studies at low cost
  - Improvement of fiber impregnation due to homogeneous fiber carpet

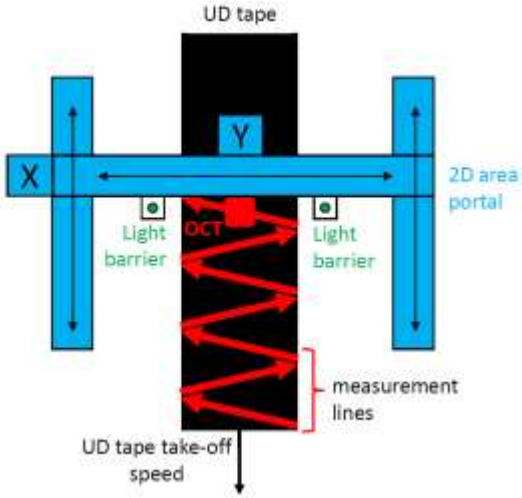


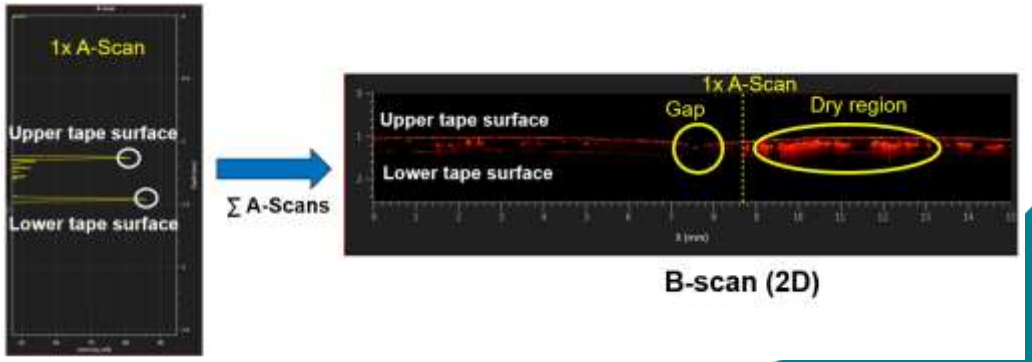


UD Tape Test Rig

- **Goal**
  - Investigation of the inline capability of methods for the non-destructive quality assessment of UD tapes
- **Main Results**
  - Lab-scale test rig for quasi-continuous measurements of moving UD tapes
  - Implementation of OCT for full cross-sectional tape quality inspection
- **Impact**
  - Better understanding of tape defects
  - Inline quality monitoring under process near conditions
  - Fast and cheap experiments at laboratory scale

