Fraunhofer

digitalTPC – Digital Twin for Thermoplastic Composites Technology

Public Project Report

Feedback from Industry

Fraunhofer research for industry

Within the framework of MAVO, Fraunhofer's internal research program for market-oriented preliminary research, the Fraunhofer-Gesellschaft bundles the expertise of various institutes into original preliminary research projects.

DigitalTPC addresses strategic research fields towards a sustainable, circular, and smart production. Digital Twins that span the entire value-adding chain represent a key technology for this. The close interdisciplinary cooperation of four Fraunhofer Institutes makes it possible to tackle such a challenging task. The digitalTPC Consortium represents a strong combination in the fields of material science, simulation, AI, and non-destructive testing.

At Fraunhofer, we believe the such fundamental technologies must be demonstrated in industry-relevant applications. Therefore, the value-adding chain to produce lightweight thermoplastic composite parts was implemented. We hope to present an attractive offer to step towards industrial application together with our partners and customers.

Michael Edelwirth
Head of Department
Internal Research Programs

PROSTEP AG – we integrate the future

For PROSTEP AG and me it is a big honor to be part of the MAVO project DigitalTPC!

It is very impressive to see the deep expertise of the different Fraunhofer Institutes within their dedicated competence fields.

We at PROSTEP AG care about the role of data within the Digital Twin. We see that it is very important to understand the purpose of the individual Digital Twin instance.

The focus of the Digital Material Twin within the DigitalTPC project is on the material and the process flow along the design, testing and manufacturing phase. The successful definition of a semantic model, which overlays these phases is a corner stone for future Industrie 4.0 and KI-based use-cases within a sustainable material management concept. We are looking forward to use these results within our own projects and in future collaborations with Fraunhofer SCAI.

Dr. Martin Strietzel
Director
PLM Strategy & Processes

Mercedes-Benz Group AG

Mercedes-Benz AG is one of the leading global OEM´s of premium and luxury cars and vans.

In our development and production sites we are faced with the challenge of providing high quality products for our customers, which are also highly efficient in terms of material and energy consumption. This must be considered for the whole complex value added chain of automotive components.

The digitalization of the value chain for sustainable lightweight thermoplastic composite parts, which is addressed in the DigitalTPC project, opens up a whole range of new potential. Especially the project focus on material aspects over several steps of production processes is of key interest in terms of sustainability and material efficiency for Mercedes-Benz. We are convinced that concepts and results of the project will be transferred into industrial process soon.

Achim Koehler
Senior Manager RD/KES
Dachsysteme

Content

Digital Twin for Thermoplastic Composites Technology

Digital Twin Systems

Digital twins of individual machines and systems already lead to significant increases in efficiency in industrial production and continuous operation, e.g. through improved production control and machine maintenance. However, their potential for value-added and material-triggered process control is still largely untapped. This applies in particular to the increasing series production of plastic-based composite lightweight structures.

The digital twin for thermoplastic composites (digitalTPC) is intended to demonstrate this potential by means of the UD tape and hybrid injection molding technology. This technology is currently establishing itself on the market and is capable of large series production. Continuous fibre-reinforced thermoplastic composite (TPC) semi-finished products (UD tapes) are thermoformed and overmolded. In particular, the complex and heterogeneous microstructure of the composite material itself has a significant influence by on the manufacturing process of semi-finished products and the structural components. This influence poses an enormous challenge for process control and quality assurance and requires the complete digitalization of the entire production process.

Objectives of the Project

The digitalTPC project pursued four important goals:

- The realisation of an extended Digital Twin representing the complete value-added chain for manufacturing of lightweight thermoplastic composites structures
- The integration of non-destructive cognitive sensors into the manufacturing processes to extract material and processing data from all sub-steps
- The definition of an extended ontology, enabling data analytics and links to continuous CAE simulation chain
- The implementation of individual quality assessment and self-adapting processing steps within the complete value-added chain

Unidirectional continuous fiber reinforced thermoplastic tape

R&D Approach

The project digitalTPC aimed at the comprehensive and holistic consideration of all sub-process steps, partly taking place at different locations, from the semi-finished product to the component production.

With the help of suitable process-integrated and cognitive sensor technology, selected relevant material, process and component characteristics (e.g. fibre orientation, pore content, semi-finished product thickness) were measured and recorded throughout the entire real value-added chain.

Measured data was linked to a continuous simulation chain across all process stages. Ontology based data analytics was provide feedback to processes and machines as part of the digital twin.

Involved Engineering Domains

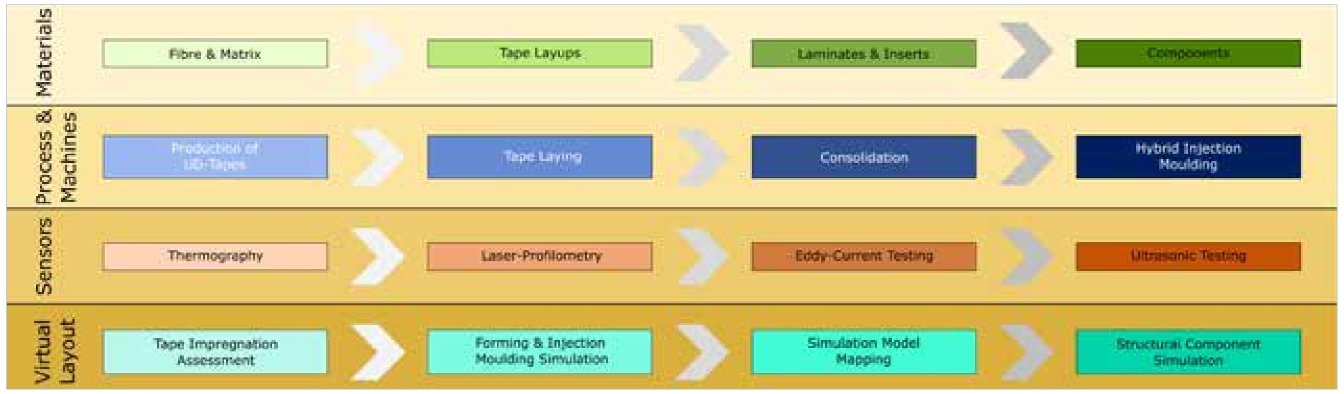
Within digitalTPC we identified four major engineering domains to provide substantial information to the digital twin:

- raw materials, intermediate products, final component
- manufacturing processes and machines,
- offline measurement and inline sensor and technology,
- virtual design and engineering software

Information from these domains needs to be

- semantically defined in a domain specific ontology,
- distributed databases need to interconnected, and
- AI-based method for data analytics have to be deployed

In the following chapters these steps will be described in more detail.



Materials	Fibre & Matrix	Tape Layups	Laminates & Inserts	Components
Process & Machines	Production of UD-Tapes	Tape Laying	Consolidation	Hybrid Injection Moulding
Sensors	Thermography	Laser-Profilometry	Eddy-Current Testing	Ultrasonic Testing
Virtual Layout	Tape Impregnation Assessment	Forming & Injection Moulding Simulation	Simulation Model Mapping	Structural Component Simulation

Major engineering domains providing data and input to the digital twin

Challenge 1 –
Optimising Tape Production

Production of UD Tapes

Hybrid injection moulding based on thermoplastic UD-tape reinforcements is a technology to produce complexly shaped composite parts. Within digitalTPC, the entire process chain from manufacturing of semi-finished products to the final part is focused upon. For components from thermoplastics, interdependencies between process and fibre orientation, thickness distributions, delamination probabilities, etc. are crucial for the final product characteristics. The locality of these attributes explains the need for greater information detail in the manufacturing twin. To analyse them, non-destructive testing (NDT) is integrated, which requires high resolution, e.g. for close-meshed, integrated recordings of the microstructures.

UD-Tape Production

Left: Tape with Carbon Fibre Reinforcement / Right: Carbon Fibres

Challenges

Within the scope of the project, the quality and grade of the UD tapes are recorded using the inline measurement systems and provided as supplementary information to the real tapes. The digital twin offers information like tape thickness and grey scale values from thermography correlated to FVG and material characteristics.

Additional Information

The digital twin enables quality assurance and monitoring of the manufactured UD-Tapes and furthermore a complete proof of tape quality (characteristics map). The data of quality is available for a complete UD-Tape role from start to finish and the comprehensive digital quality data are linked to real product and includes thickness information and fibre content.

The digital twin contributes to a cost- and thus time-saving quality assurance process.

In addition, fluctuations in quality can be responded more quickly and effectively. According to the stored correlations of the quality parameters and the process parameters to be set.

Expected Advantages

The digital twin will support a sustainable and material-saving hybrid molding process:

- Incoming inspection for tape thickness is eliminated
- Reproducible and robust process with regard to laminate thickness as an important factor for subsequent hybrid molding.
- Reduce inspection effort (incoming/outgoing goods)
- Clarify complaints + recourse cases
- Marketing (digital quality map as competitive advantage)

Challenge 2 –
Tracking Defects

Defects in Lightweight Components

One of the most efficient strategies to reduce weight by lightweight design is function integration. Here, different functions from different modules are integrated into one decreasing the number of required modules and joints. Thereby the overall weight is significantly reduced. However, this approach increases the part's complexity and the demand for sophisticated manufacturing processes. This results in a process chain that consists of several single manufacturing steps. Destructive or non-destructive quality inspection as well as testing of general functions is only possible at the end of the value chain. When the final part does not fulfill all requirements significant costs for scrap arise.

Left: Tracking defects to avoid passing them to the next value-added step. Right: Defect (gap) in tape is transferred into the tape layup

Challenges

The reasons for a part being identified as scrap can be low mechanical performance or poor overall quality for example because of surface appearance or warpage. These can be caused by various influencing factors along the process chain: single or multiple manufacturing steps are out of tolerance, defects in the raw material or defects in the semi-finished products. By creating a digital fingerprint or digital twin of the whole process chain these defects can be tracked back to their original cause. A digital twin provides material and process specific information for each step of the value chain that enables the manufacturer to identify defects at the earliest possible state. Thus, the reduction of costs can be achieved as follows:

- Defects are identified at an early stage in the production. The defect part can be extracted from the process chain and does not have to go through all remaining steps of the value chain.
- Defects in the raw material or semi-finished products do not necessarily have to result in the part being scrapped. Some defects can be healed in the same or subsequent manufacturing step for example by modification of process parameters. In this way the amount of scrap and simultaneously the costs can be reduced.

Expected Advantages

A digital twin provides the potential for identification and tracking of defects in a complex value chain for manufacturing of highly function integrated parts. Furthermore, it helps to understand the causes enabling the manufacturer to react at the earliest possible state. It allows the manufacturer to identify deficits in the quality of raw materials so that only a few semi-removed as scrap leading to a substantial reduction of costs.

Challenge 3 –
Integrated Sensors for Online Monitoring

Sensors within digital twins

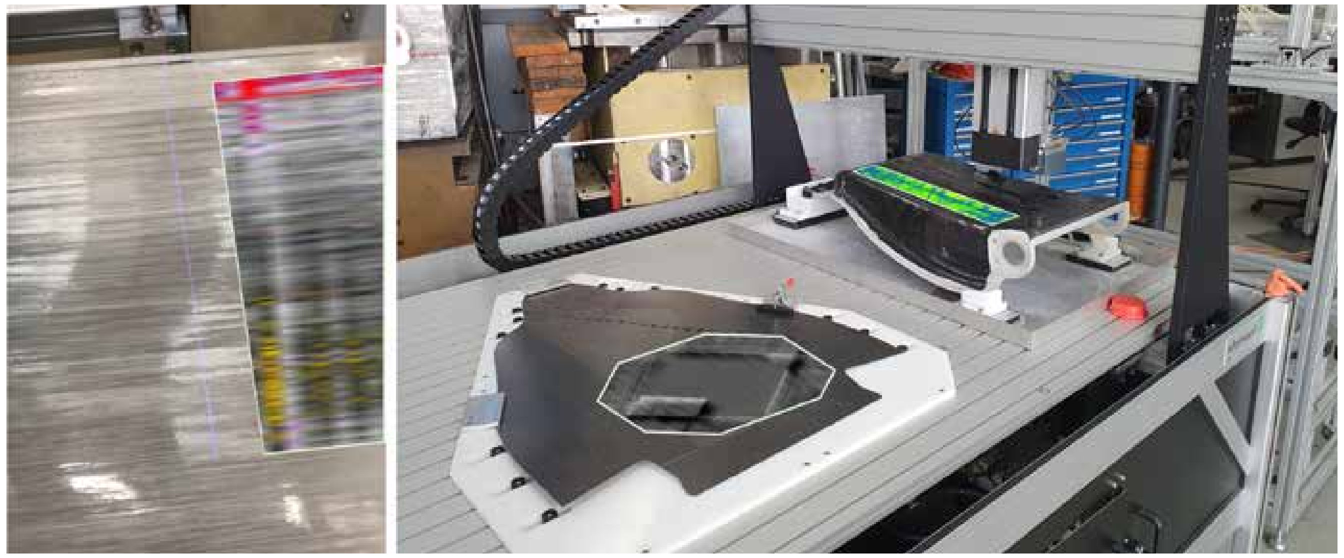
Along the complete process-chain each of the individual process steps may induce material defects and alter the manufactured quality. However, it is often unclear how the defects evolve during manufacturing and affect the properties of the final component. As a consequence, to avoid detrimental effects, defected parts are ejected. Thus, reducing the defect-incidence and/or severity due to process-parameter adaptation as well as gaining the ability to distinguish between tolerable and critical defects will contribute to a time and cost effective manufacturing. Both can be achieved using the benefits of relatable data in a digital twin.

In this perspective, the role of detecting and archiving quality deviations and defects within individual process steps comes to sensors. Since many being based on classical non-destructive testing methods, they work on different physical interaction principles. This allows to choose a suitable sensor for the desired or pre-defined target values, e. g. inspection speed, lateral resolution and defect-sensitivity.

Hence, inline-sensors can be interpreted as tools capturing a representative property of a produced part or component, such that information on defects and part-quality are expressed in a measureable quantity and fed into a digital and interoperable world. In other words, the sensors can be described as the output observer of a control-circuit.

Long term perspective

Following the overall aim to realize a fully automated and adaptive process control, the integration of sensors into a digital Framework may become one essential cornerstone. From today's standpoint it seems a viable way in near future to capture an exact image of semi-finished products as well as component-parts by means of their properties and using machine learning tools to classify the quality (i.e. defect recognition) and to counteract deviations from target values.



Left: Inline Sensors in Tape Production / Right: Inspection of Laminates and Components

Therefore, the technological realization includes

- Implementation of sensors for fast and accurate capture of all relevant properties
- Accessibility and provision of data across locations
- Supply of material-dependent sensor-data, e.g. calibration parameters
- Build-Up models for fast and automated detection of defects and quality-classification
- Knowledge on the evolution of defects throughout the process-chain
- Comparison of measurement data with simulation data
- Enhance stored data from proprietary NDT data-types towards DICONDE, a standardized, sovereign datatype including all relevant meta-data. Secondly, providing a semantic description of the meta-data
- Association of monitoring-data with timestamps and exact positions for cross-correlation with process- and simulation-data
- Analyzing the effect of tape-thickness throughout the process chain
- Objective quality evaluation: defining what a measured-quantity means in terms of the quality. building-up AI-models for an automated classification

Project realization

Limitations due to the project frame of 3 years motivated to focus on the technical implementation of monitoring systems within the thermoplastic lightweight process-chain. Thus, it is not the aim to find generalized solutions, but to fully implement an exemplary solution and learn how to interconnect NDT-monitoring with different disciplines and how to communicate data within one connected data-ecosystem. However, the implementation of monitoring systems involves:

- Choice of representative locations for the implementation of monitoring-systems
- Selection of relevant quality-features
- evaluation of suitable non-destructive testing sensors to detect the selected features
- cross-location data acquisition and -transfer to an accessible server

Expected Advantages

A digital twin would enable to push material information to the sensors to choose optimized inspection parameters. Thus, with the sensors being adjusted to the passing material, enables automatic detection of quality features and archiving on a decentral server for documentation. Using the data should enable the automatic detection of defects with subsequent quality classification, which serves as input for an adaptive process control.

Finally, optimized process parameters could be derived adaptively, increasing the reproducibility of produced quality, decrease bad parts and thus contribute to a more efficient production.

From Raw Material to a Finished Component

From UD Tapes to a Seat Backrest

Unidirectional Fibre reinforced thermoplastic matrix composites possess distinct advantages compared to thermoset matrix composites in terms of recyclability, cost effectiveness, and flexibility of design. Hybrid injection moulding based on thermoplastic UD-tape reinforcements is a technology to produce complexly shaped composite parts.

Within digitalTPC, the entire process chain from manufacturing of semi-finished products to the final part is focused upon. This process chain contains the single steps of tape manufacturing, tape laying, consolidation and the final step of hybrid injection moulding. The following section introduces each process step with their specific key process parameters effecting the product quality. The tape production is done at Fraunhofer IMWS, the remaining manufacturing steps are conducted at Fraunhofer ICT.

Fibre and Matrix

The single components for the production of UD-Tape are the fibres and the thermoplastic matrix. Initial state of the fibres are rovings with continuous fibre on coil and initial state of polymer matrix material is the thermoplastic polymer as granules. The incoming parameters of the individual components are documented for processing.

Left: Carbon Fibre on Coil / Right: Polymer Granulate

UD Tapes

Thermoplastic UD tapes are unidirectional fibre-reinforced semi-finished film products, with the reinforcing fibres consisting of glass, natural or carbon fibres, for example. The thermoplastic matrix enclosing and fully impregnating the fibres can be made of polymers such as PP, PA6 and others. The individual components are processed into thermoplastic UD tapes in a continuous melt impregnation process.

