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Conception of an eddy current in-process quality control for the production of carbon fibre reinforced components in the RTM process chain

M.Sc. Dietrich Berger*[a], B.Sc. Andreas Egloff [a], M.Sc. Jannik Summa[b], M.Sc. Michael Schwarz[b], Prof. Dr.-Ing. Gisela Lanza[a], Prof. Dr.-Ing. Hans-Georg Herrmann[b,c]

[a]*wbk Institute of Production Science – KIT Karlsruhe Institute of Technology*
[b]*LLB Chair for Lightweight Systems – Saarland University*
[c]*IZFP Fraunhofer Institute for Nondestructive Testing*

* Corresponding author. Tel.: +49-721-608-44016; fax: +49-721-608-45005. *E-mail address:* dietrich.berger@kit.edu

Abstract

The integration of quality control processes in immature production systems such as the resin transfer moulding (RTM) process in the production of carbon fibre reinforced plastics (CFRP) faces numerous challenges. Requirements towards the reliability and product design as well as the consideration of economic restrictions lead to challenging requirements for measurement systems. This paper presents the development of a process integrated quality control using eddy current inspection. The concept focuses on an eddy current sensor array that is integrated in a preforming tool and thus enables a 100% quality control of CRFP parts with minor effects on the production environment.

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Keywords: Carbon fibre reinforced plastics; Resin transfer moulding; Nondestructive testing; Eddy current; Metrology; Quality control

1. Motivation

Lightweight structures have proven themselves to obtain a high potential to reach to the international goals of CO_2 reduction, which are empowered by jurisdiction. Lightweight components, especially in the automotive industry, allow the reduction of emissions by decreased driving resistances that result in a lower fuel consumption. [1][2]

However the use of lightweight materials such as carbon fibre reinforced plastics (CFRP) is bound to both technologic and economic restrictions that must be considered in order to enable a serial production of CFRP parts to achieve a significant effect of emission reduction in automobiles [3]. Technological restrictions include the requirements resulting from the automotive industry such as the multi-material design of components and high amounts of variants manufactured in automated processes. Simultaneously the innovative anisotropic material properties of carbon fibres lead to challenges in the design process of CFRP parts, partly leading to an inevitable over dimensioning and thus result in a smaller reduction of weight than possible. To tackle this problem, the production of CFRP parts would require a high process stability that is not necessarily given in existing process chains that mostly are referred to as immature [4]. The negative economic effects therefore result in scrap parts and require innovative methods of quality control to make sure that the required quality is given.

The resin transfer moulding (RTM) process chain offers the possibility to reduce the production costs by splitting up the forming and infiltration process, enabling the possibility to detect defects right after they occur due to the draping process and exclude affected parts from the further value-added process chain right before the infiltration. Defects that can occur in the preforming process can be subdivided into local and global defects depending on their dimensions. Contour accuracy, fibre disorientations due to adjacent textile layers, folds and gaps have been identified as relevant defects in previous works [5]. Therefore quality assurance systems were

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developed in order to identify these defects under serial production restrictions such as minimized measurement times by implementing both new measurement strategies and technologies [6], [7], [8]. All of the developed systems have in common that they require individual stations where harsh influences are excluded in order to create a robust measurement environment and either require additional handling processes to link the inspected part or are based on a kinematic system that enables the movement of the sensing systems above predefined regions of interest (ROI). Especially the detection of defects that are hidden under the visual layers of CFRP is challenging as there is a lack of approaches that are suitable for 100% quality controls in serial production.

This paper presents an approach that expands existing methods of eddy current testing of CFRP by integrating stationary eddy current arrays in the preforming process and therefore enables a 100% quality assurance method that does not require any additional space on the shop floor or additional handling steps.

2. State of the Art

The following section shows why the consideration of the preforming process in the RTM process chain is important in the consideration of part quality, how existing quality assurance methods are applied on the preformed CFRP parts and why eddy current testing has a high potential as a process integrated quality control.