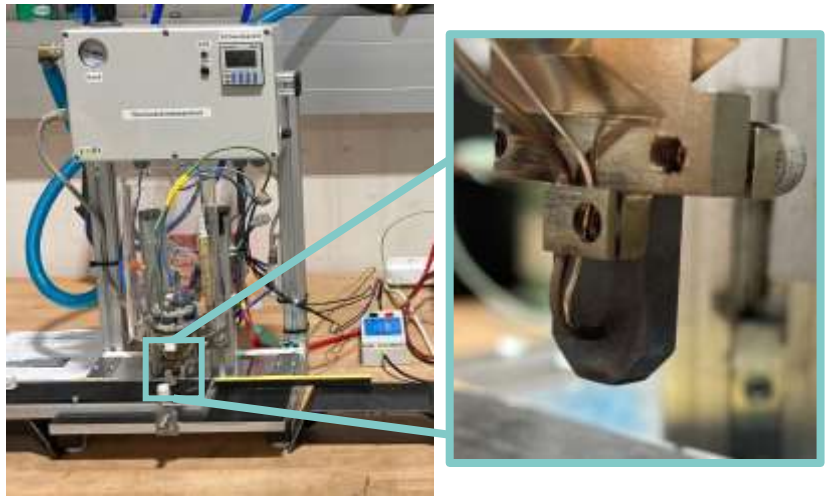


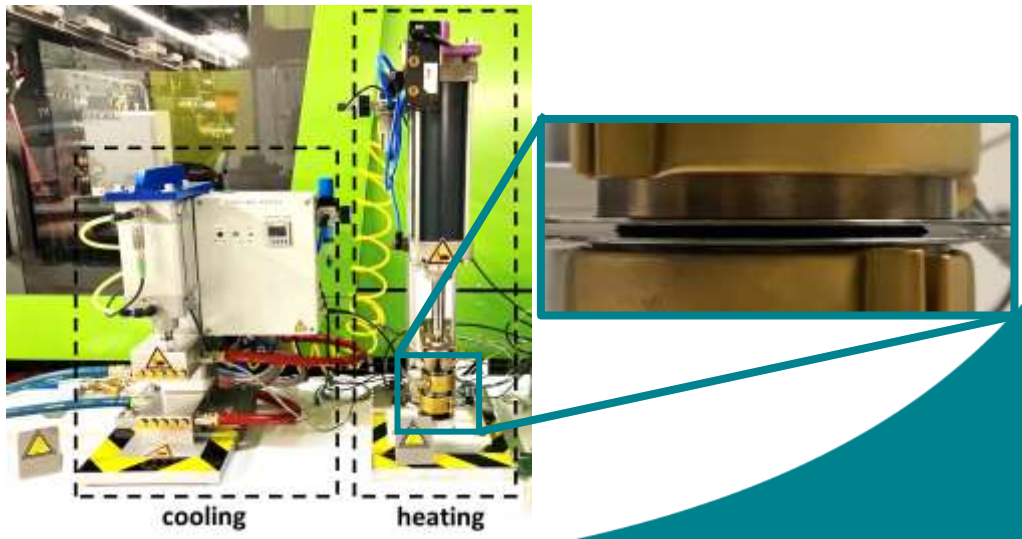




Lab-Scale Welding and Consolidation

- **Goals**
  - Investigation of process-product relations in tape welding and consolidation
- **Main Results**
  - Test rigs for lab-scale welding and consolidation
  - Deeper understanding of the influence of process parameters on:
    - Bonding (welding)
    - Squeeze flow (consolidation)
  - Optimized process conditions
- **Impact**
  - Deeper insights into related process phenomena
  - Experimental design studies at low cost





Publications

- E. Kobler, J. Birtha, A. Kapshammer, D. Laresser, C. Marschik, K. Straka, G. Steinbichler, S. Schlecht, Modeling the Bonding Behavior of Thermoplastic UD-Tapes During Hot Stamp Spot Welding, xxx
- M. Wenninger, C. Marschik, K. Felbermayer, B. Heise, T. Kranzl, G. Steinbichler, A Novel Measurement Approach based on Optical Coherence Tomography for Inline Quality Assessment of Thermoplastic Glass-Fiber Reinforced Unidirectional Tapes, J. Therm. Comp., **2023**, 36, 3943-3965, DOI: 10.1177/08927057221143371
- E. Kolber, J. Birtha, C. Marschik, K. Straka, G. Steinbichler, S. Schlecht, Modeling the anisotropic squeeze flow during hot press consolidation of thermoplastic UD tapes, J. Therm. Comp., **2023**, xxx
- J. Birtha, C. Marschik, E. Kobler, K. Straka, G. Steinbichler, S. Schlecht, P. Zwicklhuber, Optimizing the Process of Spot Welding of Polycarbonate-Matrix-Based Unidirectional (UD) Thermoplastic Composite Tapes, Polymers, 2023, 15(9), 2182, DOI: 10.3390/polym15092182