Left: Tape Production / Right: Final Tapes

Tape Layups

A tape layup consists of several pieces of continuous fibre reinforced thermoplastic tape stripes. These stripes are placed next to each other according to the desired shape or contour of the layup to create the first ply. Within a ply all reinforcing fibres are orientated in the same direction. In the following more plies are added on top of the first ply to create the tape layup as specified in the ply book. The layup configuration given in the ply book describes the fibre orientation in each specific ply as well as the total number of plies. It is derived from the load cases of the final part and adapted to suit the direction of loading.

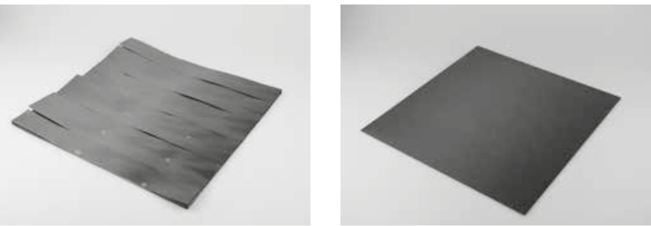
The geometry of a tape layup is usually two-dimensional and tailored to the final part's contour. For complex shaped contours, the tape layup will exceed the contour boundaries because of the limited possibilities to cut the tape in length and angle. The maximum size in x- and y-direction is therefore depending on the given contour and the tape width which affects the difference in layup contour and final part shape. The layup height is determined by the number of plies given in the ply book. In specific cases local reinforcement of layups by placing single tape stripes at defined locations can be required. This causes thickness variations within the layup leading to a three-dimensional geometry. The characteristics of a tape layup can be described by the following parameters:

- Material system (matrix type and reinforcing fibres)
- Size and shape of the contour
- Ply configuration and number of plies
- Process parameters

Laminates

In this project laminates are defined as consolidated tape layups. The consolidation process is here necessary because the tape layup is only locally spot welded with ultrasonics to allow for handling operations. After the consolidation step the laminate is available as monolithic semi-finished product. This guarantees that the baseline for further process steps is always identical. Laminates are often used as reinforcing inlays in hybrid structures. There are only few applications where they represent a part after thermoforming without overmolding. Laminates can be considered as the next semi-finished product state based on a tape layup. Therefore, the laminate's geometry is in accordance with the tape layup.

However, during the consolidation process the material is heated above melting temperature to join the single layers. Thereby a minor thickness decrease is induced. The expansion in x- and y-direction is identical to the tape layup. If required, the laminate can be cut to a defined shape using water jet cutting or a punch. The parameters to describe the laminates characteristics are identical to the ones mentioned for the tape layup.



Left: Tape Layup / Right: Consoidated Laminate

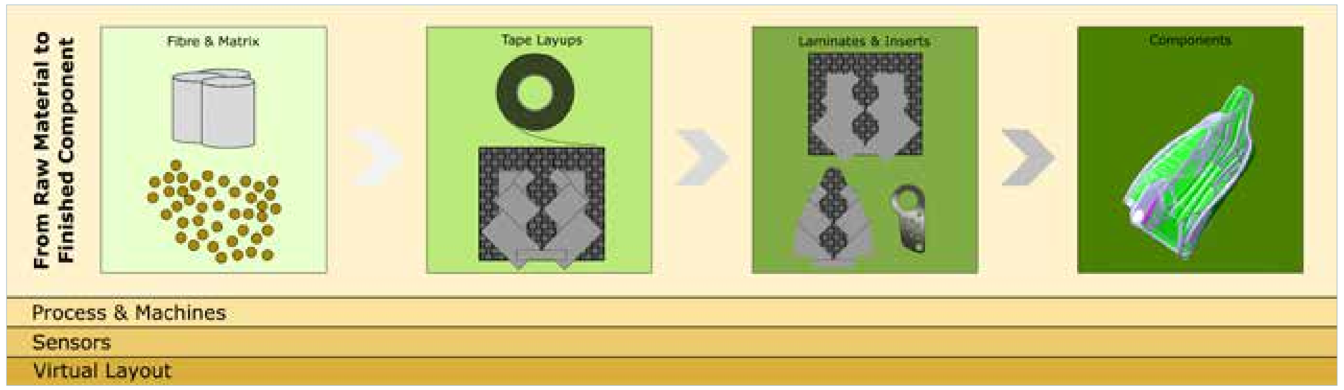
Components

The generic demonstrator part in this project represents a seat backrest which is manufactured in a hybrid injection molding process. Within this demonstrator a UD tape-based laminate is used as reinforcing inlay which is overmolded with short fibre reinforced thermoplastics. The thermoplastic used as injection molding material must be the same type as in the tape layup.

Requirements towards the part's geometry result from available design space and the load cases. Aspects that describe the component's characteristic are for example:

- Size (length, width, height)
- Material systems for laminates and injection molding material
- Process parameters (temperatures, dwell times, pressure, etc.)

Seat backrest



Manufacturing Processes and Machines

Production of UD-Tapes

Thermoplastic UD tapes are unidirectional, fibre-reinforced semi-finished foil like parts, with the reinforcing fibres consisting of glass, natural or carbon fibres, for example. The tapes are produced from fibres wound in endless form on a coil in a continuous melt-impregnation process. These reinforced tapes usually have a very high fibre content of approximately 70 mass percent, with a foil thickness of between 200-400µm.

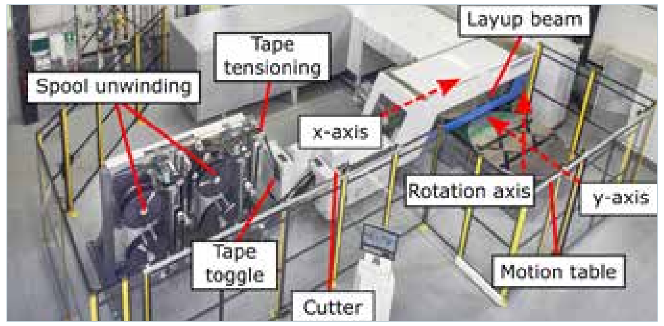
A pulling mechanism at the end of the process line draws the endless roving coils off warping creels across a spreader. Here, a gap-free fibre carpet is generated from the total number of rovings and fed to a wetting tool via the wetting unit. An extruder supplies thermoplastic melt to the wetting unit in order to pre-wet the guided fibres with the melt. The resulting UD tape then goes to a calendar, which improves the surface quality of the tape further and finally calibrates the tape thickness. The UD tape is wound on cardboard tubes for further processing. The system logs more than 40 parameters during this process, including the mould temperatures, pressures and pull-off forces at several intermediate positions.

Tape production chain

Stacking Process

The stacking process is represented by an automated tape laying (ATL) process which is subsequent to the initial tape manufacturing step. Here, the technology used is a Fibreforge automated tape laying machine from Dieffenbacher. The Fibreforge can process tapes from 50 to 165 mm in width. Therefore, a slitting process is required prior to tape laying where the tape is cut from its original cardboard tubes to the desired width. In the applied ATL process tape stripes are placed onto a motion table according to a desired layup geometry with a distinct contour. The stripes have a defined length and are positioned next to each other to create a layer. Within a layer, the fibre orientation can be chosen individually and is usually adapted to the load case in the final component. For each loading direction there is a single layer placed onto the previous one. Each layer is joined by ultrasonic spot welding to the layer below. The result is called tape layup.

To create such a tape layup the tape is spooled onto machine-specific spools from which it can be fed to the Fibreforge via a tape toggle. The tape is automatically unwound, cut into length, and transported to the layup beam. In a vertical travel it is placed onto the motion table. The first layer is fixed by evacuating air through small cutouts in the table's surface. After that, the following layers are fixed by ultrasonic spot welders. The position in x-direction is determined by the layup beam. The position in y-direction and the fibre orientation is realized by the motion table.

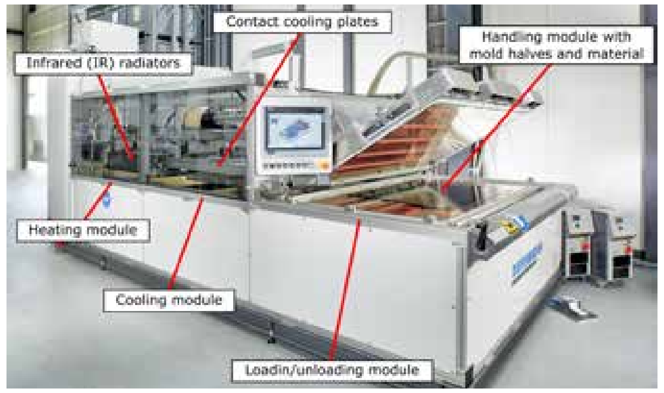


Dieffenbacher Fibreforge Tape Laying Machine

Consolidation Process

During the consolidation process the tape layup is processed to a two-dimensional monolithic semi-finished product which can be used in thermoforming or hybrid molding to manufacture a component. Consolidation means here heating the tape layup above the melting temperature of the used matrix system and cooling it down while applying pressure. Thereby the single layers of the layup are firmly bonded. The process of consolidation is realized with the Fibrecon technology from Dieffenbacher. This process uses infrared radiation to heat up the layup and vacuum to apply the required pressure. Depending on the moisture absorption of the matrix system, the tape layups are pre-dried to decrease the amount of residual moisture in the material in order to minimize the impact on porosity. Thermocouples are used to monitor the temperature within the layup during processing. The tape layup is placed in between two infrared permeable mold halves and the cavity between them is evacuated. The vacuum stays activated throughout the whole process cycle applying pressure during heating and cooling of the tape layup.

Heating takes place in the heating module which contains infrared radiators that heat the layup simultaneously from both sides until the defined target temperature is reached. With the end of the dwell time the heating cycle is completed and the mold halves are transferred to the cooling module. Here the material is cooled by contact cooling. As last step the vacuum is deactivated and the consolidated layup, called laminate, is demolded.



Dieffenbacher Fibrecon Consolidation Machine

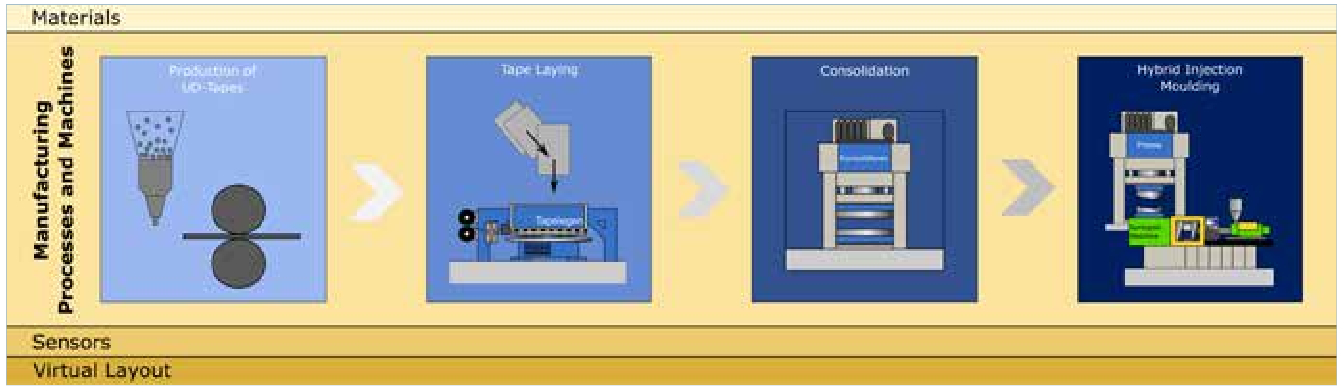
Throughout the whole process data is recorded monitoring the laminate temperature measured by integrated thermocouples, the residual cavity pressure as well as heating and cooling times. The log file can be exported for each single consolidation cycle. By using the date and time stamp as unique identifier it is possible to link process data to each laminate and import this information via a SQL data base into the digital twin.

Hybrid Injection Process

The hybrid-injection molding process is the last step in the process chain to manufacture the final component. The consolidated laminate from the previous step is used as reinforcing inlay for the demonstrator structure, represented by a seat backrest. It is pre-heated and then stamp-formed and over-injection molded simultaneously. Thereby the final component is manufactured in one cycle. The process is called hybrid because two different semi-finished products are used. On the one hand the continuous fibre reinforced laminate and on the other a short fibre reinforced injection molding compound. Different modules are combined to from this type of process. The first module is an IR heating device which is responsible for pre-heating the laminates to processing temperature. After the dwell time is completed, a robot assisted gripper picks up the laminate and transfers it onto the mold. This handling system represents the second module in the process chain.

Within MAVO digitalTPC the hybrid-injection molding process is realized with a bolt-on injection molding machine that is connected to the lower half of the mold. The mold is mounted to a hydraulic press that opens the mold in a vertical movement. Here, the hydraulic press represents module three and the injection molding machine module four. With the closing travel the mold forms the laminate. Once closed completely the press applies the required clamping force and the injection molding step starts. After cooling time is completed, the mold is opened and the handling system demolds the final component.

Process data is recorded by two of the four modules: by the hydraulic press and by the injection molding machine. The press saves logged data for every stroke. Here, the date and time stamp can be used as unique identifier. The injection molding machine creates a protocol where data is logged for each cycle in rows. A single cycle comprises the whole injection molding step so that there is a new row for each cycle or rather each component so that the cycle number can be used as unique identifier. Both process data can be integrated into the digital twin via a database.



Non-destructive Testing and embedded Sensor Solutions

General Concepts

Three locations along the process chain are chosen to acquire relevant quality-features using non-destructive testing sensors and feeding the data into the digital twin subsequently. Thus, the quality of intermediate product stages is proofed, while the development of features and flaws can be monitored, documented and archived from UD-Tapes over laminate-layups towards the finished component. Regarding the physical location, testing of laminate-layups and the finished component coincide at the hybrid-injection process. Hence, two inspection-systems are developed and integrated into the processes at each of the manufacturing sites (IMWS, ICT). To choose the most appropriate sensor-modalities, preliminary experiments were conducted to assess the detection capabilities against the most relevant defect. Table 1 summarizes the testing parameters regarding the resolution.

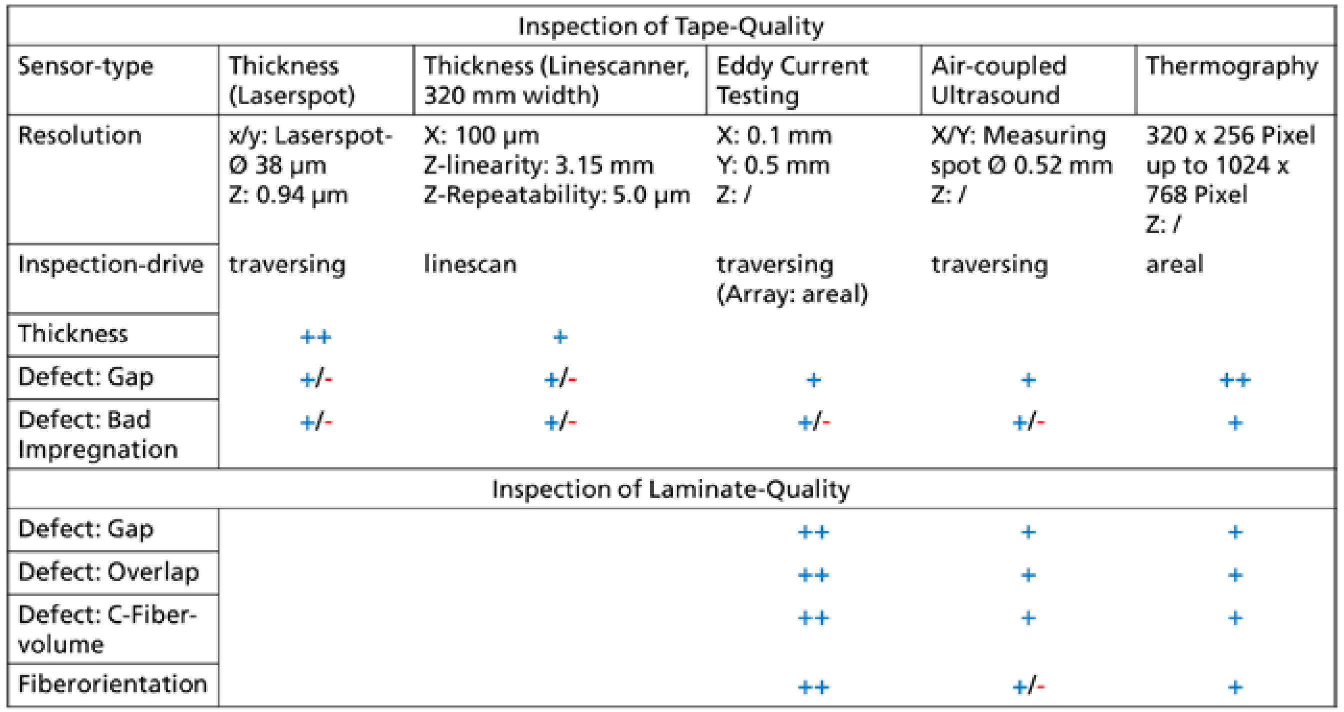
Feature Detection in UD-Tapes

In preliminary experiments, different non-destructive testing methods were applied to UD tapes to assess their capabilities to detect the most-recent and most-relevant defects regarding the tape-quality. These defects, or features, are:

- tape-thickness
- gaps and
- bad impregnation or dry-spots

In terms of reproducibility a frame was used to mount the tested tape-sections. The methods under investigation were:

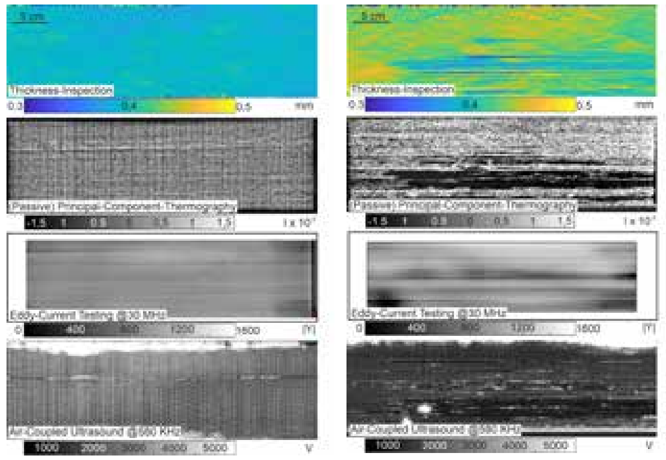
- thickness inspection system (focal spot laser, laser line scan)
- thermography (passive and active using flash light)
- eddy-current testing (absolute sensor 0061-TA-HF, 8 MHz)
- air-coupled ultrasound (focussing transducers @580 kHz)



Inspection of Tape-Quality					
Sensor-type	Thickness (Laserspot)	Thickness (Linescanner, 320 mm width)	Eddy Current Testing	Air-coupled Ultrasound	Thermography
Resolution	x/y: Laserspot-Ø 38 µm Z: 0.94 µm	X: 100 µm Z-linearity: 3.15 mm Z-Repeatability: 5.0 µm	X: 0.1 mm Y: 0.5 mm Z: /	X/Y: Measuring spot Ø 0.52 mm Z: /	320 x 256 Pixel up to 1024 x 768 Pixel Z: /
Inspection-drive	traversing	linescan	traversing (Array: areal)	traversing	areal
Thickness	++	+			
Defect: Gap	+/-	+/-	+	+	++
Defect: Bad Impregnation	+/-	+/-	+/-	+/-	+
Inspection of Laminate-Quality					
Defect: Gap			++	+	+
Defect: Overlap			++	+	+
Defect: C-Fiber-volume			++	+	+
Fiberorientation			++	+/-	+

Table 1: Evaluation of defect detection capabilities of non-destructive testing methods

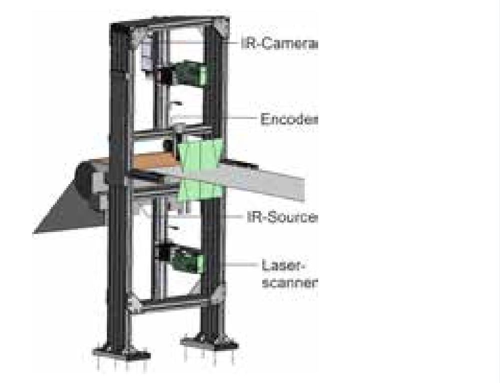
Exemplary results are displayed for a tape without defects and a tape with gaps and bad impregnation (next figure). This is a good example for a high-quality tape, showing high homogeneity, low waviness (thermography, air-coupled ultrasound) and its thickness value being near the target value of 0.4 mm. However, the detection capabilities can be better distinguished on the imperfect tape. Thermography shows a strong contrast in the areas with the bad impregnation and the voids (middle section). Although the same applies for air-coupled ultrasound, the method is less suitable for inline-inspection, due to its traversing scan-mode. Additionally, thickness-inspection is mandatory for the tape quality-inspection.



Left: Results from offline-inspection of a tape without defects.
Right: Results from offline inspection of a tape with defects.

Inspection of UD-tape quality

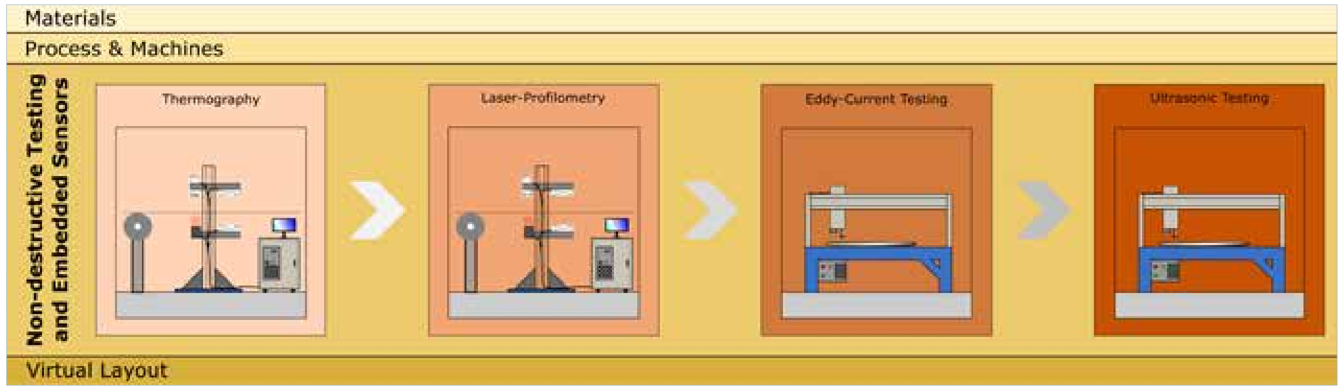
The inspection-system is integrated within the area next before the rewinding station. The manufactured tape runs through the rectangular mechanical construction, while passing the thickness-inspection and thermography-system. Due to the integrated friction wheel, any acquired data can be associated with the correct position on the tape. An electronic unit, the heart of the system, controls the whole system distributing and processing the encoder signal. Furthermore, an inkjet-printer produces location specific marks on the UD-tapes. For usage of the printing control a software-interface is implemented. The thermography-system consists of the Infrared-camera (VarioCam® HD Head800 by InfraTec) and an IR-line-source (fast mid-wave, IRD S750SM by Optron). Its power regulation depends on the tape velocity, such that the emitted heat-energy per tape-area remains constant. The cameras frame-sync signal ensures the location-specific data-acquisition, since the travelled distance of the tape between two frame-sync signals is captured and given to the system as offset value.



CAD-Model of the Inspection-System, Laser-linescanner (green, front) and Thermography system on back-side

Thickness-Inspection

The core of the thickness-inspection system are two laser linescanner facing each other. State of the art laser linecanner use likewise performant CMOS-sensors, while a sensor-series is commonly equipped with the same CMOS-sensor. Thus, the ratio of scan-width (x-direction) and scan resolution depends solely on the amount of datapoints of the CMOS-sensor. Consequently, a broader scanline comes along with a reduced lateral resolution. The same applies for the sample height, or z-direction, as a broader scan line means increasing



the measuring distance and reducing the repeatability and linearity.

A suitable system is chosen, compromising a maximized scan-width whilst high resolution. To summarize the technical-data of the system:

- 320 mm scan-width
- z-axis repeatability of 5 µm
- x-resolution of 1 mm, up to max. speed of 16 kHz
- Resolution of 3200 Scanpoints in scan-width

Consequently, four laser-linescanners are needed in total to scan the 500 mm broad UD-tape. Two on top and two below the tape. However, within the project framework only two are used, while the system is ready to be extended. To execute the inspection, the software requires adjusting the line-scanners towards a norm. To check for any drift during the inspection, the system asks for the adjustment again at the end of inspection. Therefore, each scan head can be adjusted in five axes until the measured thickness values suffice a demanded tolerance-interval.

Thermography

The main part of the thermography system is the IR-camera. The used VarioCam® HDHead800 by InfraTec comes along with

- a spectral range of 7,5 µm up to 14 µm
- detector-resolution of 1024 x 768 pixel
- adjustable frame-rate, with maximum of 30 Hz
- thermal sensitivity of 50 mK

Due to the near-distance measurement, it uses a wide-angle objective. The IR-line-source (IRD750SM by Optron) is located below the tapes, facing the IR-cam. Its wavelength-spectrum lies between 0,5 µm and 10 µm, whereas the maximum intensity can be found at 1,6 µm. The main advantages are the fast reaction, e. g. in case of standstill, and the emitted wavelength spectrum. Only low-Intensity wavelengths lie inside the cameras spectral range, which avoids damaging the detector due to strong direct emission.

During online monitoring the camera acquires the IR-Intensity, which is transmitted from the line source through the tape. The tailor-made software performs image-processing steps, such as correction of the image distortion, cutting to relevant image size (tape width x flow direction), stitching of individual frames and assigning the image to the according tape position.

Laminates and components

A second series of experiments was carried out to evaluate the detection capabilities of defects in consolidated laminates and the finished component (seat backrest). The contemplated methods are:

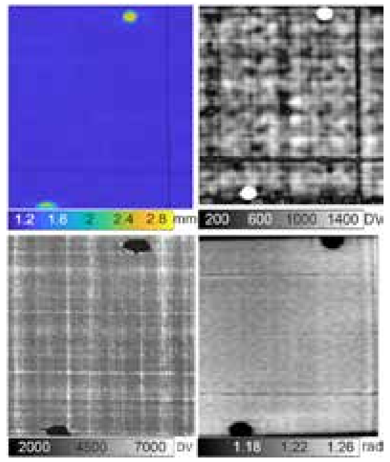
- thickness Inspection system (focal spot laser, as reference method)
- impulse thermography
- eddy-current testing (absolute sensor 0061-TA-HF, 8 MHz)
- air-coupled ultrasound (focussing transducers @580 kHz)

For better comparison and local assignment, applied markers on the laminate serve as coordinate system. In contrast to the UD-tapes, typical defects have bigger size and can occur throughout the sample volume. As a result, the lateral resolution at the surface is of less importance than the ability of through-thickness inspection. Quality-critical defects and features include:

- laminate-thickness
- gaps
- overlaps
- carbonfibre-volume and orientation

Exemplary inspection results of a laminate-plate with two artificially introduced gapping defects can be found in the following figure. A slight reduction in thickness can be seen due to the gaps. Though, the thickness inspection is used as a reference method due to its low inspection speed. The Images of the three NDT methods are very similar.

However, the fibre-orientation is clearly visible, while the fibre-volume-content can be deduced from eddy current images. Further, the defects (here: horizontal and vertical dark line) can be most clearly distinguished from the inherent structures and discriminated as defects.



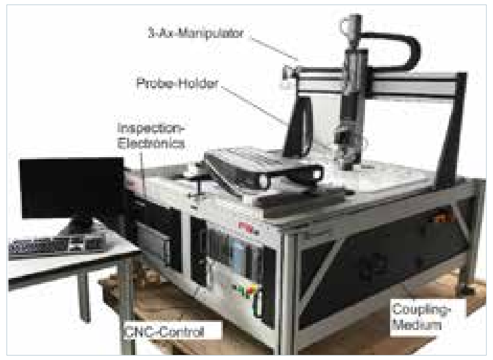
Results of laminate with gaps.
Top: thickness-inspection, eddy current testing
Bottom: air-coupled ultrasound, lock-in thermography

Ultimately, the seat backrest was inspected with ultrasound, as it is a well known and automatable method for volume inspection. C-images of the two defined regions A and B are displayed in the top image (right). Representative features, e.g. the reinforcing tapes (orange-red) and the thermoplastic stringers (white) are evident.

Inspection-System for laminates and components

The monitoring methods for the laminates and the components are both integrated at the production site at Fraunhofer ICT, before and after the hybrid injection-moulding. For interaction within the manufacturing-cycle, the inspection control communicates with the roboter control. Hence, it enables eddy current testing before the production-processes of thermo-forming and injection moulding, as well as subsequent ultrasonic testing. Besides a common 3-axis-flatbed scanner, the machine-body contains the CNC-machine control, the testing equipment and an industrial computer for data-processing. The manipulator-head holds the eddy current array with 4 coils as well as the ultrasonic transducer, both being spring-loaded for consistent contact-pressure whilst scanning.

The system can switch between the transducers automatically. However, the inspection itself is carried out based on a controller, developed at Fraunhofer IZFP. The eddy current inspection starts, as soon as the robot discards a laminate on the system. After completed inspection, the laminate is transferred to the hybrid-injection molding, after which the robot places the finished component on the system for the final ultrasonic inspection in contact. Therefore, the necessary coupling medium, which is stored in the inspection system, gets pumped to the transducer. In the current version this process step is restricted to the flat areas. If requested, providing the system with a flexible multi-axis positioning-system will enable the inspection of the whole component.



Construction and elements of the online-monitoring system at Fraunhofer ICT

Eddy Current Testing

The used probe combines a fast inspection with required lateral resolution. Therefore, the main features are:

- array with four coils
- spring loaded probe and coils
- inspection frequency at 8 MHz
- scan in meander-form with step size of 0.1 mm in scan- and 1 mm in index-direction

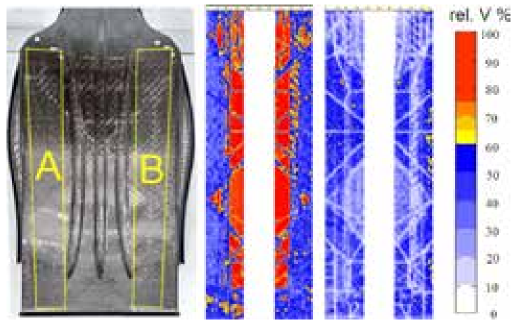
The spring-loaded probe prevents damage from the sample and ensures each coil to maintain the same distance to the sample during inspection. Due to edge-effects and the fixation, only relevant areas are inspected. After completion, the manipulator-head retakes its rest position and indicates end of task to a user or the robot control. Subsequently, data-processing starts by means of rescaling and application of available filters. Finally, the post-processed data is displayed, saved in DICONDE-Standard and uploaded automatically to the DICONDE-Server, which is located at Fraunhofer IZFP.

Ultrasonic testing

As the system is switched to ultrasonic inspection mode, it awaits the robot-signals for an inserted component. When the robot leaving the working area of the manipulator, the inspection starts in the two defined regions of interest. The main testing parameters are:

- contact-mode using spring-loaded single transducer
- Acrylic forerun for improved acoustic coupling
- 5 MHz inspection-frequency
- 80 MHz Sampling rate
- Drive mode: comb-wise with step size of 0.5 mm in scan- and 2 mm in index-direction

The acquired data and meta-data are stored in the DICONDE-standard and uploaded on the DICONDE-Server at Fraunhofer IZFP.



Ultrasound c-Image of a seat backrest in sections A and B at 1mm (middle) and 1.9 mm (right) depth

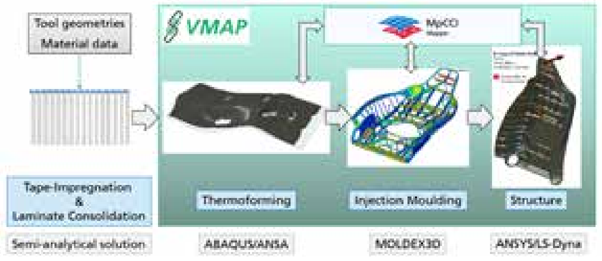
Virtual Layout of Processes and Products

CAE Chain: Semantics and VMAP Data Standard

A simulation chain are parameterized CAE workflows that enables comparison and transfer of physics-based computational analysis to new scenarios, particularly subsequent manufacturing steps, unit tests of final components or new measured material or boundary conditions that must be checked by analysis. In digitalTPC, we follow the view of maximizing transferability along this chain through a "standardized" CAE approach. Firstly, the data format of inputs and outputs should be compatible, e.g. by using common, open data format for the exchange of high resolution data, such as VMAP. With VMAP, a vendor-neutral data standard for the exchange of CAE data is efficiently based on HDF5 data structures and allows for seamless I/O and mapping. Secondly, the semantic representation of the CAE step should be commonly interpretable, i.e. by using a common ontological description. The latter is described in more detail in the section to follow. In short, we annotate simulations with meta-data and inter-link it with the actual manufacturing processes and measurements. This is crucial due to the involvement of multiple participants and many software products.

Models for UD-Tape Production

With semantically meaningful representations within the framework, individual computational solutions are still possible using efficient proprietary tools. In this fashion, the CAE chain shown in the figure below combines all essential simulation steps in an efficient, automatable, and interpretable form and enables integration into the product development cycle.



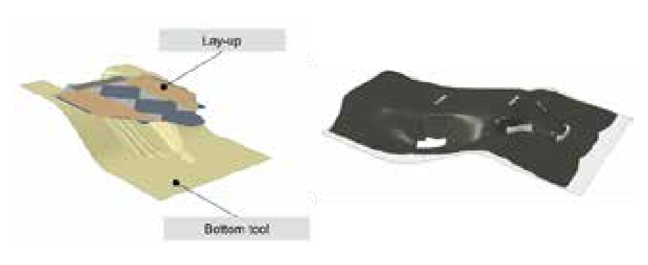
Simulation chain to transfer process-influenced material states and conditions

Within digitalTPC, the CAE chain consists of five main steps. The manufacturing process of the CFRP tape and consolidation is simulated in a semi-analytical approach. Three further main simulation steps follow; thermoforming, injection moulding and structural simulation.

The UD-tape production assessment calculates the penetration depth of the polymer into the long continuous fibres depending on the input materials and the input parameters, such as temperature, pressure, polymer granulate, etc. The laminate layup is then estimated using the individual thickness distributions and material properties. The goal is to provide specific material conditions for the high-resolution simulations of the component production.

