ROBUST DEVELOPMENT, VALIDATION AND MANUFACTURING PROCESSES FOR HYBRID METAL-COMPOSITE LIGHTWEIGHT STRUCTURES

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ABSTRACT

Hybrid metal-composite structures offer high potential in lightweight engineering. These hybrid structures combine different materials to create components that are far ahead of the classic designs in terms of strength, stiffness and weight. Next to the advantages, the manufacturing of such components is highly complex. Additionally, increasing requirements of the components effect increasing engineering effort. The multitude of adjustable and interacting parameters leads to a complex and multi-disciplinary product development process. The correlations and interactions of the process and disturbance parameters on the properties are partly unknown for hybrid lightweight structures. For a reliable manufacturing process with low defect and reject rates it is essential to monitor the process and material properties during production. In this paper, a concept is presented how non-destructive testing (NDT) can be integrated into the development process model of hybrid metal-composites. A methodical approach to modelling the product development process is used, describing the methods and models used in the process, as well as the generated data. Moreover, several NDT methods were evaluated for quality assurance of hybrid metal-composites.

1. INTRODUCTION

Due to their outstanding mechanical properties, fibre reinforced polymers (FRP) are becoming increasingly important for use in mobile systems. The combination of FRP with metallic components allows the realization of new hybrid metal-composite structures (MCS), which offer advantages compared to classical solutions in terms of degree of function, design space and weight [1]. Innovative MCS are predestined for highly stressed structural elements such as body parts of cars [2]. On a prototype scale, such hybrid structures have been already designed, manufactured and tested successfully [1-4]. Some of the hybrid concepts were successfully transferred into application [5]. Nevertheless, the transfer of MCS into industrial application is still challenging. The multitude of adjustable and interacting parameters in the areas of design, dimensioning, manufacturing and quality assurance (QA) leads to a complex and multi-disciplinary development, validation and manufacturing process [4].

In general, VDI 2221 describes the product development process in a systematic way with several phases [6]. For the development of lightweight structures HELMS presents an approach of strong interaction of different engineering disciplines [10]. A guideline for knowledge-based engineering is provided by VDI 5610 [8]. In the implementation there are several approaches from assisted product configuration to deep-learning propose of manufacturability in CAD-systems [9]. GÖTZ reviews an interaction of relevant parameters across the engineering phases from development to QA for a tolerance management of classic structures [7].

MCS are new challenges for the test methods due to their more complex design compared to classical design. Non-destructive testing (NDT) methods can be used to detect defects in the interfaces of the components and in the structure of the components themselves without destroying the components. Thus, NDT is an important element for QA integrated in the manufacturing process as well as during operation of the components to increase safety and reduce the reject rate [11]. The suitability of the individual NDT method depends, among others, on the material to be examined or the interface itself and its properties, on the defects to be found, the defect sizes and the geometric conditions in the component and in the contacting area [11, 12]. The ultrasonic method is very well suited for the characterization of planar connection areas, since it provides clear signal reflections perpendicular to the connection surface in case of detachments [13]. Electromagnetic methods and also optical methods are very well suited to provide precise information on the structure and material properties in the near-surface range of components. The eddy current method [14-16] allows to detect surface cracks, inclusions, delaminations and to map fibre orientations. The optical coherence tomography (OCT) reveals both cross-sectional, as well as sub-layer depth information of composite materials [17, 18]. With a favourable combination of NDT methods, a large part of the resulting defects can be detected and sources of defects can be eliminated.

For small and medium-sized companies in particular, the associated high development costs and long development times, combined with high technical risk, lead to considerable barriers to the implementation of hybrid components. The goal of this paper is therefore to lower the development and industrialisation barriers for hybrid lightweight structures.

2. HYBRID METAL-COMPOSITE STRUCTURES AND MANUFACTURING PROCESS

To investigate the complex interactions between geometry, material and properties influenced by the manufacturing process, a technological test specimen was designed [3, 4]. This generic structure in Figure 1a was abstracted from a complex, highly loaded area of a car body component (A-pillar) [2, 4]. The geometry was simplified and designed symmetrically, whereby the respective thicknesses of steel and thermoplastic composite sheets (TPC) with glass fabric as well as the material combination were taken from the A-pillar. The validation of the generic structure is performed in component tests comparable to the main load cases of the A-pillar. As an example, the main load case of the car rollover, which corresponds to a unilaterally clamped bend, is given in [4].