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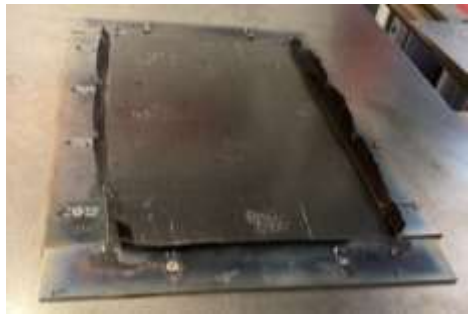
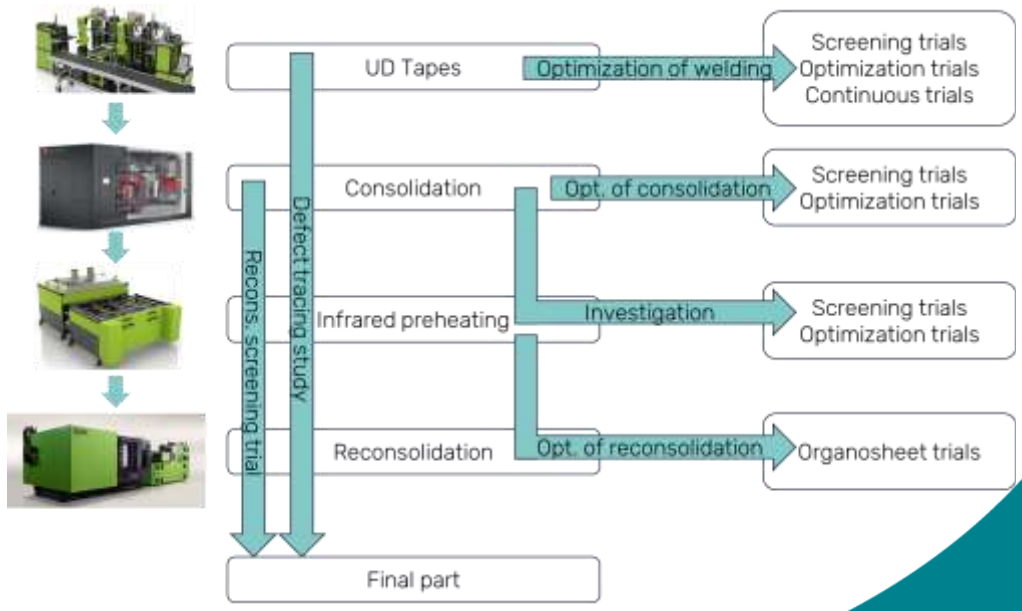
Process Optimization

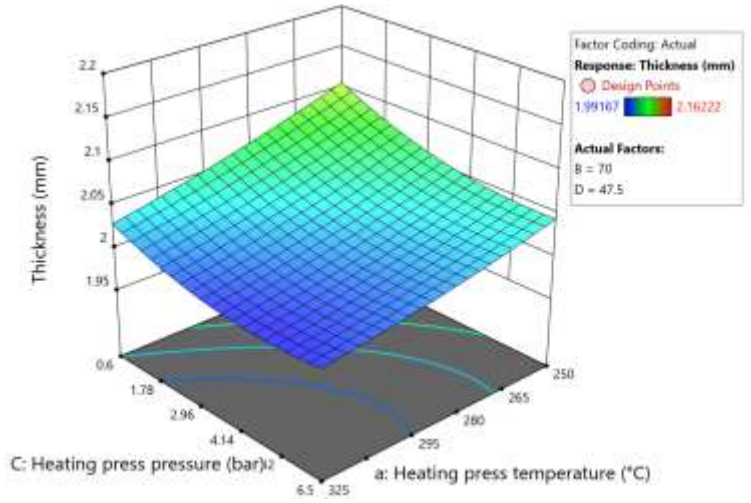
- **Motivation**
  - Optimization of the entire composite production chain
- **Main Results**
  - Implementation of frame tool for an improved consolidation quality
  - Using high temperatures and low pressures during consolidation results in optimal final part quality
  - Consolidated plates deconsolidate during preheating due to residual stresses
  - Assistant systems for sub-process steps
- **Impact**
  - Optimization of the process for a given material is well-understood, supported by a robust technical understanding





Process Optimization - Consolidation

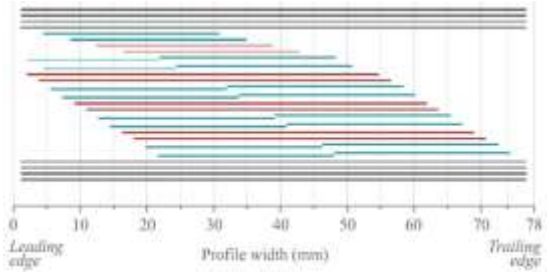
- **Motivation**
  - Optimization of the consolidation steps
- **Main Results**
  - High temperature and pressure cause squeezing of matrix
  - Frame tool implemented to prevent squeeze flow and extend process window
  - Improved bonding strength (23% increase) and reduced void content (4.64%) at desired thickness (2 mm)
- **Impact**
  - Optimization of the process for a given material is well-understood, supported by a robust technical understanding