Thermoforming Simulation

DigitalTPC deals with the complexity of long and short fibre reinforced plastics (LFRP & SFRP). The CAE approach helps engineers understand essential product-process-material interrelationships. As the real hybrid injection-moulding process combines thermoforming and over-injection of a polymer matrix as well as short reinforcements, there is a need to perform separate simulations for the injection moulding and thermoforming. The thermoforming simulation is conducted in Abaqus and determines the deformation from the two-dimensional blank into the final complexly curved three-dimensional component shape with considering physical and chemical mechanisms of global and local formability of the consolidated thermoplastic laminate. Thus, this simulation step resolves the local mechanical properties attributed to the long-fibre-reinforcement.



Thermoforming simulation pre-forming and post-forming

Injection Moulding Simulation

Process-induced manufacturing effects such as gaps or fibre relocation can lead to deviations in the initially assumed mechanical properties. Therefore, a holistic component optimization approach must include information from the manufacturing process. In order to obtain the volume content, distribution and orientations of the short reinforcement fibres that are introduced during injection moulding, a respective simulation was performed in Moldex3D.

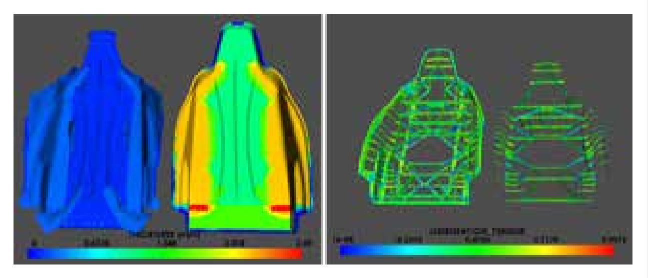
This step allows to assess the material flow of the polymer melt enriched with short reinforcement fibres, which overflow the thermoformed base geometry and into the many ribs and channels that are geometrically designed to cross-stabilize the demonstrator part. It also allows to estimate the injection time with would in production correlate to the injection-related contribution to cycle time. Finally, the injection moulding simulation may reveal areas prone to build enclosures, pores and unfavourable orientations of the fibres in dependence of injection pressures and temperatures.

Multi-step CAE Mapping

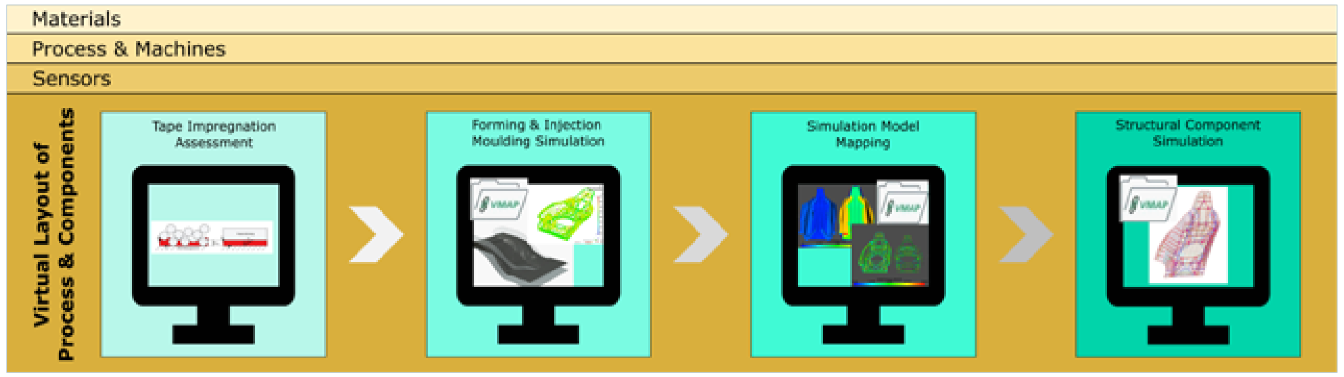
The result quantities of the simulation steps are exported to VMAP for CAE mapping: this is a direct reuse of local properties in a subsequent simulation of the final component. As example, we demonstrate the long and short fibre orientations (see figure below). Like the simulations, also the mapping is split in two stages. First, orientations and thicknesses of 15 virtually draped local ply layers is interpolated onto the LFRP regions of the structural mechanics model and then translated into shell element local material angles. In the second step, the volumetric distribution of short fibre orientations is mapped to the corresponding SFRP parts of the target model. The mapping is executed with the MpCCI Mapper, a file-based projection tool, for which a SWIG python interface is available for automation and integration. As efficient, robust and versatile interpolation approach, a k-nearest inverse distance weighted Shepard interpolation is implemented, allowing for data transfer between arbitrary locations. But for higher interpolation accuracy Finite Element shape function interpolation or the Log-Euclidean Framework can be used.

Structural Simulation

Now, the composite material properties including fibre orientations, pores, matrix, thickness distribution and layering are available in the structural model with a defined load case to run impact simulations. This model is built in ANSYS for the explicit dynamics code LS-DYNA. It calculates a standard quasi-static equivalent load case according to the European regulation ECE R17. Two load steps have to be satisfied by the given rear seat geometry for validation. In step 1, a moment of 373 Nm is applied about the backrest fixation, while step 2 applies an additional longitudinal force of 890 N on the head section. The permissible maximal displacement is 102 mm and the component must not show fractures after the extra 890N of force are applied on the headrest. With this, we demonstrated the feasibility to reuse core information across the simulation analysis of TPC part production. To date, main parameters that can be varied for their influence on the structural performance are the thicknesses variations in the tape lay-up, besides stiffness. Through the CAE chain integration into the meta-management system, automatable introduction of machine parameters and measurements to calibrate and tune the physics simulations, as well as applying data-based augmentation and acceleration is possible and can now become focus in future work.



Thermoform- and injection moulding simulation mapped to geometry for structural calculation, displaying the layer thickness distribution (left) and the fibre orientation (right)



Information Management – The Ontology Model

Basic Ontologies – EMMO, BFO and MpCCI Ontologies

Ontologies as information models logically define assets and interactions in complex data ecosystems: digital twins. Unlike for system models, an open world allows them to concepts like global uniqueness, unlimited extensibility, projection and granularity. These advantages are what makes them so powerful. They offer means for interoperability with other systems that are unknown during the initial design phase and that evolve over time. Yet, this comes at a cost: it requires great effort to reach agreement between experts on the terms and requirements and then formalize the domains of knowledge. Therefore, the landscape of ontologies in engineering is still in its infancy despite important, yet widely unrelated examples (MCCO, IEO, etc.).

Luckily, the progress of recent years is most notable in top-level ontologies. Especially EMMO and BFO have become important common semantic anchors. While the rigour of EMMO allows for deep consistent concepts of materials physics, its derivations are still too abstract for industrial practise. The BFO finds more concrete application, e.g. with the project ontologies connected to Platform MaterialDigital. Still, an intermediate ontology layer is needed to reconcile the crucial domains of knowledge for digital twins systems, a gap filled by the MpCCI Ontologies: project-independent domain ontologies prepared to be connected to the BFO (and some defined relations to EMMO classes), for consistent rooting of twin semantics. The digitalTPC ontology is a corresponding extension.

Taxonomies based on existing Standards and Conventions

The image above shows the rooting in the MpCCI Ontologies and which major domains of knowledge are modularised and connected. As far as possible, we follow publically available definitions, industry standards and well-accepted standard literature for the major taxonomies and relations. This simplifies adoption to existing workflows in industry, use and reuse. Industry standards are not logically consistent, nonetheless they are important common ground of negotiated terms and concepts. As examples, readers may be familiar with these sources (excerpt):

- Material: DIN EN 10027, DIN EN 573, EN 1753, ISO 15165, and standard literature,
- Manufacturing: DIN 8580ff., DIN 8505, EU-guideline 2006/42/EG,
- Measurements: DIN 1319, DIN 50100,
- CAE: FKM-Guideline, NAFEMS Glossary, VDI 3633, ISO 10303, VMAP.

The digitalTPC classes detail out the project specifics. While the domain of construction and design, in particular CAD and PLM are not used in depth in this pilot project, respective placeholders prepare future extension. The needed material classes for polymerized thermoplastics with carbon and glass fibre reinforcement are one focus, UD-tapes and the semi-finished components are another. Further detailed domains are the custom non-intrusive measurement systems, the simulation models used in the CAE chain and their simulation tools, as well as the data management and processing. Basic principles of storage and access and categories of processing algorithms are represented for use as meta-data labels. Overall we obtain over 1300 classes.

Object Properties

Object properties connect instances of classes to form relationships. Project-independent properties are explained in detail in the MpCCI ontology documentation. Since the use of a minimum number of advisably general properties is recommended, digitalTPC does not significantly detail them out further, but rather apply them. Refinement is better achieved through detailed classes.

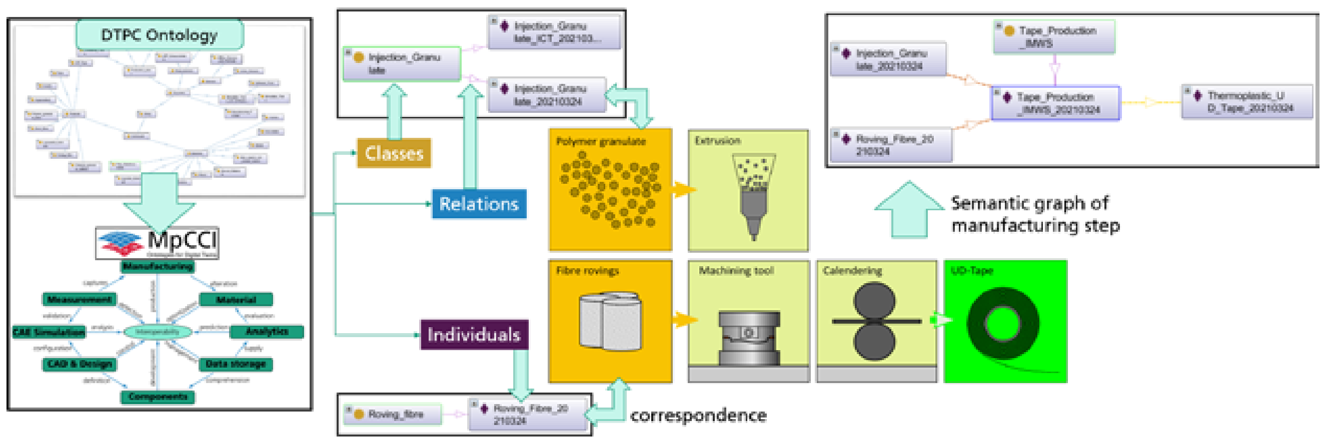
Among the most important object properties for this twin are: isPartOf (mereological hierarchies), isMadeOf & altersCohesion (material assignments for components & manufacturing), hasOutput & isInputFor (as suggested), hasFormat, hasResource, isStoredAt, etc.(data management assignments), measures, calculates, configures, simulates, etc.(direct process assignments). Besides the trivial use as predicates in RDF triples, object property restrictions are used for class definitions. This allows, for instance, binding all individuals that carry out a measurement to the class of measurement systems, or in CAE, assure that for a VMAP attribute its VMAP group always exists in which it is stored, whether or not the group is explicitly specified.

Data Properties

Much effort for the digtialTPC ontology extension allots to data properties. Data properties are those relations that hold a data value (string, integer …) in its range without further semantic meaning. Unlike object properties, they are used in extensive specific variations in digitalTPC, for two main purposes: 1) to bind pieces of meta-data to the class instances, and 2) to connect class instances with actual entries in distributed databases. The first use is moderately interesting, as only the core meta-data can be maintained directly in a triple store: Holding many data values that can be stored otherwise is inefficient. While (only) the data set as such is available as an individual, the data properties bind the channels of data bases to them, such that the values can simply be parsed, e.g. in reduced excerpts or in a temporary in-memory triple-set. With this approach, almost 800 data properties are defined in the project, precisely due to the many signals from measuring systems, machines and simulation chains. Common global data entries are timestamps, sizes, number of entries, calibrations, etc. Yet, the majority of data properties is essentially pre-categorized into material, product, simulation and machine properties and finally according to the different process steps or the various systems and tools. As the process runs in the workshops, they produce data sets, for which the meta-data management creates instances. These have their associated data properties, queries for which can be evaluated by pushing them into a second evaluation against the database in which these data channels are stored. The data entries in these sets can now be retrieved and further evaluated, while they are never stored or evaluated in the triple store.

Individuals

Instances are also called individuals in the semantic web context. For unfamiliar readers, an important distinctions must be emphasised: classes are not "in the world", meaning they are merely our chosen categories – ideas that such resources could in principle exist. Individuals on the other hand exist, whether or not we define them as class members. Therefore, we strictly mean such individuals when talking about digital correspondences to items. This is illustrated in the head image, where we can see a sketch of the first process step, the tape production. For instance, take the ontology class "Roving Fibre". It does not indicate whether any fibre actually existed in the workshop. In contrast, an individual of this class, e.g. "Fibre_20210324", is the unique identity of the actual fibre used on a particular day. So the creation of instances is the "population" of the digitalTPC ontology classes.In fact, instances are usually not stored with ontologies, except for low-volume testing purposes. Individuals are often created automatically in large numbers, which quickly becomes intractable when manipulating ontologies. Thus, it is conventional to create separate datasets containing individuals and their relations. Such a "knowledge graph" can be pictured as a set of RDF triple expressions (subject-predicate-object), which fix the URIs of each individual and their explicit dependencies. The resources used in the knowledge graph do not need to be included, as long as their resolution is possible, either through building a union of the graph with the ontologies or simply by openly publishing the original ontology resources' URIs. With those definitions resolved, one can perform inference on the graph in order to make hidden connections of the concrete digital assets explicit.



Minimal example of usage of ontology framework for semantic graph of the tape manufacturing step

Distributed Databases and Semantic Search

Search and data retrieval

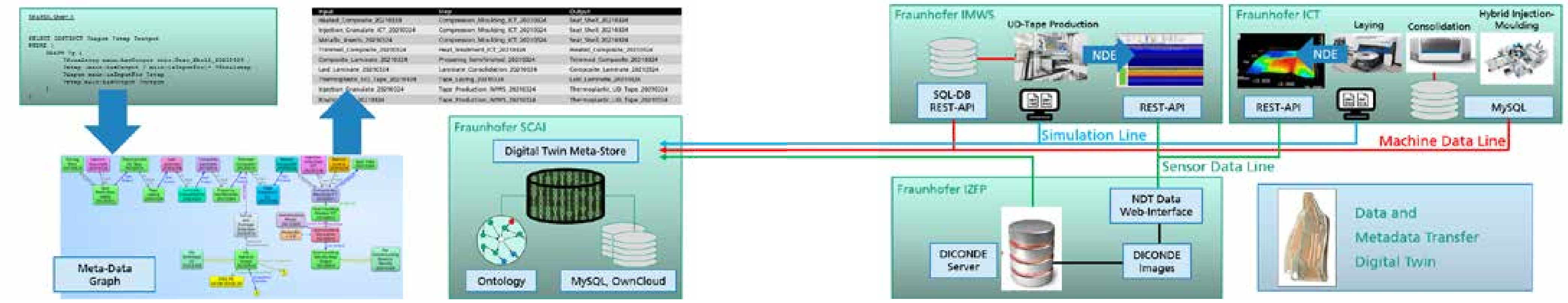
The management of twin assets begins with creation of meta-data entries and their transfer into the meta-data store – a triple server. This persists a meta-data network (see figure below). The meta-data no longer depends on local environments, but only on the ontology model. It is searchable and many qualitative features of the twin can be retrieved with a corresponding SPARQL query, namely information that is fully identified by meta-data and therefore directly accessible (for example, all process steps that were run to produce a particular component). In contrast, we suppose interest in a deeper, quantitative feature of the twin. Now, a two-step procedure is required: 1) Semantic search on the metadata store according to the meaning of the required information, and 2) database query on the distributed systems to get fully resolved dataset entries (e.g. maximal pressure of the press in the hybrid-injection moulding step). The reason is that the quantity of interest is not resolved semantically, thus hidden within a large dataset. Additional analytics is also possible in the second step and the ontology classes allow for representation of such analytics processes to reach them through this procedure.

Distributed data-base systems

In digitalTPC, we designed the architecture of distributed data bases and meta-data management system as an early-phase data space. The overall concept consists of several local data bases hosted at each institute, a fileserver, the triple store and the meta-management system. In the first version, the data space partly depends on access through a virtual network, yet the endpoints can in principle be configured to communicate over the open network to other sites with sufficiently secure measures, i.e. custom encryption, personalized X.509 certificates, etc. On the top level, we can distinguish three main data communication channels, the machine data line, the sensor data line, and the simulation data line.

The machine data for the production sites at IMWS and ICT is directly linkable to the management system at SCAI. For the tape production machine data at the IMWS, a REST-API is set up (analogous to project Mat-o-Lab), which was developed using DJANGO network. The python-written database connector at SCAI can retrieve the tape machine data channels through this interface, poll for new data and read entire datasets. Similarly, the machine data at ICT is stored in a MySQL / Maria-DB. Again, a connector at SCAI allows for poll of data updates, metadata and entire datasets through a common interface. Here, a direct data base connector for SQL queries is used.

Sensor data (from non-intrusive testing) is sent from the sensing units in the production lines at ICT and IMWS to an optimized database for image based testing at IZFP (DICONDE) and to the backup-fileserver at SCAI (Owncloud). The DICONDE Server has a REST-API following the DICOM standard, for which a connector based on open libraries is implemented at SCAI. Due to network security requirements, the use of this connector was only partly tested. The same data can be queried from the fileserver using a respective API alternatively. The simulation data is uploaded to the Owncloud fileserver system. Hence, the same connector allows for retrieval of CAE files and meta-data of the simulation runs.