Several methods of NDT are available for the validation of component properties by QA. To increase the robustness of product development process an integration of these NDT methods in an early stage of the process is useful (Fig. 1b). A basic difference can be made here between integration on a method level and on a component level. The method level describes the requirements of the measurement system (e.g. measurement parameter, accuracy, sensor size, distance to the measurement object, etc.) for the component or manufacturing process in the form of design and manufacturing rules. This ensures that the component and the manufacturing process are designed in such a way that QA of the component can be implemented. At the component level, virtual or physical sensitivity analyses (e.g. effects of varying fibre angles) from preliminary investigations are used to adapt the component or the manufacturing process at an early stage if requirements are not met. This early validation step makes it possible, for example, to transfer the real measured fibre angle into the component dimensioning or to adapt the process so that the manufactured fibre angle in the component corresponds to the dimensioning.

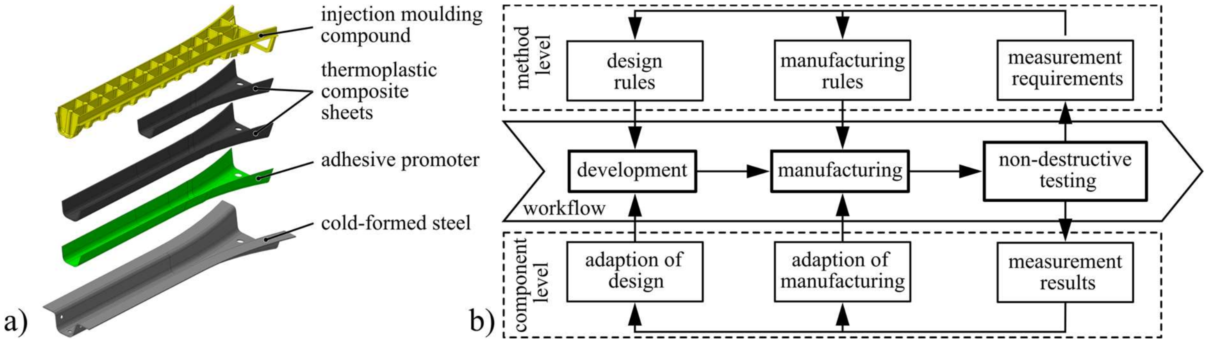

Fig. 1. a) Generic hybrid metal-composite structure; b) Approach of integrated non-destructive testing in the development process

The process chain of the MCS with the individual process steps and semi-finished products is shown in Figure 2. The possibilities of inline QA are discussed in all process steps as well as for the starting and intermediate products. The metal sheet is formed into a 3D shape by deep drawing. Afterwards, a surface pre-treatment, usually by means of an adhesion promoter or plasma treatment, is necessary to create a bonding between the metal and the TPC sheet. QA of the metal structure after forming, using optical 3D metrology, can monitor geometrical deviations [19] and detect defects like wrinkles or cracks.

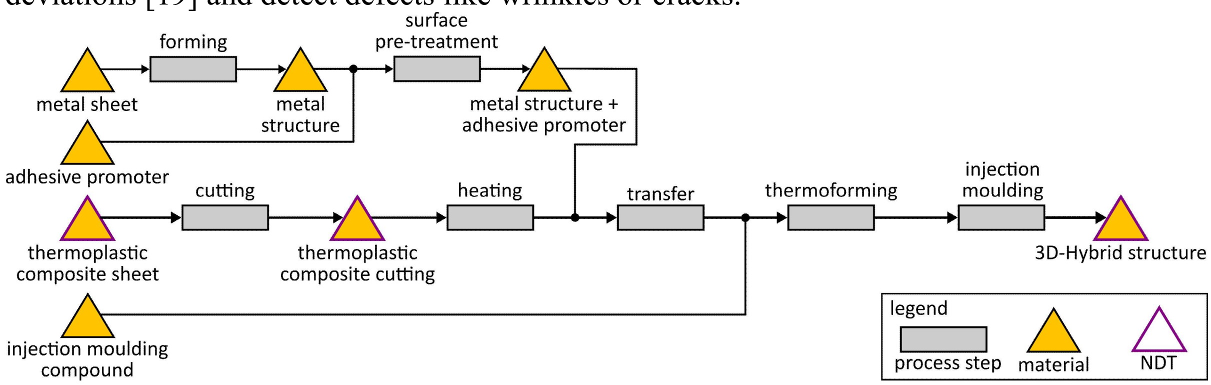

Fig. 2. Process chain model of manufacturing process of metal-composite structures