Laminate and Component Optimization

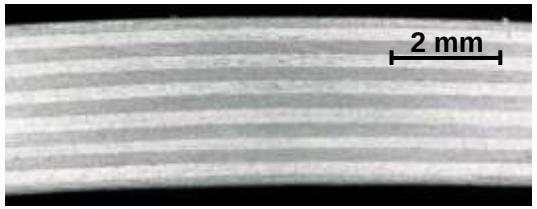
- **Motivation**
  - Component designs suitable for high-rate processing
  - Tailored laminate architectures for geometric and weight/performance optimized components
- **Main Results and Impact**
  - Interaction between laminate design strategies, laminate quality, and structural performance
  - Specific tooling and process design solutions

Pick-and-place tape laying cell

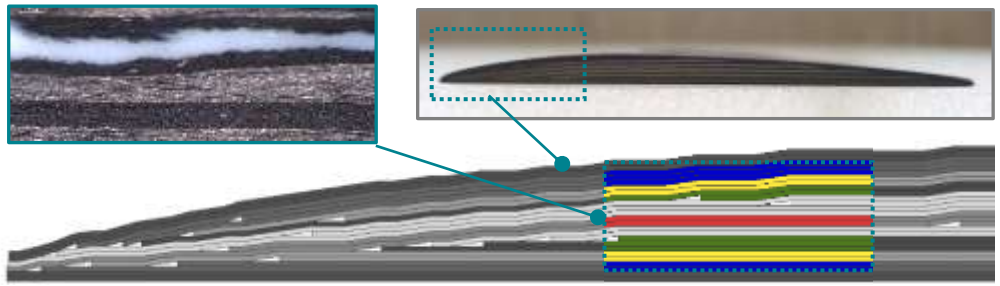


Experimental laminate architecture

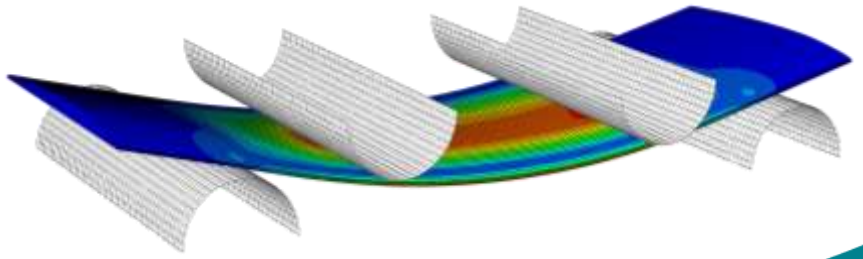
Structural component testing



Optical analysis



Experimental study on the effects of pure polymer core layers



Structural analysis by FE-simulation

Publications

- D. Laresser, J. Birtha, E. Kobler, M. Binder, R.C. Adam, M. Gürocak, M.-C. Miron, Z. Major, Stiffness Equivalent Substitution of an Airfoil Profile by an Automated Manufacturable CF/LM-PAEK Tailored Laminate Architecture, 23rd Int. Conf. Comp. Mat. (ICCM23), Belfast, **2023**.