2.1. Preforming

The RTM-process can be subdivided into four main steps: Prearrangement of the used textile, preforming, infiltration and finishing. The separation of forming and infiltrating steps in this process chain allows intricate part geometries that however simultaneously have adequate properties regarding the infiltration quality for serial production. Furthermore a preforming step upstream allows purposeful fibre orientations, which are needed for a load specific design of the manufactured parts. The main tasks of the preforming step are the shaping of semi-finished textiles and the fixation of single CFRP-layers in the layer structure. Especially the shaping is challenging due to the missing plasticity of the material, which strongly affects the shape accuracy of the preformed parts, which represents a significant quality characteristic. An insufficient degree of shape accuracy may appear as pleats or target-actual-differences considering the part geometry itself. Inconvenient fibre orientations that are bound to these types of defects lead to a decreased load bearing capacity of the part due to its anisotropic behaviour. Local misalignments can appear as fibre gaps that lead to resin accumulation during the infiltration or in-plane waviness both leading to a weakening of the composite. [9]

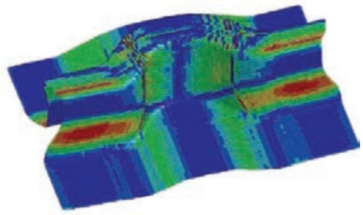

Fig. 1. Draping simulation [10]

The design process of CFRP parts already considers computer aided methods as can be seen in Figure 1. Critical areas that are affected by previously described defects (red zones in Figure 1) are identified by modelling material properties in finite element computation and reproducing potential process parameters in subsequent simulation studies [10]. Disadvantages of this simulation based characterization of the preforming step is the strictly theoretical consideration of highly complex procedures affected by factors that are not part of the digital model und thus need to be analysed in experiments. An experimental classification of critical shape-material combinations is currently analysed in [9].

Commercial preforming technology can be subdivided into sequential and global systems: Sequential preforming systems are characterized by a layer wise insertion of textiles in the used cavities allowing a high degree of quality regarding the features described above. Global systems however include one draping step for the whole layer stack, leading to short cycle times however with lower part qualities. [9]

Automated preforming systems consist of positive and negative moulds with the textile stack in between, being forced together by separately actuated cylinders. A prevenient melting of binder material with heat radiators enables the retention of the moulded shape and the transitions between single CFRP layers. The applied forces in the preforming step can be applied by pneumatic cylinders with comparatively low forces, which allow the integration of additional elements in the forming mould without unfavourable deformations of the mould. Heating elements are inserted in preforming tools to permanently keep the melting temperature of the binder during the preforming process and improve the target-actual-difference of the preformed part.

2.2. Nondestructive testing of CFRP

The availability of nondestructive quality control techniques is an inevitable necessity for a profitable serial production of CFRP parts in the automotive industry. Especially the control of highly stressed components that are relevant for the safety of the passengers is required in order to deliver reliable parts that are simultaneously using the full potential of lightweight design without oversizing the affected components. [11]

Various nondestructive testing methods (NDT) already show their capability in production systems of the aerospace industry where different types of defects in CFRP can be detected depending on their location of occurrence, size and influence on the weight carrying capacity of the component [12]. The estimation of these effects of the described defects that may occur in the RTM process chain is investigated in the Priority Programme 1712 funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) where all types of defects are subdivided into two main groups consisting of in-plane and out-of-plane defects that can be detected with optical measurement systems [13]. Currently in-plane defects such as layer delamination, pleats or misorientations of fibre layers have the highest effects on the load bearing capacity of CFRP components according to Figure 2, which implies the weight of defects that might occur on both visible external and invisible internal structures. Out-of-plane defects are considered pleats or contour deviations of 3D geometries. In-plane defects may appear as missing CFRP-rovings, gaps between filaments or fibre displacements.