After surface pre-treatment with an adhesion promoter foil, QA can detect defects such as inclusions also with optical 3D metrology. Parallel to the process steps already mentioned, the TPC sheet is cut to size. QA using optical 2D measurement technology of the TPC cutting can check the cut edge for geometric deviations and fibre breakouts [6]. With 2D measurement technology, deviations in the fibre angle can only be detected on the surface. In this paper, another possibility by optical coherence tomography is presented, to check the fibre angle in several layers as an inline measuring method. The QA of the main process steps heating, transfer and thermoforming of the TPC sheet and of the injection moulding is presented in [3, 4, 6]. The last process step in the chain is testing.

3. NON-DESTRUCTIVE TESTING METHODS

In order to enable the comparison of different test methods and to develop a validation strategy, various test methods were first evaluated with regard to their basic suitability for testing on exemplary samples. We consider ultrasonic testing, eddy current testing, optical coherence tomography, X-ray inspection and active thermography as potential suitable testing technologies.

The ultrasonic testing (UT) is an acoustoelastic method which can detect differences and transitions in the acoustic impedance of components. Various testing scenarios can be investigated by applying different frequencies, angles of incidence and coupling conditions. Typical defects to be addressed are delaminations, material variations and cracks. A clear advantage of UT is the availability of information about the depth, at which an irregularity is located.

The eddy current (EC) testing is an electromagnetic method. Changes in the electrical impedance and thus in electrical conductivity are recorded by means of a coil technology. A depth information is not available, due to an integral response in the coil sensor. Additionally, the penetration depth is also limited depending on the material composition and frequency used. Even though, the technique is often considered to be limited to the surface, we are able to penetrate several layers with this technique. Advantages of the technology are: it is comparably very fast, works without any coupling agent and with quite low technical effort. Typical defects to be detected are surface cracks, inclusions, delaminations and material changes.

The optical coherence tomography maps the optical scattering intensity within the sample. The physical process provides 3D information due to its design alone, is very fast with over 30 B-scans (line depth scan) per second, works contact-free and without the use of ionizing radiation. To obtain depth information within the material composite, the material must be semi-transparent in the range of the wavelength used (VIS/NIR). The process cannot penetrate into metals or information cannot be obtained even in the layers below, but the surface is again directly mapped in 3D. Typical characteristics to be detected are defects (such as cracks, inclusions, delaminations and material changes), fibre orientation, cracks and position, as well as surface properties (such as roughness and defects). All data are available with the corresponding 3D assignment.

The X-ray inspection shows variations in the absorption behaviour of the materials which is originated in most cases by variations in density. Depending on application and use, two-dimensional images of the interior of the structure by radiography (but without depth information) or three-dimensional data sets by microcomputer tomography can be generated (with depth information). Typical defects to be detected are material changes, pores and inclusions.

The active thermography records the thermal conductivity of a component. For that, a small but defined heat input takes place via different methods, and the heat flow in the component is analysed in time via an infrared camera. The method is comparably fast and completely contactless. Typical defects to be detected are surface cracks, inclusions, delamination, and material changes. The both last mentioned testing methods are considered within this study only as methods for comparison, because of their complexity, expansive set-up and (in case of X-ray inspection) the involvement of ionizing radiation. Moreover, the active thermography has a relatively low resolution. Both methods are not considered further more as future standard testing and evaluation technology for the manufacturing processes for hybrid metal composite lightweight structures.

3.1 Ultrasonic Testing

The ultrasonic testing results performed at a test sample #1 are shown here as an example. This sample is a layered structure with total thickness of 3 mm and the symmetric composition steel-TPC-steel. The measurements were done in immersion technique with two devices and different testing frequencies: Scanning Acoustic Microscopy using 20 MHz and conventional ultrasonic scanning using 10 MHz. Figure 4 illustrates the scanning from the metal side: a number of defects are clearly visible in all images. They are located below the steel layer in the interface to FRP or in the upper FRP part itself. If we scan the same area from the FRP side we do not see that indications.