- D. Laresser, J. Birtha, E. Kobler, R.C. Adam, M. Gürocak, M.-C. Miron, Z. Major, 3D-Consolidation Process for Direct Manufacture of Advanced Continuous Fiber-Reinforced Thermoplastic Composite Components, xxx

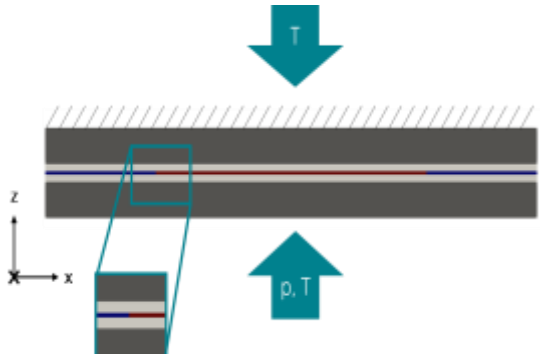
- J. Birtha, C. Marschik, E. Kobler, K. Straka, G. Steinbichler, S. Schlecht, P. Zwicklhuber, Optimizing the Process of Spot Welding of Polycarbonate-Matrix-Based Unidirectional (UD) Thermoplastic Composite Tapes, Polymers, 2023, 15(9), 2182, DOI: 10.3390/polym15092182

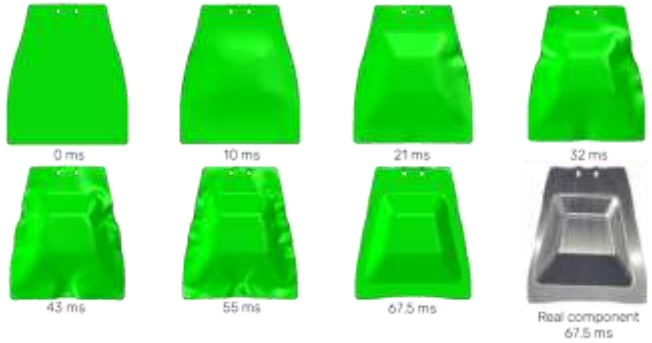
- J. Birtha, E. Kobler, C. Marschik, K. Straka, G. Steinbichler, S. Schlecht, P. Zwicklhuber, Using Heating and Cooling Presses in Combination to optimize the Consolidation Process of Polycarbonate-Based Unidirectional Thermoplastic Composite Tapes, xxx

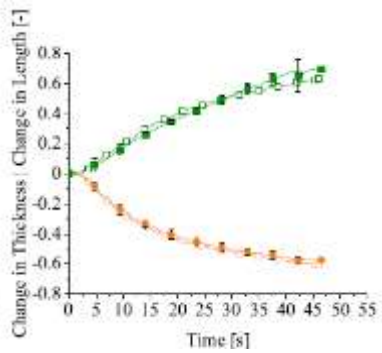
Inhalt

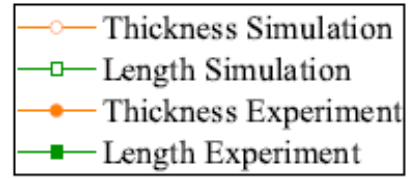
- Introduction
- Inline Measurement Systems
- Material Characterization
- Lab-Scale Equipment
- Process and Component Optimization
- Simulation

Simulation









UD Tape Extrusion → Tape Laying → Consolidation → Preheating → Forming / Functionalization

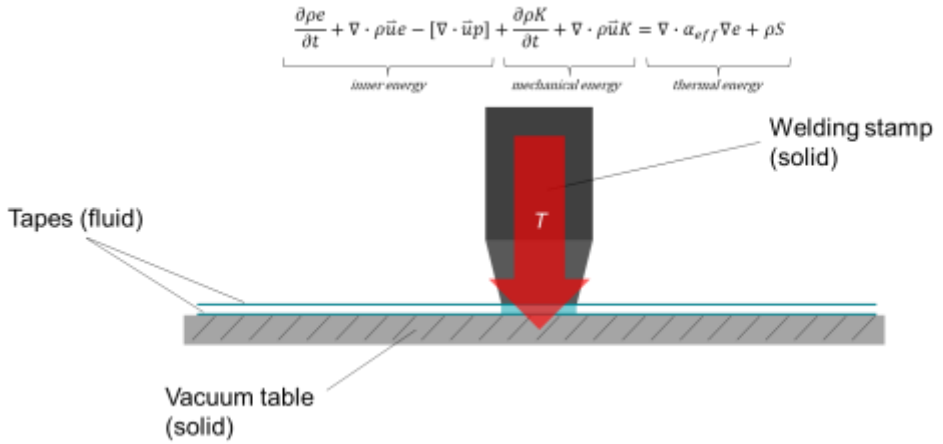
- Welding of UD tapes
- Consolidation of tape stacks
- Preheating of composite parts
- Forming of composite parts