On the one hand, this architecture enables each institutes domain experts to retain their own data, hosting local platforms optimized for the respective kind of data. On the other hand, distributed systems are more robust for multiple participants and digitalTPC mimics possible larger scale industrial applications in this regard. Distribution of sources and consumers of data is often a key limitation, and with this architecture, digitalTPC thus prepares future extension to a data space that complies with the Industrial Data Space (IDS) association's recommendations.

Metadata Store

As a store for the digital twin meta-data, a Apache Fuseki Triple Store was set up as an online service. This implementation is very popular, open source, and has high performance benchmarks. It can be used as a standalone system, which communicates only through secured SPARQL endpoints during operation.

As motivated by the ontology information model in previous chapters, this form of storage of semantic information is extremely useful. Triple relations build networks of information, so-called knowledge-graphs, and with a Fuseki-store, these can be maintained and accessed very efficiently. It is possible to maintain separate graphs of meta-data. The ontology itself by convention for practical and security reasons stored on a separate server and accessible directly over HTTP.

SPARQL Communication and Abstraction

To communicate with the endpoints using SPARQL, we set up a single query and upload endpoint for this project for the sake of demonstration, yet more advanced industrial solutions may use several stores with multiple endpoints each, exposing for instance different security layers.

SPARQL is a standardized language to communicate triple information. An example question to pose via SPARQL is the following. Given the final produced component on a particular day, e.g. seat shell 20210324, what are the exact runs of each of the machines involved? What are their inputs and outputs? Such questions can be formulated in SPARQL and the metadata store response contains the triples that fulfil this requirement (see image).

In the future, engineers working with digital twin systems will generally not be proficient SPARQL users. Except for expert-mode queries, common and often posed questions are better abstracted using an intuitive interface layer. With this, we construct the SPARQL syntax from an interface mask that uses clickable or natural text inputs as variables. For instance, from a displayed component involved materials can be toggled directly and connected CAE simulations can be retrieved via respective buttons. Finally, users can access an entities content while the database connectors realize this in the backend. The data can also be directly processed for further analysis.

Triple generation and linkage to local databases

The digital equivalent of real-world counterparts are unique individuals belonging to ontology classes. For the operation of the digital twin, a procedure that automatically builds such individuals in analogy to the real world process or computational process is needed, i.e. instance creation (annotation) and cross-linking algorithm. In digitalTPC, they are created when new data sources are available. By design, the management system polls metadata updates from the distributed databases. It then maps new metadata onto the ontology by parsing core terms, such as timestamp, names, IDs. It then executes the generation algorithms for those instances that do not directly represent datasets. This procedure, implemented in Python and TTL, can be executed repeatedly to create new versions of meta-data graphs. The TTL templates contain required pipelines to create individuals and link them and build timestamps into the individuals' URIs. For interested experts: TTL templates are easier to maintain and deploy compared to pure code, plus they are system- and version-independent. In summary, a tape production run will cause creation of the next used fibre instance, this will cause creation of an input relation, and so on. The general ontological definitions allow the inference of further triples subsequently.

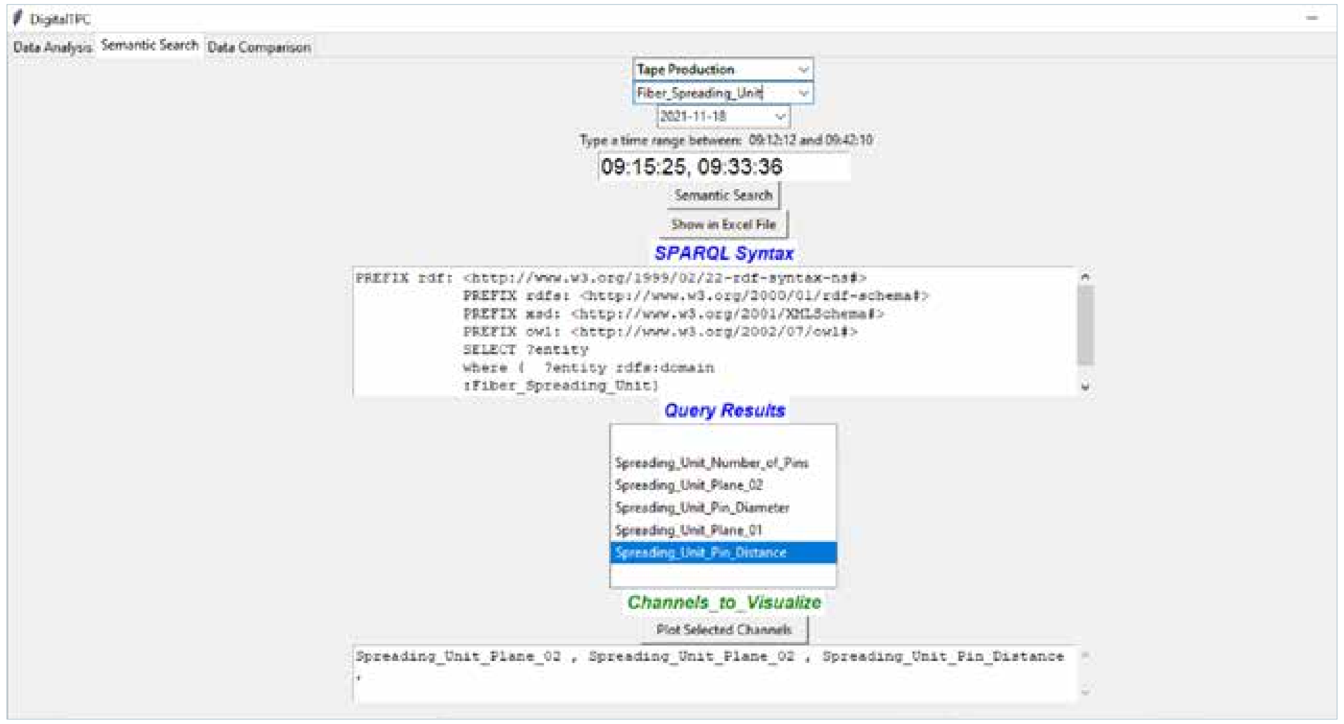
Analytics for Process and Engineering Data

Python Framework

The data processing algorithms in context of the use cases of digitalTPC were developed in python. The advantages of this popular language are numerous, openness, reuse of libraries, modularization, and deployment among them. For one, this allowed for a central software framework in python, from which the data connectors to the data bases, the handling of meta-data and communication with the triple store, and of course the data analytics can be handled. Moreover, the python code wraps many of the functionalities in a set of graphical user interfaces to browse digital twin and display data and analysis results. While extendable towards further, more typical application scenarios, the GUIs are trimmed for the use cases and research questions of digitalTPC in this first project. The user interface has been developed with Tk-inter library. A knowledge graph-based was developed to provide a user-friendly user interface.

Data Pipelining

The data flow from the sources e.g., sensors or machines are gathered fully or semi automatically using secure authentication methods including Token, User/Pass, Smart Cards, VPNs, or hybrid methods by combining these techniques. The data transmission techniques are performed using RestAPI or indirectly using Owncloud service. All the mentioned methods have been implemented using Python and Django library which can be easily integrated to other modules. The data pipelining has been implemented in 2 modes of offline using serial architecture and online mode using timer- and interrupt-base architecture.



Tape Production

Fiber_Spreading_Unit

2021-11-18

Type a time range between: 09:12:12 and 09:42:10

09:15:25, 09:33:36

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
            PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
            PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
            PREFIX owl: <http://www.w3.org/2002/07/owl#>
            SELECT ?entity
            where {  ?entity rdfs:domain
            :Fiber_Spreading_Unit}
```

Spreading_Unit_Number_of_Pins
Spreading_Unit_Plane_02
Spreading_Unit_Pin_Diameter
Spreading_Unit_Plane_01
Spreading_Unit_Pin_Distance