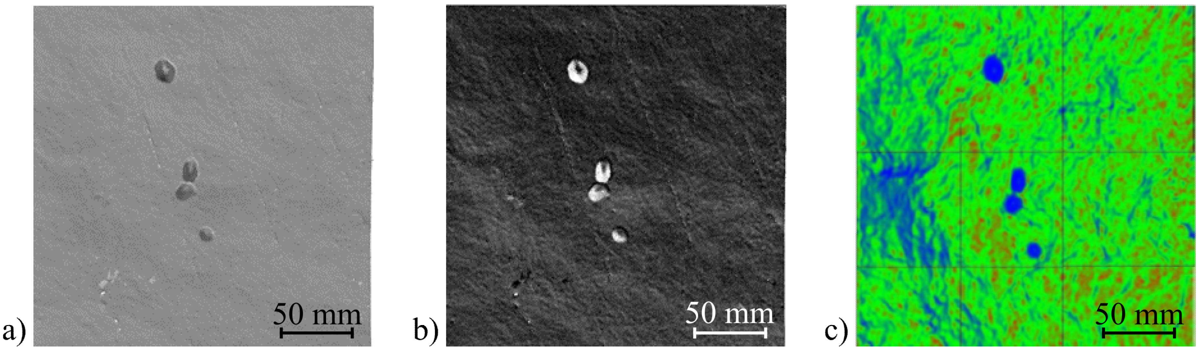

Fig. 3. Ultrasonic C-scans (230 x 230 mm²) taken with a focused transducer at 20 MHz in the SAM and plotted for different analysing parameters (a, b) compared to a false colour C-scan taken with an unfocussed 10 MHz transducer by the classical system (c)

This shows that the ultrasound does not penetrate the FRP to provide an echo from the FRP steel interface behind. In the false colour C-scan there are very distinct wavy structures which we attribute to the FRP fibre structure and/or the steel FRP interface. While the ultrasonic immersion testing has a high resolution, it has its limitations when it comes to curved structures. Here an alternative approach is needed. A promising option is the application of guided elastic waves excited e.g. by an ultrasonic goniometer [21]. Any inhomogeneity in the structure leads to a change in the propagation velocity and scattering of the waves, which can be detected.

3.2 Eddy Current Testing

Due to the physical functionality of the eddy current method and here especially the limited penetration depth of the technique, it is particularly suitable for the detection of surface defects as well as for the determination of layer thicknesses of non-conductive or poorly conductive layers. Extensive investigations show that it is possible to characterize fibre composites for different properties and defect types with the help of an eddy current scan. Defective fibre components can be detected as well as faulty or missing fibre layers, angle defects and also delaminations within the fibre composite. The following figure presents some examples.

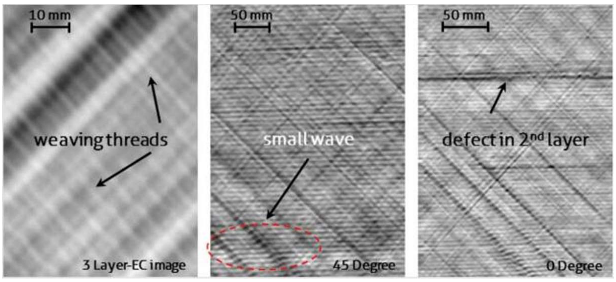

Fig. 4. Typical eddy current scan images on FRP with specific structures and defects [11]

The fibre structure is clearly visible in the scan images, in fact, of all fibre layers that can be penetrated by the field under individual adjustment. Based on these data it is still possible to determine the fibre orientation of individual fibre layers as well as individual fibre bundles very accurately. This application has already been implemented together with the external company Suragus in a marketable device system, as the following figure illustrates.