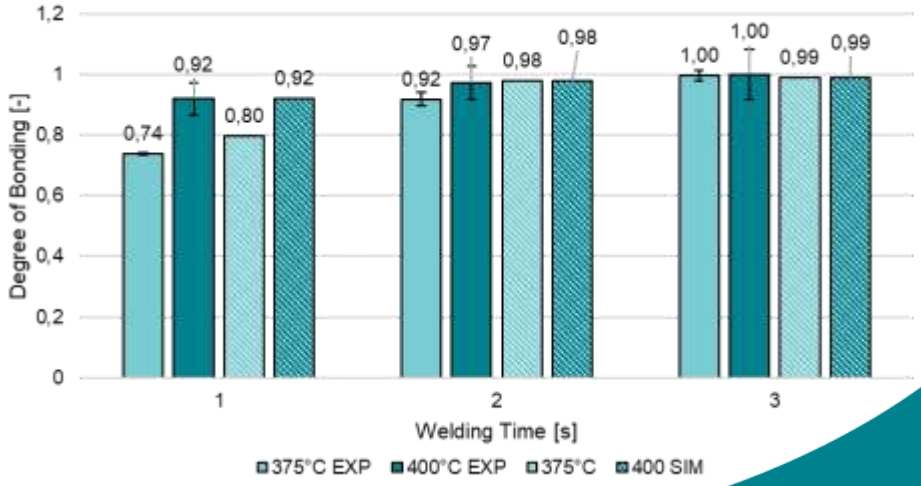
Simulation

- Saves materials and energy by eliminating experimental trial-and-error procedures
- Reduces time and costs in design and optimization studies
- Serves as the basis for the development of digital twins

Welding of UD Tapes

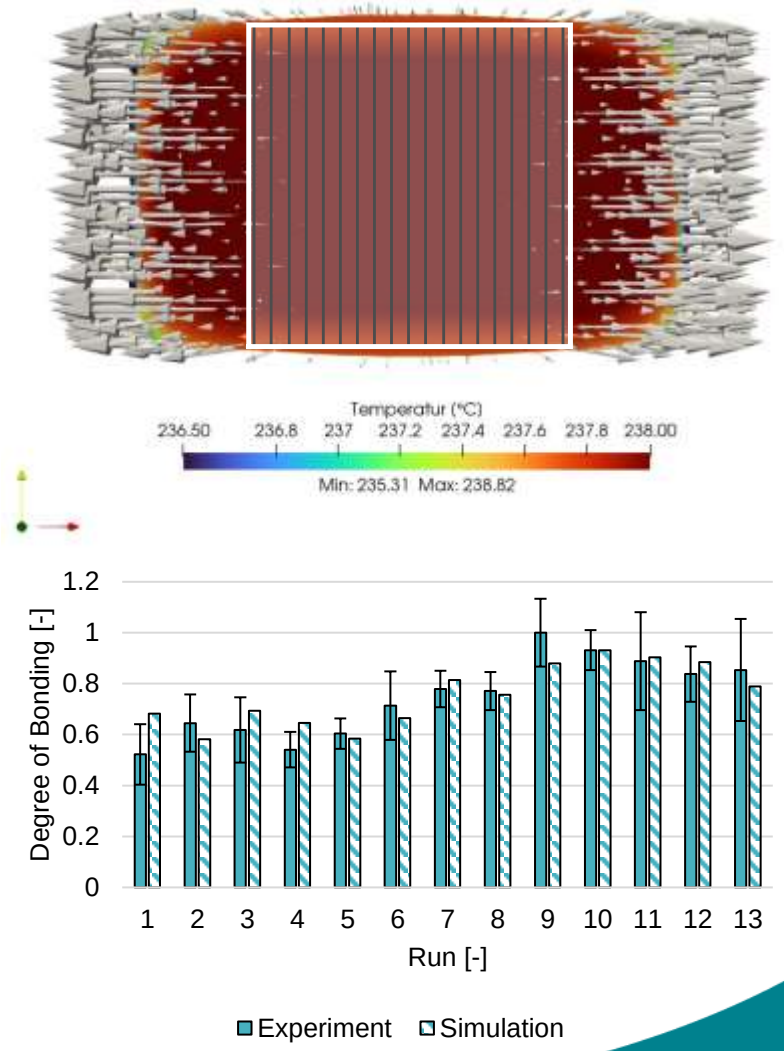
- **Goal**
  - Evaluation of ideal process conditions that provide sufficient bond strength at minimum cycle time
- **Main Results**
  - New multi-region, multi-phase, and multi-component-mixture modeling approach to predicting the welding behavior of UD tapes
  - Successful validation with experimental data (mandrel peel tests)
- **Impact**
  - Tool for process design, optimization, and troubleshooting