```
Spreading_Unit_Plane_02 , Spreading_Unit_Plane_02 , Spreading_Unit_Pin_Distance
,
```

Figure 1: User interface for semantic search

Semantic Search Engine

By using the ontology-based semantic search module in the SCAI software tool, a user can easily access the machine channels independently or in company with the correspondent Diconde image(s). The user can select a time slot for a more precise search, such that the tool automatically calculates the time stamps in the relevant records of the SQL-based tables of the machine data.

The user can start a semantic SPARQL query, access, retrieve and visualize target data (see figure above). In the screenshot, the channels of the Lamination Consolidation machine of ICT on a specific date of the experiment were searched and presented to the user.

In the query results, a list of channels is shown, where the user can visualize selected channels. The user can add or remove the channels from the second list below. The user can also focus on an interesting time slot when e.g., there is a fault in it. The valid time range (i.e., minimum and maximum) is automatically calculated from the database for the machine and within the selected date. The tool will save visualization results in the format of plotted image files with the channel name as shown below. The visualization process is applied by clicking on “Plot Selected Channels” button.

To automatize semantic search and retrieval, the data properties in the ontology are named according to the given same channel names in the SQL tables. A target data property is retrieved using SPARQL querying within ontology entities. A connector module finds the corresponding column entries in the SQL table and exports the channels’ content of the selected time slot to an Excel table or visualizes it in plot format. By selecting two dates for comparison, the tool first calculates the maximum valid time range of these dates and shows it to the user, so that the user can select the correct time.

An experienced user can manually type SPARQL scripts (see figure below). However, users without knowledge in SPARQL can select the target machine module from filters. The user interface automatically generates the SPARQL codes and applies them to the ontology and the relevant data is retrieved.
The SPARQL querying is applied to the ontology through the following steps: Rdflib library converts the translates SPARQL code to triple graphs, then these graphs are compared to the existing graphs inside ontology, when they are same the third element of the triple stores are listed as output or results.
The raw results are URL-based results are automatically cut to provide short but sensible results.

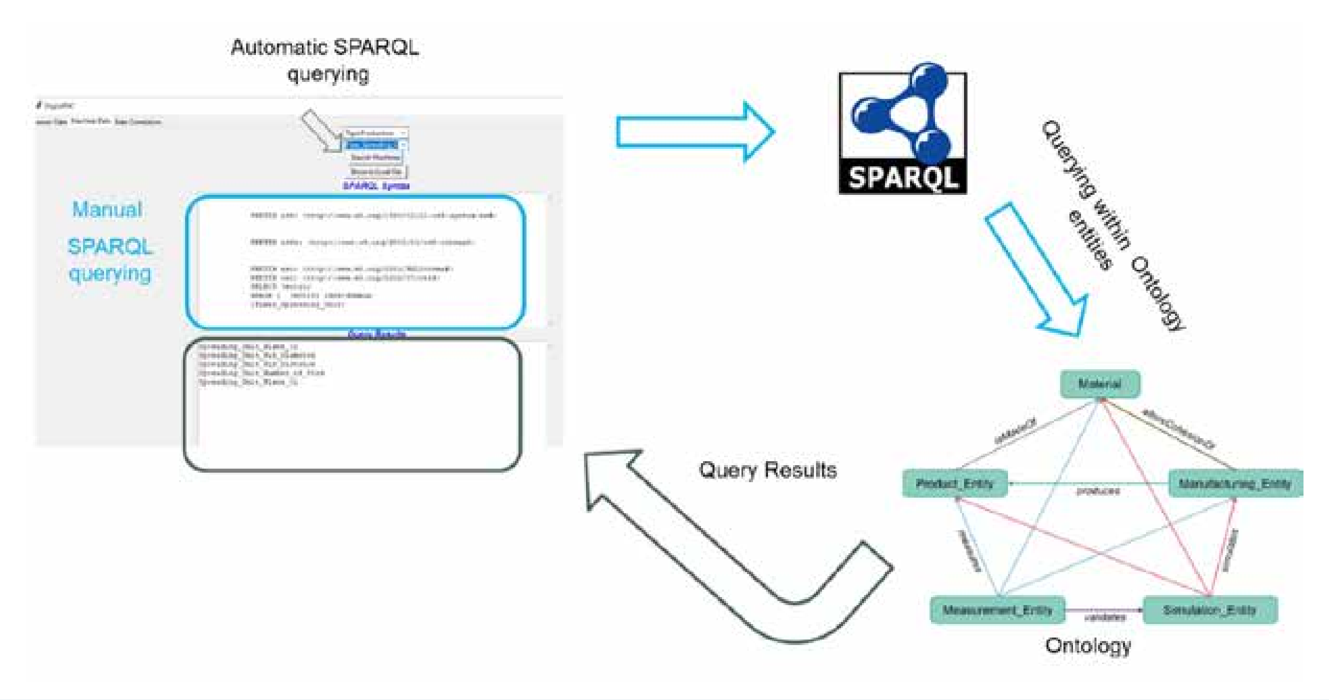


Figure 2: Applying semantic search from GUI on the ontology and showing results of it on GUI

Data Correlation

In another searching scenario, the user can manually select an image of his interest (e.g., with gaps) from a timely sorted list of Diconde images. The tool automatically correlates the image to a slice of the machine data, which is captured at the same time. To this aim, the tool first obtains the correspondent time range for capturing the image, then this time slot is mapped to a time stamp slot using the mapping information which is available in the SQL tables of the machine data. Within this time stamp slot, the relevant raw values and channel names from the 3 diverse SQL tables are retrieved and stored in an Excel table or visualized in various plots. The above procedure could be iterated for all the Diconde images in an experiment on one date. The user can run this procedure for a group of images, the results are stored in separate files with the same name as Diconde files. The snapshot of this scenario of the tool is shown below.

The user first selects the experiment date sensor type (i.e., Laser or Thermography) by the combo filters and clicks on “search sensor” button, then a list of images including names, i.e., Time of capturing and image position appears. The user can click on each item of this list, then a preview of the image and a button “Show Machine Data” appear, by clicking this button, the timely correspondent machine data to this image are extracted and gathered in an excel file.

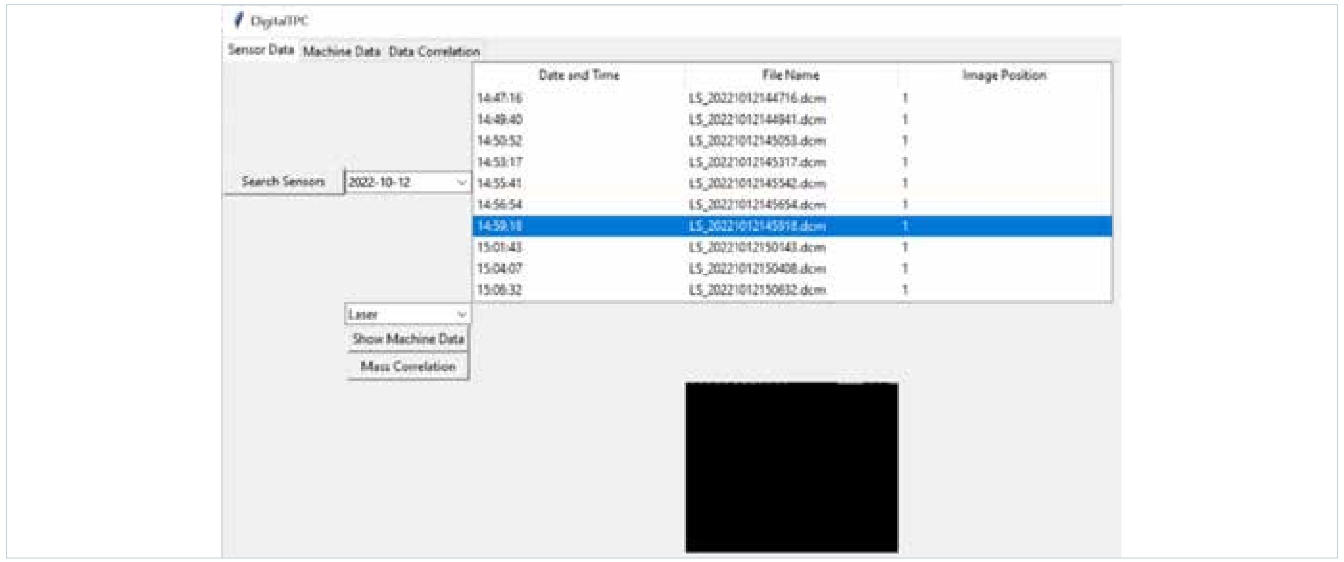
By clicking on “Mass Correlation” the correspondent machine data for all the images are extracted and stored in the excel files with the same name as of the image.

Generally, the machine data is stored in 3 separate SQL tables, namely `dechannel`, `defile` and `desegment`. Selected column names of the tables are listed below:

<table>
<tr><th colspan="5">Desegment</th></tr>
<tr><td>Fileld</td><td>ChannelNr</td><td>SegmentNr</td><td>ValuesInSegment</td><td>Average</td></tr>
<tr><th colspan="5">Defile</th></tr>
<tr><td>Fileld</td><td>TimeStamp</td><td>FileName</td><td>FileType</td><td>Complete</td></tr>
<tr><th colspan="5">Dechannel</th></tr>
<tr><td>Fileld</td><td>ChannelNr</td><td>Name</td><td>Unit</td><td>IsDigital</td></tr>
</table>

Among the columns in the SQL tables of the machine data, only a few columns (i.e., ‘_Average’ or the average values of a certain channel/sensor in a given segment of values, ‘_Name’ or channel name and the absolute time) are of interest for the end user.

The absolute time entry does not exist in the tables and the interesting information does not exist in the same table and is distributed in separate tables. To allow further meaningful further analysis, the ‘_Average’ values from `desegment` must be connected to `_Name` in `dechannel` and `_TimeStamp` in `defile’, it is performed by using the common key of ‘FileId’. Considering the high number of channels (160) and long length of the channels, the variable length of the channels, the task of correctly extracting the information is difficult.



Date and Time	File Name	Image Position
14:47:16	LS_20221012144716.dcm	1
14:49:40	LS_20221012144941.dcm	1
14:50:52	LS_20221012145053.dcm	1
14:53:17	LS_20221012145317.dcm	1
14:55:41	LS_20221012145542.dcm	1
14:56:54	LS_20221012145654.dcm	1
14:59:18	LS_20221012145918.dcm	1
15:01:43	LS_20221012150143.dcm	1
15:04:07	LS_20221012150408.dcm	1
15:06:32	LS_20221012150632.dcm	1

Figure 3: Correlation between Machine and Sensor Data

Comparative Analysis

The comparative thickness analysis or studying changing the thickness of the tapes over time between two experiment dates is another interesting option for the users. Each thickness image (see Figure 4) is divided into two upper and lower parts and the cumulative intensity of the pixels values of the images of each part is calculated. This value is calculated for every image of the experiment date and plotted for various times.

The quantity of images in terms of sensors and experiment dates are listed in the table below.

	2022-04-12	2022-10-12	2021-11-18
Thickness Measuring	24	20	320
Thermography	57	32	155

The quantity of images for different sensors and experiment dates

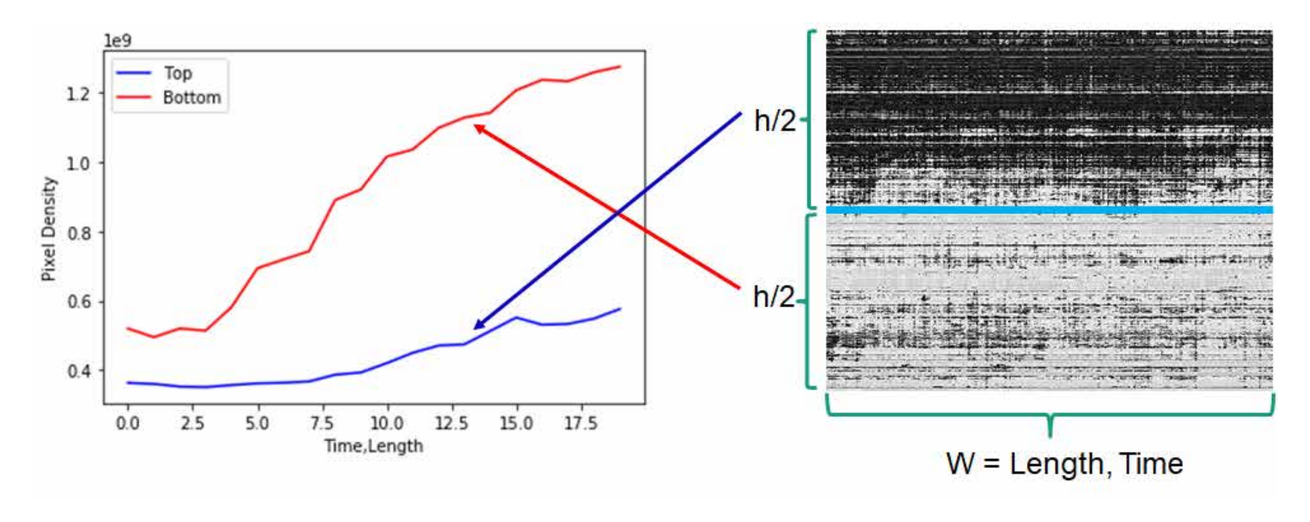


Figure 4: Thickness profile over time for upper and lower parts of the tape

Use Case: Optimising UD Tape Production

Introduction

There are many effective variables involved in tape production. Setting the optimized parameters set is a very tough task. Material experts must perform many trials and errors to find the optimized parameter set. This recursive procedure takes much time and needs many expensive machine runs which consume unnecessary resources. The traditional quality control is slow, unreliable and imprecise.

In digitalTPC project, a vision-based system is designed and adapted to automatize the quality monitoring process.

The advantages of this system are summarized below:

- Fast quality control
- Precise quality control
- Automatic quality control
- Removing extensive manual documentation in manual quality control
- Storing the images and machine data in stable servers for further data processing

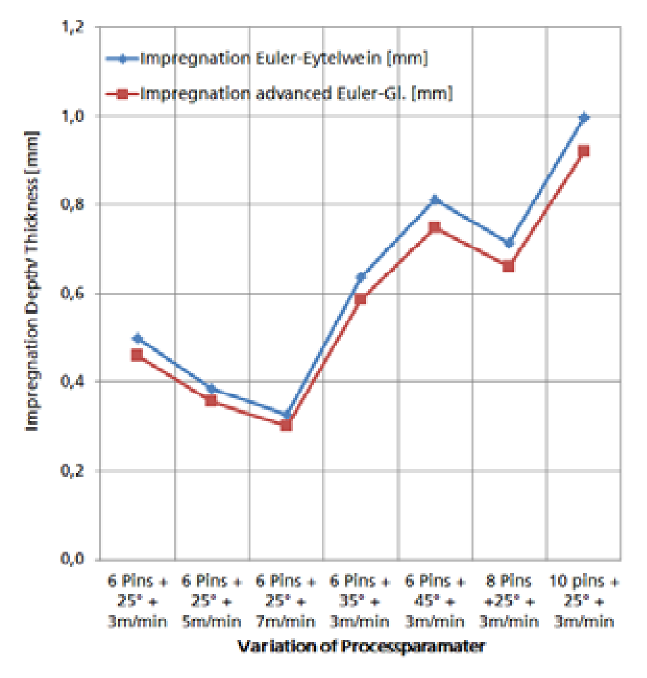
The demo system allows experts to find the optimal parameters for each input material aiming to minimize the production faults.

This demo works with the following steps:

- The production machine produces tape.
- The sensor system which consists of a thermography-system and a laser-based thickness inspection system captures video data online from the tape production line.
- The image processing module then analyses these videos and finds possible faults namely middle voids and bad impregnated on sides of the tape.
- The second software module finds and shows the machine data corresponding to the faulty tape images.

Thickness comparison of simulation and measurement

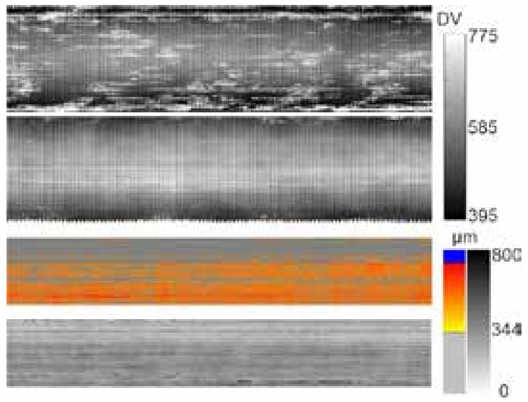
The large number of factors requires an equally high and complex level of input parameters for a simulative representation of the impregnation process. Within the framework of initial investigations using suitable software components of ANSYS Workbench, models were presented for the FEM-based calculation of the pressure buildup generated by the fibre withdrawal movement in the wetting tool. Here, attention was paid to compatibility with other program modules for the future development of the simulation process. First results with available unidirectional material system show comparable results to the theoretically performed calculations considering the used solution algorithms. In the further course, tests were carried out to simulate the melt gate installed in the wetting nozzle. After successful simulation, the aim was to extend the geometric model of the wetting nozzle step by step and to combine it with the model of the pressure calculation. This shows that the complexity of the impregnation process and the vectorially directed flow processes involved, as well as the fibre deformation due to the special wave geometry of the wetting nozzle, require a significant additional effort in the development of the process simulation. As a final consequence, an analytical model had to be developed and programmed for the fibre motion in the nozzle, and the same applies to the modeling of the fibre-matrix interface. This is adapted using empirical data from manufacturing trials. Based on the process boundary conditions, it provides an indication of whether the spread fibre carpet is fully impregnated with thermoplastic melt. This is based on an approach by D'Arcy for determining the fibre impregnation depth, which is compared with the real tape thickness. Modelled process steps, materials, physical effects, etc.



Variation of Process Parameters for Impregnation

Online-Monitoring of Tape Quality Criteria

Exemplary online monitoring results for 3 meters of a faulty tape and a tape with optimized parameters are displayed in figure above (top: thermography, bottom: thickness). In the top-image, plenty of bright stripes are evident in the x-(horizontal) direction, indicating voids and gaps. They occur more frequently next to the edges, since the edge-areas are typically of a reduced quality. Clearly, the gaps are absent in the second thermography-image, due to improved process parameters. In the middle section, several light continuous striations can be seen, which most-likely come from a slightly reduced amount of fibres. When comparing the thickness images, a more homogeneous distribution is seen with improved process parameters (second image). Secondly, the values lie closer to the target value of 400 µm thickness.



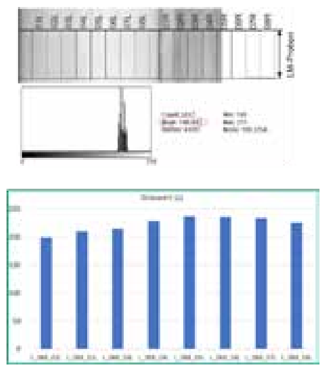
3 m x 0.5 m Thermography-result (top) and 2 m x 0.32 m thickness-inspection (bottom), production from 18.11.2021 and 12.04.2022

Connection of Tape Machines with Monitoring and Analysis

The DICONDE-standard includes meta-data that is associated with the inspection data. For assignment, the main tags are time and location on the inspected part. Example given is the meta information for the thermography image from 12.04.22:

- Modality TG ('Thermography')
- Date: 12.04.2022/ Time 10:51:02
- Image Position Start: 24 m
- Pixel Spacing: 0,496 mm (X), 0,485 mm (Y)

Using the temporal and spatial information, the inspection results can be correlated with the process parameters. Further, for the process parameter set of the production date (e.g. 12.04.22) additional simulation results give the fibre volume content (as grey scales, see figure below) and the tape thickness. Thus, the simulation results can be validated using the inspection data.



Gray Value Correlation Image can correlated to Fibre Volume Fraction

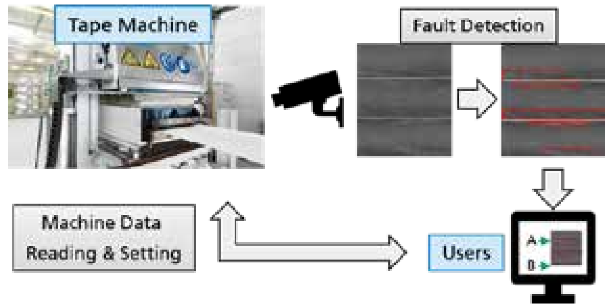


Illustration of the proposed tape quality control system by connecting tape production machine data to the evaluated thermographic images.

Use Case: Holistic Quality Assessment of CF-PA6 UD Tapes

Manufacturing of CF-PA6 UD Tapes

Modern structural applications in lightweight design, e.g. in automotive and industrial engineering require high strength composite materials with low weight. Carbon fibre reinforced UD Tapes with PA6 matrix system provide high level mechanical properties on low density and enable composite structures with excellent durability in terms of mechanical loads (static and crash load as well as fatigue loading) and thermal conditions (continuous service temperature up to 100°C / short term up to 180 °C). Efficient continuous production of such a high performance semi finished composite product requires reliable processing technology and holistic quality monitoring of the process and the product to ensure high quality and reliable products. To demonstrate the capability of the digitalTPC for holistic quality assessment of continuously produced CF-PA6 UD Tapes manufacturing trials were run on the UD500 pilot production system at Fraunhofer IMWS equipped with inline laser thickness sensor system and NDT thermography system (described above). The trials were run in the following configuration:

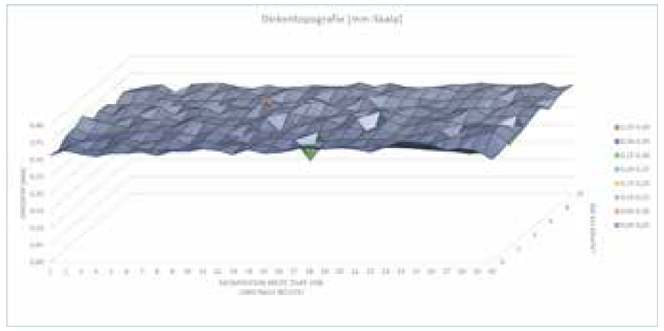
UD500 setting
- Spool system with 60 roving spools
- Spreading unit UD500_113
- Wetting tool UD500-PA-CF-001
- Single Screw Extruder / 45D / 120kg/h
- Twin Role Calander / water cooled
- Omega Pull Unit
- Processing speed 3,3 m/min
- Winding Unit / 2 Positions / 300 mm Core Diameter

Raw materials
- CF Torray T700SC-50C 24K
- PA6 BASF Ultramid B24

After an initial ramp up phase (heating up the tool system, equipment and material, ramp up processing speed) the process was run in a steady state. The NDT system was used to monitor quality parameters of the processed UD tape.
To initiate an artificial disturbance to the process stability and to test the machine control and inspection system, the melt temperature as well as the wetting tool temperature was increased from 260 °C up to 280 °C by operator input and setting of corresponding set values in the machine control during processing trials.

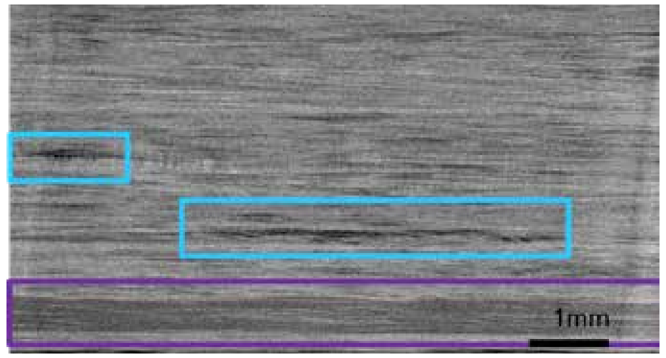
Quality Features of CF-PA6 UD Tape

The implementation of UD tapes in different assemblies requires various quality features. One important feature is the thickness distribution or thickness variation in the tape, as this is amplified due to the layered structure in the laminate, which in turn affects the mechanical tolerances in the assembly.



Thickness profile

Depending on the application profile, 10 - 20% is accepted as a tolerance limit by industrial users. For an optimal load transfer in the application, a homogeneous fibre distribution over the tape cross-section is indispensable. This can only be guaranteed by the lowest possible number of fibre-free areas in the semi-finished product, called »gaps«. Caused by process and material factors, fibre gaps result from twisting of the rovings and from fibre matrix interaction during the impregnation phase.