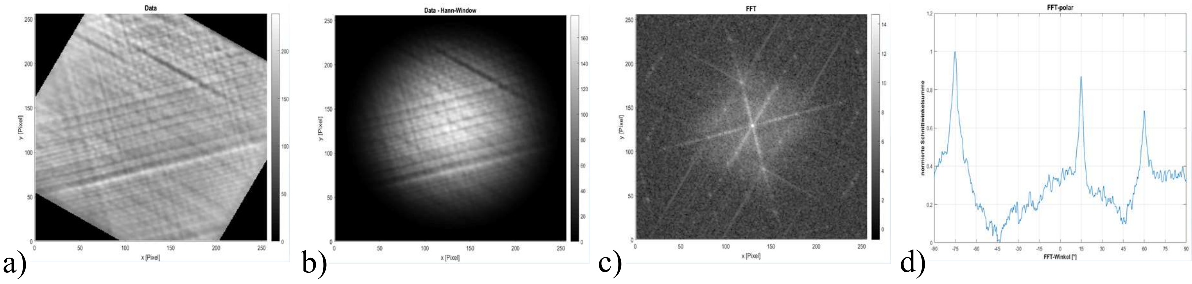

Fig. 5. Determination of the fibre orientation based on the scan images of the eddy current [15]: a) rotated raw data, b) raw data with Hanning window to eliminate disturbing edge effects, c) 2D Fast Fourier Transform of image "B", d) threshold classification by summing up the spatial frequencies found in the 2D FFT

It should be noted that in this application the fibre composite must be the top layer of the hybrid structure to achieve good defect detection probabilities. Furthermore, the eddy current method clearly reaches its limits when defects are located in the boundary layers between individual components of the hybrid assembly. The ultrasonic method is much better suited for this purpose. A good application for the eddy current method is to determine the thickness of the adhesion agent on the steel sheet. Investigations have shown that it is possible to penetrate the adhesion agent with the eddy current method and thus determine the thickness of the coating. A requirement here is that this area is freely accessible during the test. Then the detection of defects in the adhesion agent is also possible.

3.3 Optical Coherence Tomography

The non-destructive real-time imaging via OCT allows to explore the nature of defects in and structural information of fibre composites [17]. The size, geometry and location of defects in the composites can be determined and the cross-sectional and volumetric images clearly demonstrate the possibility to analyse the complex fibre structure with OCT for composite research, as well as for industrial QA and production monitoring [18, 20]. It can be used to obtain structural information of the composite materials such as distribution of glass fibres and orientation. The OCT method delivers information about changes in the optical properties in the volume of a (semi)transparent material. The (semi)transparency is in this case related to the emission spectrum of the light source used in the OCT system. Typically, an OCT tomogram is built from subsequently acquired B-scans showing the changes in the intensity of the backscattered light as a function of depth. The same tomogram can be cut in the surface plane giving top-side view at different depths, the so-called Z-scans. Standard image processing methods such as intensity averaging or summation can be used to obtain a projection image showing surface or subsurface features to their best advantage.

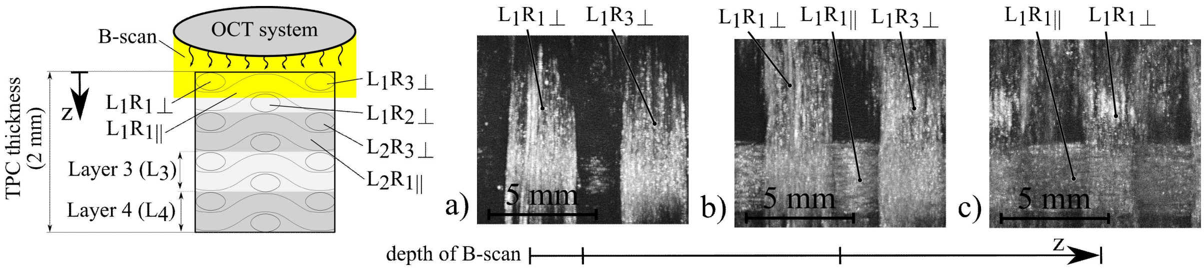

Fig. 6. OCT B-scan of a thermoplastic composite sheet with woven glass fibres

Figure 7 presents a schematic representation of an OCT system performing B-scan on a glass fibre fabric combined with a polymer matrix in a 2 mm TPC sheet. As it can be seen, we can obtain visual information from the first layer of rovings. The B-scan is performed with 28 kHz and a pixel size of 20 µm in 13.2 seconds. The resulting tomogram was cut in Z-scans and analysed. The resulting layers were divided into three groups showing different roving and processed into average intensity images. The resulting images are shown in Fig. 7 (a-c). As it can be seen, the OCT imaging delivers the information not only for the uppermost rovings ($L_1R_{1\perp}$ or $L_1R_{3\perp}$) of the first layer, but also for the underlying rovings ($L_1R_{1\parallel}$) and the deepest roving of the first layer ($L_1R_{2\perp}$). From the second layer on, rovings can no longer be visualised.