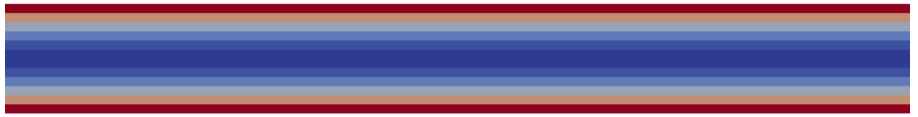
Consolidation of UD Tapes

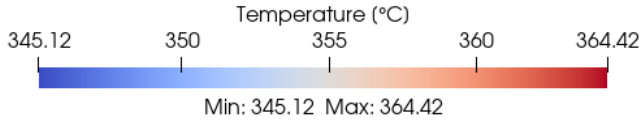
- **Goal**
  - Prediction of the quality of the consolidated part depending on input material and process settings
- **Main Results**
  - New multi-region, multi-phase, and multi-component-mixture modeling approach to predicting the consolidation behavior of UD tapes
  - Successful validation with experimental data on lab and industrial scale
    - Temperature and thermodynamic behavior
    - Squeeze flow and part dimensions
    - Bonding quality
- **Impact**
  - Deeper understanding of phenomenological effects

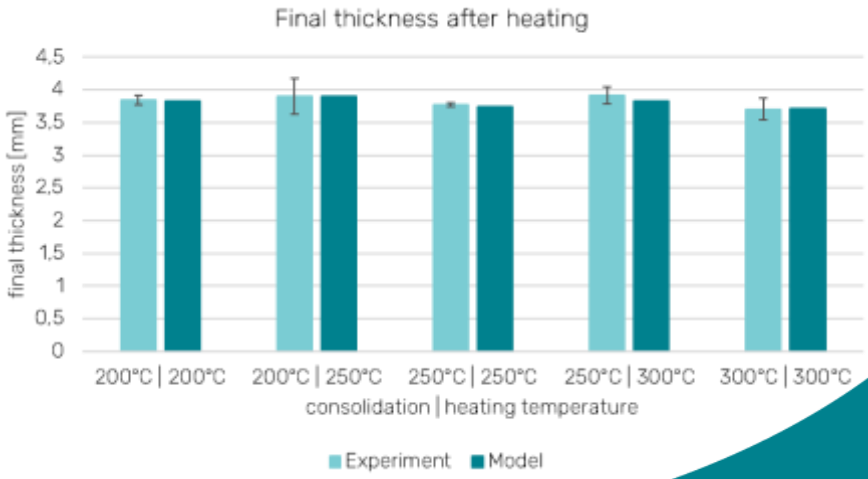


Preheating of Composite Parts

- **Goal**
  - Prediction of part quality depending on input material and process settings
- **Main Results**
  - Coupling of analytical and numerical modelling techniques
  - Prediction of
    - Temperature at core of part
    - Thickness change due to deconsolidation
  - Successful validation with experimental data
- **Impact**
  - Near real-time prediction possible