Gaps visualized by X-Ray computed tomography

In addition to the fibre volume proportion, the corresponding impregnation quality is also decisive for the mechanical performance. An evaluation criterion of the impregnation quality is the amount of so-called »dry spots«, which are represented by unwetted fibres in the tape. Further quality characteristics are the nodulation of the individual fibres and the waviness of the tape.

Bumps

These various types of features will affect the quality of the UD tape product in various intensity. So first of all, there was a classification developed which takes into account the criticality and significance of defects for the categories of structural performance, subsequent processing and marketing aspects (see picture ‘Classification …)

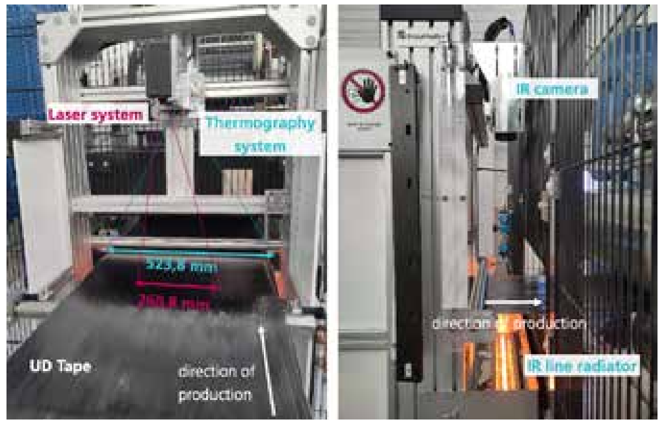
Processing and Image Data

The manufacturing system UD500 is equipped with laser thickness profile measurement system and active thermography system as described above. Both systems are attached to a flexible mounting rack which enables their adjustment to the manufacturing system and field of view.

For current trials the fields of view of the thermography and the laser system were adjusted as follows (see on fotograph):

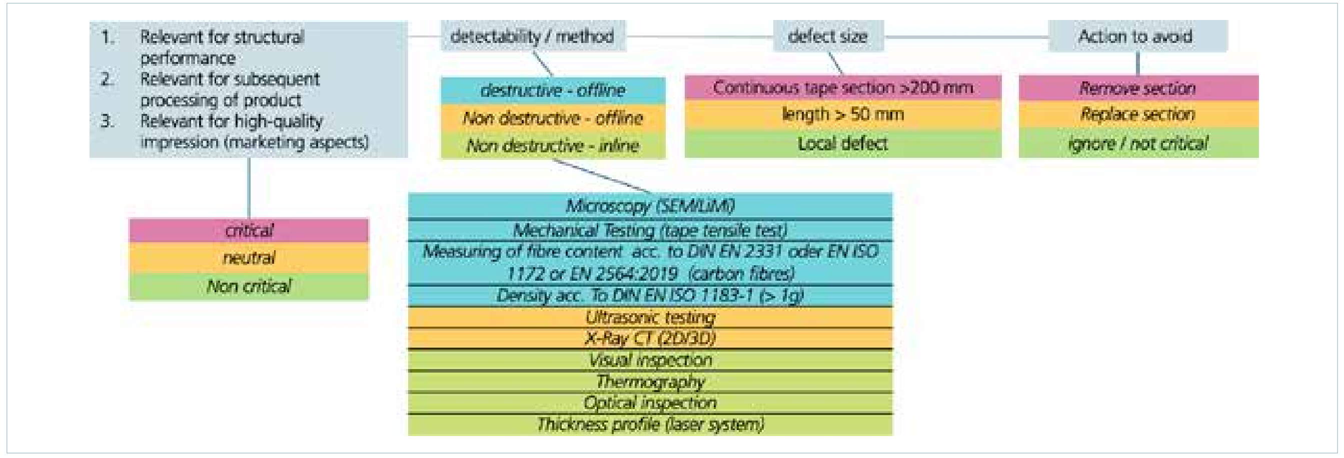
- Thermography system: 523,8 mm (complete width of the tape)
- Laser system: 260,8 mm in the center region of the tape

Data from both measuring systems was stored in DICONDE format and uploaded to the DICONDE server.



Manufacturing systems UD500 with integrated laser and thermography sensors; indication of sensor field of view in front view (left); thermography system in side view (right)

Processing data from the machine units were recorded via the DataXplorer interface and stored in an SQL database. Within a 30 min period data recording time during the manufacturing trials ca. 4 GB data was stored by the inspection systems, including the processing data. Synchronisation of all data sources was done by a time stamp and interpretation of corresponding meta data sets by the data management system.



Classification of defects of UD tape products

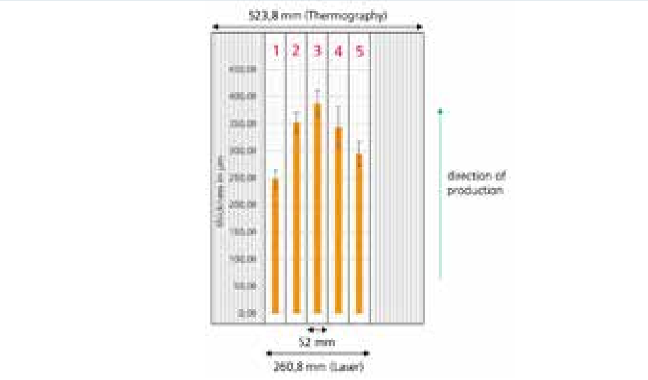
Evaluation of UD Tape quality

The data management system developed within the project enables correlation of the data sets recorded from the diverse sources

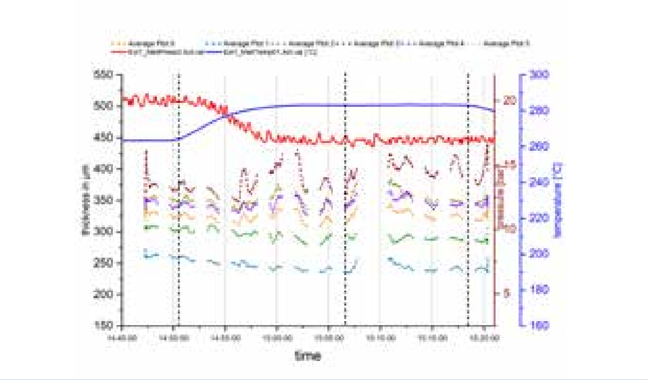
- Laser thickness data
- Thermography data
- Processing data

Evaluation thickness evolution

The laser thickness measurement system allows a time series analysis of mean thickness as well as thickness profile analysis. For a time series analysis the measuring field was devided in 5 regions with respect to the tape width (see picture). The mean values show a significant thickness variation with thicker area in the center region and smaller thickness in the edge region of the tape.



Tape section with arrangement of 5 regions for thickness measurement, orange columns represent measured thickness mean value per region

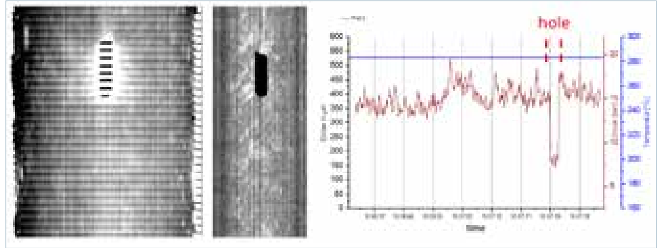


Time series analysis of measured thickness in 5 regions over UD tape width (dotted lines) and melt pressure (red line) and melt temperature (blue line)

The blue line in the diagram indicates the evaluation of the melt temperature, which was increased from 260 °C to 280 °C. It indicates that it takes a time periode of ca. 15 min from stable processing conditions at 260 °C to stable processing conditions at 280 °C. Corresponding to the temperature increase the melt pressure decreases slightly from ca. 20 to 17 bar, which corresponds to decreasing melt viscosity of PA6 matrix system on elevated temperatures.

Automated Feature detection

For validation of feature detection capability artificial defects were used. By doing so, the defect detection capability of the different inspection systems (thermography and laser thickness measurement) was evaluated by a correlation analysis. The picture shows exemplarily images of a cutted hole in the UD tape product, which could be clearly detected by both systems (see pictures).

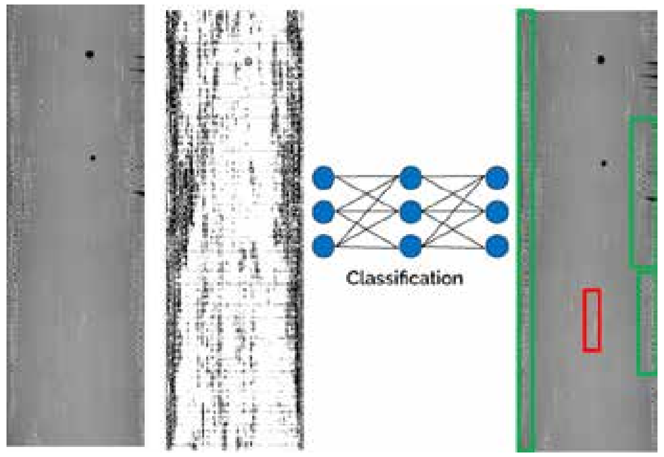


Correlative analysis of thermography image (left), thickness data image (center) and thickness time series (right) of artificial cutted hole in the UD tape

For further automated image analysis by image processing-based algorithm, a sort of image filters is designed, deployed and tuned to find the location of voids on the tapes. The filters are namely image equalization, filtering, binarization, opening, closing, etc.
The fault detection module uses a Feature-based Machine Learning algorithm, which generates some candidates of voids, and then from each candidate geometrical features, namely bounding-box, area, aspect-ratio and position, are extracted. In the next step, a machine learning (ML) model is trained, using these features over many samples of voids on multiple tapes. Finally, the trained model can detect the voids on the unseen tape samples automatically.

The first image (left) below shows a top view of the thermoplastic tape. In some regions, it seems brighter than in others. The cause is the higher density of polymer in these regions. The second image (middle) is the adaptive threshold result of the first image, showing best suited algorithm than other thresholding methods in the case of tape analysis.

To improve the detection task, we use morphological operands, which paste the adjacent white pixels in the binary image. In the next step, the area and position of the white regions are calculated. The sticking points of dense polymer regions are recognized in this way and the quality of tape production is quantified. The ML model can automatically detect and classify the voids over bad impregnated (red frame) and gaps (green frames) on the tapes (most right image).

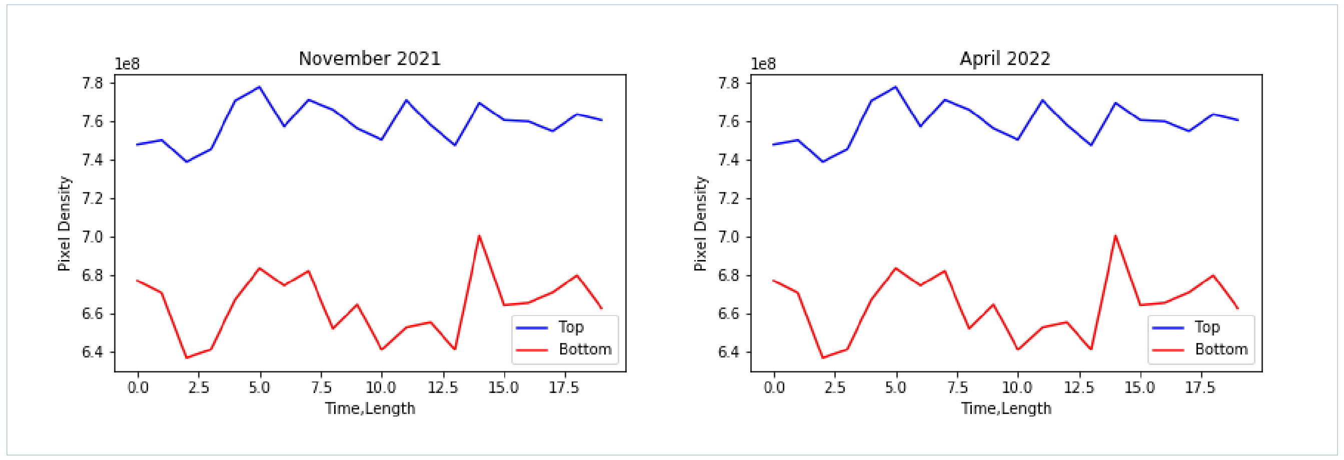


Automated feature detection in thermography images by use of machine learning models

By the use of inline inspection system including morphological evaluation by thermography inspection and thickness profile measurement as well as automated image processing and feature detection a powerful tool within the framework of the digital twin was developed for efficient and precise quality control of the continuous UD tape production process. Which represents a key requirement for using resource efficient UD tapes in future lightweight applications which have high load carrying capacity.

This plot shows changing the balance of the tape thickness over time. The user by comparing this plot with a similar plot from another date can get very valuable clues for the impact of setting the various manufacturing parameters on the quality of the tape over time.

The image on the page below shows the overall comparison between two diverse dates e.g., interesting machine channels or tape thickness profiles over time. When time passes, the thickness of the tape increases in the left plot of the first date but in comparison, in the right plot of the second date, the thickness does not change drastically over time. Because of numerous channels and records, investigating, tracking and analyzing the channels are very tough tasks even for a single image. To address this issue, the tool visualizes the channels' content using various plots. Diverse channels from a pair of dates are first selected, then their length are equalized and then they are visualized in the same plot. It allows an effective comparison of the same channel over diverse dates.



Thickness profile comparison between two diverse dates of experiment

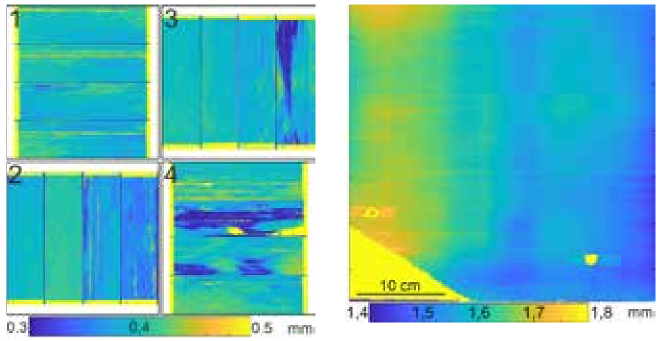
Use Case: Tracking and reducing material irregularities

Tape thickness as indication of irregularities

Among other features the thickness of a UD tape plays an important role when it is being processed in the process chain of tape laying, consolidation and hybrid-injection molding. Variations in the tape's thickness are likely to affect the tape layups' thickness distribution. During consolidation this leads to locally inhomogeneous pressure. Thicker areas will be subject to higher pressure so that squeeze flow will be more distinct. This may lead to fibre undulations, inhomogeneous fibre volume distribution and porosity. However, the main effect will be a varying thickness across the laminate as the squeeze flow can not compensate for the thickness variations in the layup respectively the tape. For subsequent hybrid-injection molding the laminate thickness is a key feature. Molds that are used in this process are designed according to the laminate thickness that will be utilized as reinforcing inlay. Therefore, the laminate has to fit into the given design space. If the laminate is too thick the mold might not be fully closed. This will result in incomplete mold filling as the flow paths for the injection molding compound are not defined anymore. The same applies if the laminate is too thin as the injection molding compound might overflow the laminate locally. As a result, the tape thickness was identified as one quality feature that was tracked throughout the process chain within MAVO digitalTPC project. In this application example it is explained, how the tracking can be realized. At first an approach to detect thickness features using non-destructive monitoring is presented. Then it is explained how defect information can be transmitted along the process steps with focus on data management. The third section proposes a solution to realize the segregation of irregular material. Finally, the resulting thickness variations of the consolidated laminate is assessed based on non-destructive measurements.

Inspection of thickness-evolution using NDT

Offline investigations contemplated how thick, thin and inhomogeneous UD-tapes affect the laminate-thickness. The tremendous thickness-gradient, (see figure right) coming from layer 2, indicates a much higher severity of overall thickness-deviations compared to local inhomogeneities, such as bad impregnation (see layer 3, left). It is assumed that plastic mold flow compensates local inhomogeneities.



Effects of tape-thickness (top, layer 1-4) on laminate-thickness after consolidation.

Transmitting Defect Information along the Process

This demonstrator benefits from the gathered information by the digital twin system to track the tape faults in semi-finished component production in Fraunhofer ICT aiming to eject the tapes with a fault level greater than a user-defined threshold. The steps of this demonstrator are depicted in the above image and explained as follows:

- The detected faults in the tape production step are localized using intelligent image processing algorithms.
- The relative position of each fault is calculated by using the position information in the heather of the DICONDE file and the position obtained by the localization algorithm.
- The position and area of each fault are saved in a table of an excel file.
- The demo then uses this information to decide whether a given tape piece is qualified to be used in the tape laying step.
- The threshold is set empirically by the end-user.
- The faulty pieces are rejected from the production line and therefore the quality of the product is preserved.

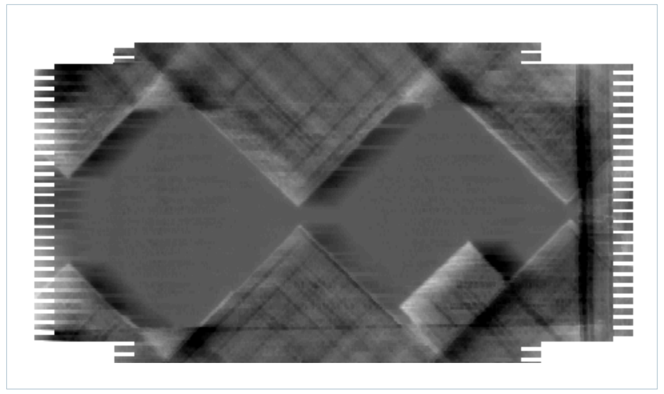
Realization of segregation of irregular material

The output generated within the previous step is a separate file that has to be load into the tape laying equipment's SPS. In combination with the tape laying data programmed according to the layup to be manufactured the machine's control can interpret the data and generate specific commands that are included into its program. These commands enable the handling of tape defects by either creating cut outs or placing tape stripes with minor defects in areas where these defects have no effect on the final component's mechanical performance. In the first case the equipment calculates which stripes have to be cut out due to the information given in the data. If the next tape stripe is affected by a defect in the tape, it will be cut but not placed on the motion table. Via a switch it will be guided into a storage box. If the tape defect is affecting more than one tape stripe it will repeat this step until there is no defect in the tape anymore. In the second case which was conceptionally discussed within MAVO digitalTPC the algorithm used to generate the failure analysis data has to identify what defect types are critical and what are not relevant. This information has to be handed over to the tape laying equipment which then can decide whether to cut out the tape or place the stripe somewhere else.

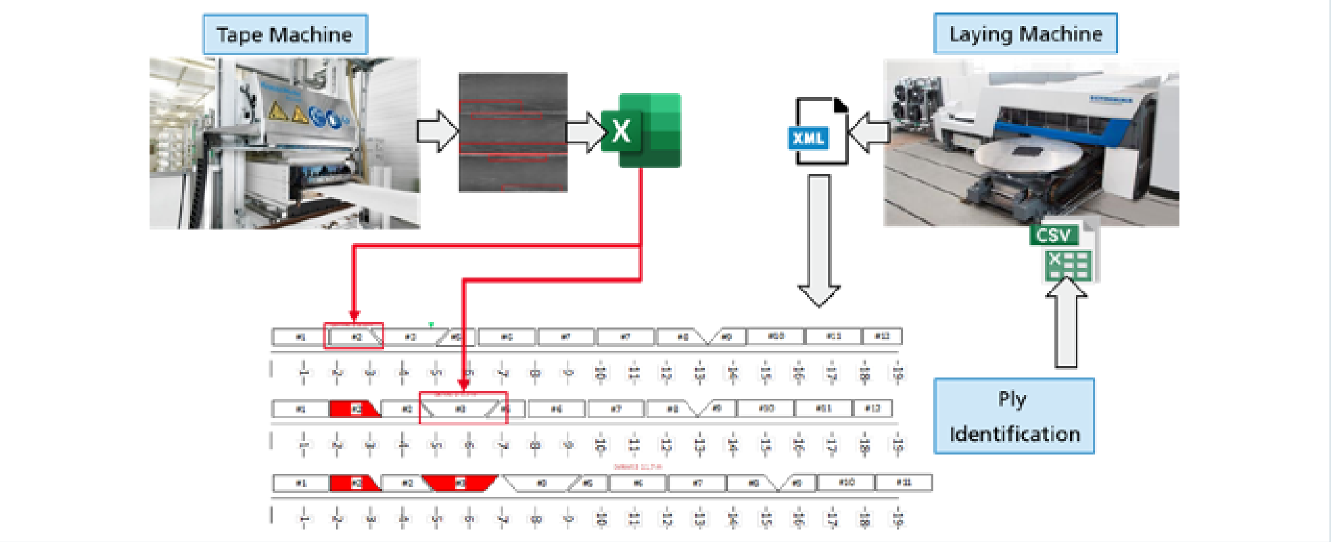
Conceptual demonstration of a posteriori testing on component

To enable the measurement and detection of defects in a consolidated laminate a measurement device was designed and built up within MAVO digitalTPC. Its aim is to detect material specific defects at two stages in the process chain. Therefore, it is equipped with an eddy current sensor and an ultrasonic sensor. The eddy current sensor is used to analyze defects at the laminate which is the semi-finished product after the process step consolidation. The ultrasonic sensor enables the measurement of defects at the final component after hybrid-injection molding is completed.

Regarding the tape thickness, which was identified as a quality feature, an application approach was made in order to measure thickness variations based on the eddy-current image. However, besides thickness variations, the eddy current gray values were found to comprise edge effects, fibre orientation and fibre volume content. Thereby, the result from eddy-current testing can be used as actual state of the laminate in a comparison against the target state which can be derived from the ply book for the laminate. The given example reveals overlaying tapes (dark contrast) and a tape cut too long.

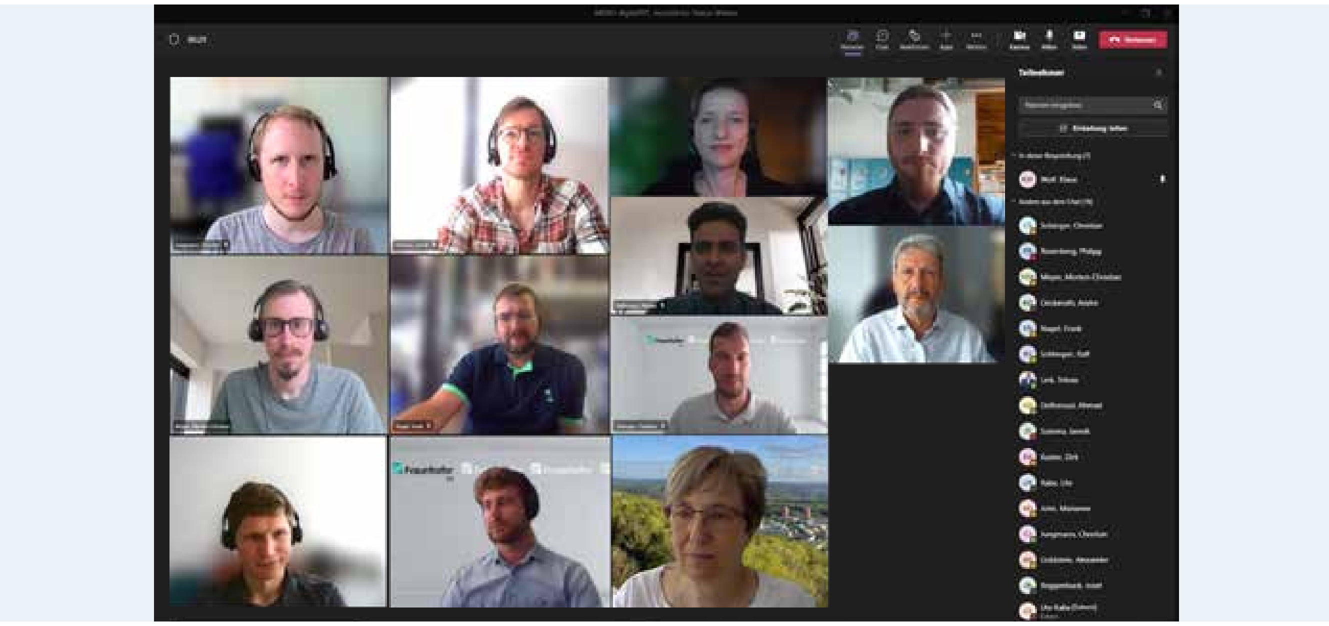


Eddy current testing of a cutted laminate plate right before hybrid Injection-moulding



Visual explanation of the proposed tape ejection system based on evelation of thermographic images and production machine data in ICT.

Best Practices – The Process of Digitisation



The digitalTPC team at one of its many online meetings

A cooperative process using “one-plus-four” essentials

Each digitalization project is unique, and yet, engineers face common challenges and benefit from following similar procedures. We distilled our experience from MAVO digitalTPC to best practices for a systematic processes. This helps to lead past the initial chaos to holistic solutions. Integrated with any engineering design cycle (waterfall, V-model, UPON for ontologies, etc.), it bundles common focus points of digital twins in each development phase.

The integrative nature of engineering, software development and operation in mind, each development phase has separate key experts. Therefore, digital twin projects are primarily about cooperation. Participants of this process effectively learn at first to organize themselves, and in hindsight, this organization is astoundingly similar to the final twin system. In some way, the final automated, computerized procedures are only as good as the human exchange – as a formalized version of them.

In this frame, we identified “one-plus-four” pillars as essentials for future digital twin projects that demand for parallel continuous integration.

1) The use case:
Everything starts from the industrial demand. What the twin should do defines what the twin should contain. It is only possible to set up a good architecture, if it is clear what to sort and connect. It is likewise crucial to have a clear picture of the optimization potential, technological goals & KPIs. This makes domain experts / engineers important actors, but also important communicators.

+1 – Data space:
The value of a digital twin can only be exploited with stable, secure and seamless access of twin assets. A data ecosystem requires data sources to be compliant in a machine processible fashion. Seemingly dry matter, continuous attention towards data access, storage, formats, interfaces, permissions and property pay off, be it for one data base or distributed data spaces.

+2 – Semantic framework:
When systems talk, they need a common language. Formal information models are required for uniform terminology, roles and relations of cross-influenced assets. Importantly, this describes the “meaning” of our resources and therefore forms the qualitative basis for interpretation of results. One key question naturally asks for the necessary granularity to resolve this meaning of the data sets and models.

+3 – Data processing: CAE, Analytics & AI:
This is the most intuitive pillar: for new insights, a quantitative processing of data must finally produce results. All methods apply: ranging from projections, feature extraction, surrogate-modelling to transformation-based analysis. Careful choice of rule- & data based modelling and analytics algorithms is therefore a central task over the entire life of the twin.

+4 – Uncertainty assessment:
One of the most discussed challenges with digital twins is uncertainty. Classically termed “verification and validation”, it must now become even more central to investigate uncertainties, sensitivity and repeatability in such complex systems of automated merging of measurement, machine data and simulation data.

Use Case Definition and Requirement Engineering Phase

Each development iteration increases the complexity step by step. It is advisable to start with a very coarse view and refine the granularity only where needed. The use case is always in focus, but developers of a digital twin can accelerate and improve the conceptual approach by constantly questioning the use case and how a digital twin helps with it.

Requirements that emerge from this questioning are constantly maintained. The focus is on the perspective of the global digital twin system and tasks for single sub-systems are completely relegated to the experts. Thus, we also obtain a new indication of the required granularity of the digital twin in each cycle.

For the first iteration, we pre-defined catalogues of important questions that leave sufficient room for adaptations according to use case. Using question-naires and intuitive shared documents and lists, this sharpens contrast at an early stage.

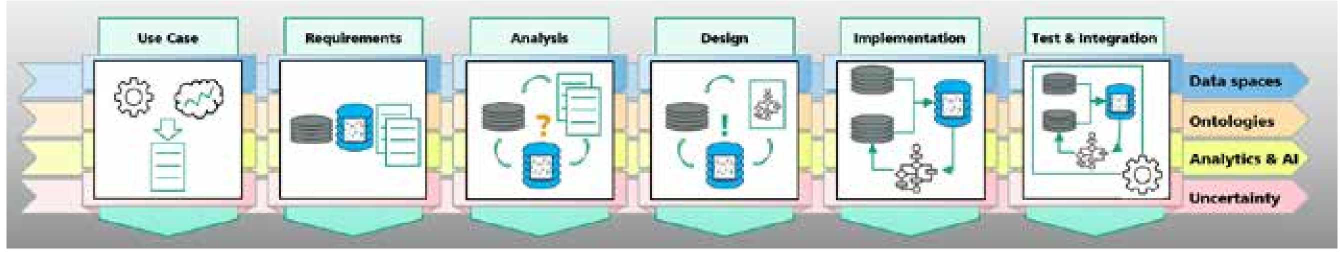
- use case outline in coarse system view
- formulation of key quantities and acceptable bounds
- essentials as minimal ontology scope
- loose collection and iterative refine-ment of data sources, participants and interdependencies
- deep discussion of the status quo of data storage & access automation
- contrasting with possible alternatives
- possible data processing methods as candidates to reach use case goals.

System Analysis and Digital Twin Design Phases

The analysis phase explores limits and opportunities of building blocks and the design phase draws the solution concept.

- collections of terms are cleanly defined and sorted
- accepted categories are organised in glossaries and hierarchies
- a conforming reference base is central exchange of information.
- investigation of appropriate analysis tools: when is which data available in which quality.
- new methods, new dependencies: iterating retrieval of dependencies of data space architecture, software and of system participants.

In contrast to the bottom-up requirement engineering, the system analysis freely introduces possible solution concepts based on experience or open recommendations in a top-down manner, e.g. by choosing and evaluating methodology candidates.



Digital Twin software development process - the main pillars

The digital twin design is the detailing of the analysis outcomes as solutions. Starting from system diagrams, UMLs and specification sheets, a master system is formulated and iteratively refined. From data base types, interfaces and analysis chains, the teams describe the ecosystem from the perspective of the use case. They make explicit which challenges are faced and how to solve them by applying the analysed methodology. It is very advisable to become as concrete as transforming activity charts to pseudo-code.

DevOps Phases: Implementation to Configuration

From this point onwards, implementation, testing, configuration and monitoring of the digital twin system are conducted in an integrative manner. Since the system is never complete, development and operation fade into one another and continue indefinitely. A development plan directs DevOps methods to realize this.

The implementation increases in complexity, pertaining to storage layer, APIs, analytics and frontend. Typically, the first building blocks are greatly simplified. In this, low-threshold data storage systems are used (e.g. a simple OwnCloud file-server before using a DICONDE server), off the shelf data loaders and ad-hoc data analysis methods. Similarly, first versions of measurement systems are tested offline, simulation models run manually and then increasingly integrated into the system.

These low-threshold interims are not only helpful to avoid bottlenecks, but crucial buffers in such complex systems. This way, all components advance in parallel. Fixed tests are defined and implemented to monitor the progress and immediately adjust requirements through feedback loops.

Finally, operation is facilitated with abstraction layers and user interfaces. The design and implementation of these is advised to be postponed to a point where the final function and usage of the digital twin system can be judged with high confidence.

Lessons Learned

…or which questions are still open after finalization of the project:

- Development of a digital twin of a complex production process requires an interdisciplinary approach
- Ontology can be established as a common language for collaborative work
- Development of a hollistic digital twin is a very complex and challenging task and needs to be simplified, via consideration of use cases, limit level of details, …
- There is not only one way to a digital twin. Hence, discussion between the domain experts is essential
- Risk related to the vulnerability of the modular measuring systems for the industrial production process
- Effort for data harmonisation from various sources (machine control, measuring systems, DICONDE)
- Vulnerability to cyber-attack Restart data systems, data transfer restricted
- Interoperability of simulation software remains a challenge
- …

Short introduction of the institutes

Fraunhofer IMWS

The Fraunhofer Institute for Microstructure of Materials and Systems IMWS is a methodologically oriented Fraunhofer Institute in the material sciences and materials engineering disciplines. The Fraunhofer IMWS is a contact for industry and public clients for all issues concerning materials and systems – with the objective of increasing material efficiency and profitability and to use resources carefully.

Within the Polymer Applications Department we work on issues regarding polymer processing and optimization of polymer materials. The aim of our work is to achieve improved energy and resource efficiency by using the materials and processes developed by us on an industrial scale. Our clients in the field of mobility applications, i.e. cars, aircraft and rail vehicles, profit from our work just as much as companies in the plastics or polymer industry and in mechanical engineering.

We supply solutions, for example, for thermoplastic-based lightweight construction, tyre applications or the use of bio-based polymers in high-volume production. We consider the entire value-adding chain, from the microstructure of the material through to the tailormade component. We develop on a small scale and, among other things, in the Fraunhofer Pilot Plant Center for Polymer Synthesis and Processing PAZ we have plants up to industrial scale and can carry out prototype mould validation.

Our know-how includes

- Raw material selection
- Microstructure design
- Processing technology
- Characterization of material properties on a laboratory, test centre and pilot plant scale
- Analysis of component properties, including predicting their behavior in use
- Modelling and simulation
- Process development

Fraunhofer ICT

We focus on the scalability of processes and the transfer of research results from laboratory scale to pilot plant scale and in some cases to pilot-level application.

We currently have about 580 employees, who carry out research and development in our core competences of chemical processes, energy systems, explosive technology, drive systems, polymer technology and composite materials. The total area of the institute in Pfinztal is 210,000 m², of which more than 27,000 m² are laboratories, offices, pilot plants, workshops, test ranges, and infrastructure. One of our departments is located at the East Campus of the Karlsruhe Institute of Technology (KIT). Well-equipped laboratories with cutting-edge safety features and energy-saving technology are available at the institute, as well as all the analysis and testing procedures needed for research in our specific fields. The Fraunhofer ICT has a close working relationship with numerous universities and colleges, especially with the Karlsruhe Institute of Technology KIT. Fundamental and application-oriented knowledge is utilized and further developed in hundreds of projects each year. The Fraunhofer ICT supports its clients and project partners from the original idea to the prototype phase or even to small-series production, according to their requirements. Clients and project partners are mostly from the automotive and transport sectors, as well as the fields of energy, environment, defense, security, and chemistry and process engineering.

Competence In Polymer Engineering
Material and process innovations provide the impetus for the development of advanced products. Long-standing experience in material and process development makes our institute a competent partner for application-oriented research and development in polymer and composite material technology - from the initial idea and the concept development through to the manufacture of prototypes.
We develop materials, processes and methods for our customers in the automotive, aerospace, construction, packaging, toy and leisure industries. In addition to individual topics from and along the value chain, we also provide solutions for long-term social challenges, in particular sustainable mobility, the circular economy, hybrid lightweight construction and the digitalization of process chains.

Fraunhofer IZFP

Sensor and Data Systems for Safety, Sustainability and Efficiency

Fraunhofer IZFP is an internationally networked research and development institute in the field of applied research. Its activities are focused on the development of "cognitive sensor and data systems" for the nondestructive monitoring of industrial processes and value chains. The Institute's technical understanding of inspection and sensor physics is supplemented by technologies and concepts from AI research, which are used to develop sensor systems for the NDT of tomorrow. In addition to pure production processes, the activities cover equally processes from materials and product development, maintenance, repair, and recycling of materials.

The current research focus relates to the development of sensors that are suited to capture production-related microstructural patterns and to merge them in the sense of an individual fingerprint, a so-called "product DNA". In the future, these "digital product files" will open up completely new approaches for the optimization of a material and product lifecycle.

Our vision

We are pathfinders and pioneers in the transformation of classic non-destructive measurement and testing technology towards NDE 4.0, ensuring a sustainable and efficient (material) recycling economy. Our sensor and data systems take predictive, intelligent and autonomous decisions on how to generate, to process, to forward and to archive relevant information from their data.

Our mission

Fraunhofer IZFP uses its competences in the fields of

- (unconventional) sensor systems for volume and surface properties
- software and services for sensor data management along the data value chain
- software and services for data analysis and data value creation with AI and ML techniques
- consulting and holistic services around measurement, testing, data value creation and standardization

to develop sensor and data systems for safety, sustainability and efficiency. We optimize circular processes for materials and products to ensure advanced industrial manufacturing and processing, as well as healthy living, nutrition, and supply security.

Fraunhofer SCAI

Methods and Algorithms

The Fraunhofer Institute for Algorithms and Scientific Computing SCAI combines know-how in mathematical and computational methods with a focus on the development of innovative algorithms and their take-up in industrial practice – bringing benefits to customers and partners.

SCAI's research fields in Computational Science include machine learning and data analysis, optimization, multiphysics, energy network evaluation, virtual material design, multiscale methods, high performance computing, and computational finance.

In the field of bioinformatics, SCAI offers its customers comprehensive services in information extraction (text mining). Here, the most important application field is the modelling of neurodegenerative diseases.

Connections to university research are established through the chair of Prof. Dr. Michael Griebel at the University of Bonn. SCAI also cooperates with the Bonn-Aachen International Center for Information Technology (B-IT) and the Bonn-Rhein-Sieg University of Applied Sciences.

Multiphysics Solutions

The virtual design and development of efficient manufacturing processes and advanced products is a major goal for any industry. Multiphysics co-simulation and integrated virtual engineering workflows are used to model effects of complete manufacturing history of the used materials and components, as well as the inferences of physical effects represented by coupled CAE models. The MpCCI interface portfolio from Fraunhofer SCAI provides a vendor neutral software solution for direct code coupling and seamless data transfer in integrated CAE workflows.

Digital Twins link real world data from production machines and physical tests with virtual models and simulation results. Smart analysis tools help to find correlations between data and increase prognostic capabilities over time. The emerging MpCCI Twin Toolbox will provide general architecture concepts and sophisticated twin modules to enhance your Digital Twin realization.

The smart combination of multiphysics modelling with smart digital twin concepts will provide better insights into manufacturing processes and complex product behaviour.

Contacts and Project Partners

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Fraunhofer Institute for Algorithms and Scientific Computing SCAI

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