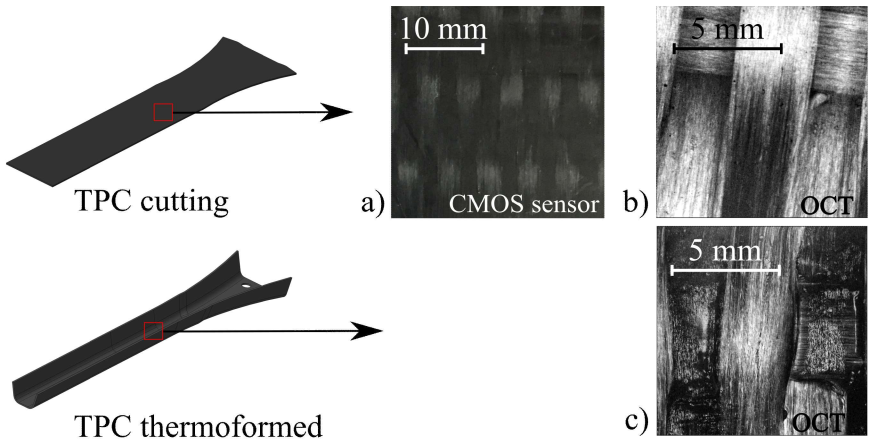

Fig. 7. OCT scan applied on a TPC cutting and thermoformed TPC sheet and compared with a standard industrial camera with CMOS sensor

The OCT method was applied to different types of thermoplastic composite materials. Figure 8 shows scans obtained on a TPC sheet cutting and a thermoformed TPC sheet. Compared to image 8a from a standard industrial camera with CMOS sensor, the OCT images in b and c provides a higher level of detail and the fibre rovings can be visualised clearly without interferences by the plastic matrix.

4. PROCESS MODEL OF THE DEVELOPMENT PROCESS

The development, manufacturing and testing is supported by an understanding of the process as well as the interaction of relevant parameters across the phases of the product development process. By a description of single process steps, requirements for these steps are deduced. Combined with a placement in the process chain, this enables the description of rules for previous phases and a consideration at an early stage as shown in Fig. 1b). In a next step linking of parameters across the phases can be a basis to identify key parameters in the design phase, control them during test-phase and develop a testing-friendly design.

First, a description of the development procedure is done using a process model that is structured with regard to the phases in VDI 2221 [6]. These phases consist of process steps (PS) in different levels (LE) of detail as shown in Fig. 3. If a higher detailing level is useful, steps can be specified by a set of sub-steps.