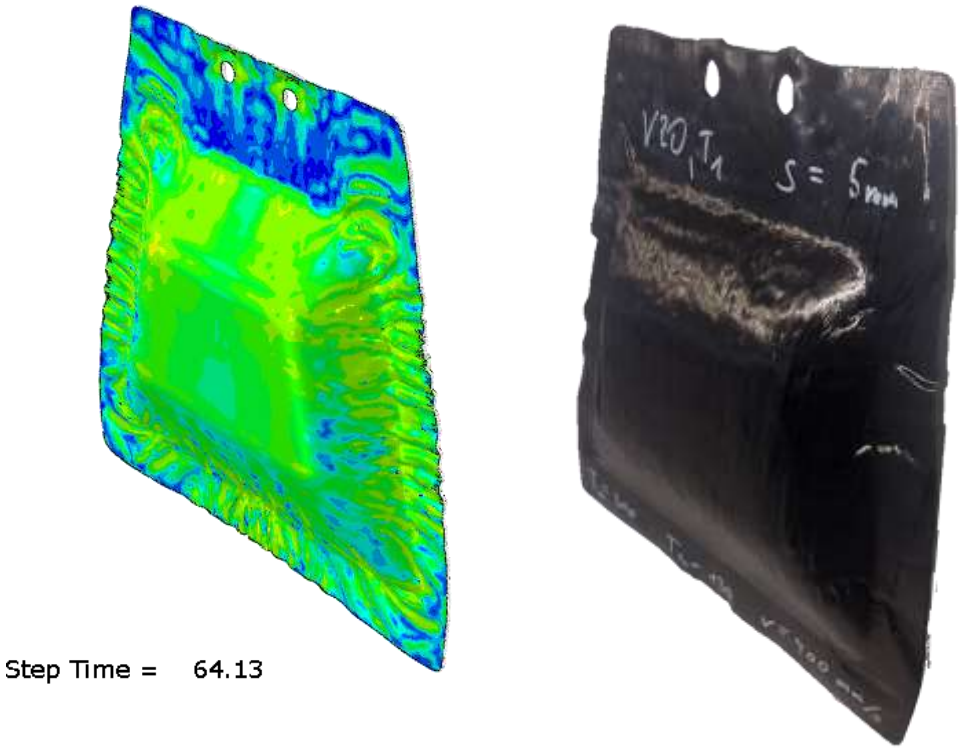






Forming of Composite Parts

- **Goal**
  - Identification of potential manufacturing defects without direct experimental investigation
- **Main Results**
  - Implementation of a FEM solution able to model the forming process of UD thermoplastic composite stacks
  - Coupled thermal and mechanical simulation that predicts localized defect formation and evolution during forming
- **Impact**
  - Deeper understanding of UD composite stacks' behaviour during the forming process
  - Insight on the behaviour of the laminate during the component design phase



Publications

- E. Kobler, J. Birtha, C. Marschik, K. Straka, G. Steinbichler, P. Zwicklhuber, S. Schlecht, A Novel Multi-Region, Multi-Phase, Multi-Component-Mixture Modeling Approach to Predicting the Thermodynamic Behavior of Thermoplastic Composites during the Consolidation Process, Polymers, **2022**, 14(21), 4785, DOI: 10.3390/polym14214785
- E. Kobler, J. Birtha, B. Cäsar, L. Gahleitner, G. Mayr, K. Straka, C. Marschik, G. Steinbichler, P. Zwicklhuber, S. Schlecht, Modeling the Thermodynamic Behavior of Thermoplastic Composites during Preheating in an Infra-Red Oven, 23rd Int. Conf. Comp. Mat. (ICCM23), Belfast, **2023**
- E. Kobler, J. Birtha, A. Kapshammer, D. Laresser, C. Marschik, K. Straka, G. Steinbichler, S. Schlecht, Modeling the Bonding Behavior of Thermoplastic UD-Tapes During Hot Stamp Spot Welding, xxx
- E. Kobler, J. Birtha, C. Marschik, K. Straka, G. Steinbichler, S. Schlecht, Modeling the anisotropic squeeze flow during hot press consolidation of thermoplastic UD tapes, J. Therm. Comp., **2023**, xxx
- E. Kobler, Modeling the Consolidation Process of Thermoplastic UD Tapes, PhD Thesis, Johannes Kepler University Linz, **2023**