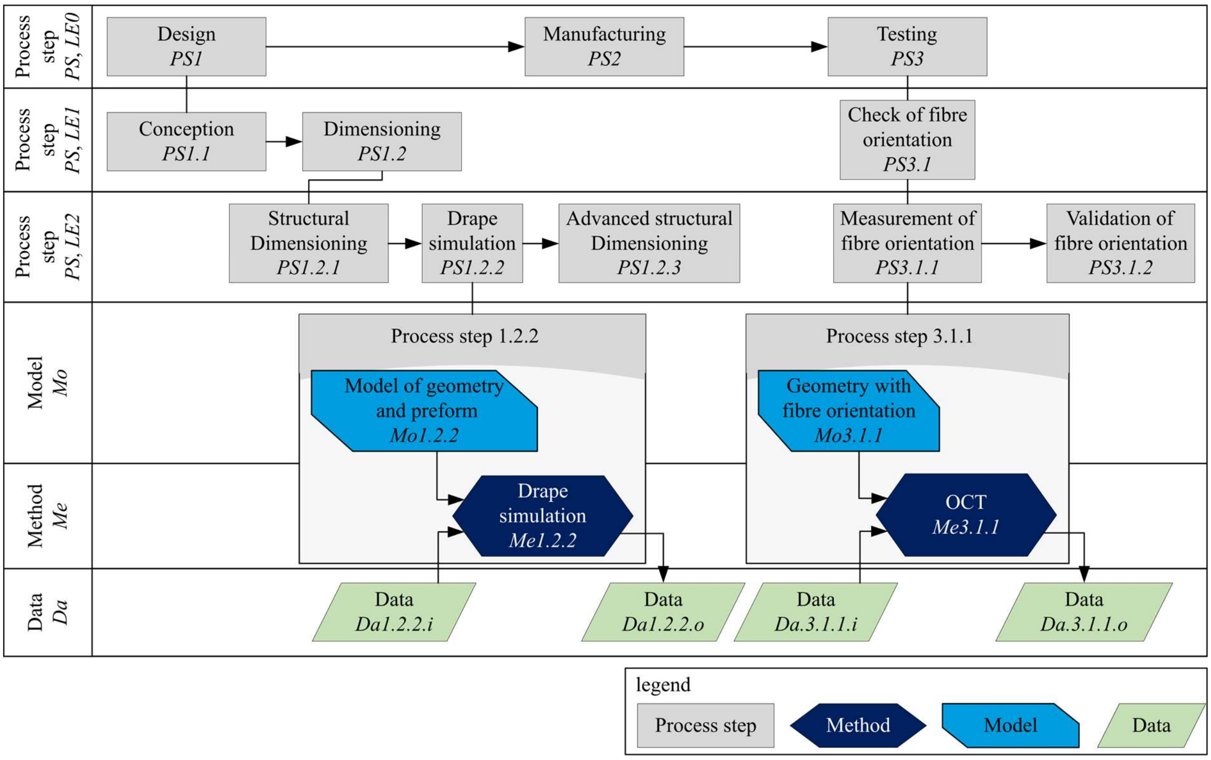

Fig. 8. Exemplary process steps in the process model for the engineering development process

In Fig. 3 this is shown with process steps "structural dimensioning", "drape simulation" and "advanced structural dimensioning" as sub-steps of "dimensioning". While "structural dimensioning" gives a first impression of structural capabilities, the "advanced structural dimensioning" uses the results of a drape simulation and provides a more detailed representation of the structural properties. In order to assure an identification, process steps are numbered in order of action with hierarchical numbered sub-steps. For characterisation of process steps with highest level of detail an approach of FELDHUSEN and GROTHE is used, stating every process step consists of an executive method (Me), an associated model (Mo) and a set of data (Da) [10]. These model and method succeed the numeration of the associated process step.

Data is stored in a data platform as parallel stream. For each process step, data from the data platform are assorted as input data. Secondary results from generated output data is added to the data platform. While input and output data succeed the numeration of associated process step, data at the data platform need an independent numeration with regard to their topic. In the example of Fig. 3 output data Da1.2.2.o and Da3.1.1.o are stored in the data platform and their parameters can be used for a comparison in process step of validation.

Additionally the model supports a documentation including the process on the one side and the methods and models with description on the other side. This includes additional process related information like person responsible, required experts and attended time. By storing the information in a catalogue, they are available for following development processes. In this way, a support can be given on the one side in planning with meta information and on the other side in execution by stored methods and models.

5. CONCLUSIONS

In this paper, an approach of the integration of non-destructive testing (NDT) in the development and manufacturing process of hybrid metal-composite structure is shown. In order to enable different test methods and to develop a validation strategy, several NDT were evaluated. The most suitable like ultrasonic testing, eddy current testing and optical coherence tomography have been further investigated. The test methods were first examined for their application to FRP as shown in the examples. A distinction between method level and component level helps in the use of data from the NDT in an early stage of the development process and for integration of quality assurance steps in process chain model of the manufacturing process. A process model is shown to document the development process. This model is based on an approach by FELDHUSEN and GROTHE and can describe process steps at different levels as well as methods, models and data to specify the process steps. In further steps a higher level of integration of the NDT into the manufacturing process and into the described methodology of the development process must follow. Furthermore, a merging of the information from the manufacturing process with the presented methodology of the development process is necessary to create a linked and interacting process to lower the development and industrialisation barriers for hybrid lightweight structures.

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