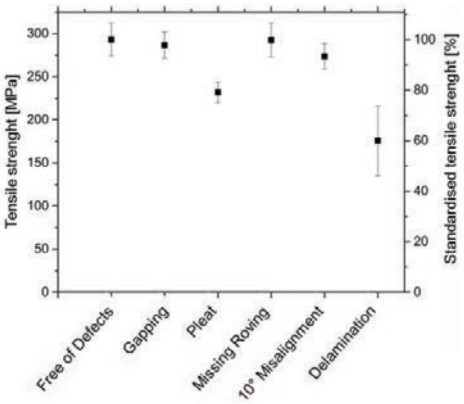

Fig. 2. Effects of Defects in CFRP structures

The applied systems consist of 2D CMOS cameras used for image processing algorithms that are able to determine fibre orientations of visible CFRP layers. Laser triangulation sensors are applied in the digitalisation of 3D shapes in order to detect foresaid defects like pleats. Standard deviations of the 2D system reach 0.1° in the detection of fibre orientations. The optimization of laser triangulation systems for the inspection of CFRP is subject to current research activities that aim for a maintainable compromise between the achievable standard deviation of the measurement system and the complexity of inspected geometries [7] [8]. The main advantage of these optical systems is their in-line applicability on CFRP preforms that have a restricted mechanical stability and therefore are no object of investigation for classical quality control systems such as coordinate measurement systems with tactile probes. Drawbacks of optical systems however are the interferences with foreign matters on the inspected surface and the optical properties of carbon fibres themselves, which are strongly reflecting and thus complicate the setting of the system parameters [14]. Furthermore only exterior defects can be detected as the described optical systems are not able to examine the internal structure of CFRP parts, which however has a significant share in the total load bearing capacity.

NDT techniques that are capable of the characterization of interior structures such as ultrasonic testing either require coupling media or solid interior structures for the conduction of ultrasonic waves, which is the reason why it cannot be reliably used on CFRP preforms [15].

A system that is applied in order to balance this drawback is thermal imaging, which is based on inhomogeneous thermal conductivity between CFRP and internal defects. Especially with regard to the quality control of preforms, this method has a high potential for the integration in the production process because of the process related heat that could be used for thermography purpose instead of additional heating components. The resolution of thermography systems is restricted by both the optical sensor's potential and the Noise Equivalent Temperature Difference, which represents the minimal detectable temperature difference inside the inspected object and varies between 3 and 15 mK, depending of the recorded pixel's size. [16, 17]

Moreover the development of both 2D and 3D imaging computer tomographs (CT) gains more and more importance considering their in-line application in production processes. Measurement times between 5 and 10 minutes allow the industrial application of these systems. Restraining factors are the high volumes of data that represent the scanned specimens and need to be processed automatically under consideration of 100% measurements [11]. Furthermore CT systems are sensitive equipment that are mostly used in measuring rooms that provide robust environmental conditions such as stable temperatures or dynamically decoupled fundaments. Length measurement errors of commercial systems such as the Zeiss Metrotom 800 lie around $MPE_E = (8 + L/100)$ µm. [18]

In summary there are several restrictions that affect the applicability of quality control systems in serial production such as adequate measurement instrument capabilities, robustness against harsh environmental conditions on the shop floor and measurement times that don't exceed station times of the production line. In this context, eddy current testing proved to be a reliable method for the characterization of CFRP parts under consideration of these restrictions and is depicted in the following paragraphs.

2.3. Eddy current testing

The functionality of the measurement method presented here is based on the electrical conductivity of carbon fibres and the associated manifestation of eddy currents within them. These currents are causing a change in impedance between two electric coils that can be stimulated by a high frequency AC voltage to create this effect. Two coils are used as excitation and receiver coils. The underlying principle is shown in figure 2 and was already used in [19] for the validation of material simulation routines. Both coils were positioned at a fixed distance of 1 mm from a CFRP test piece with known layer structure and rotated by 5 degrees at the sample level after every measurement. By entering the measured values into a common coordinate system, a histogram can be created that provides information about the impedance changes depending on the depth and thus about the fibre direction of the CFRP layer structure.

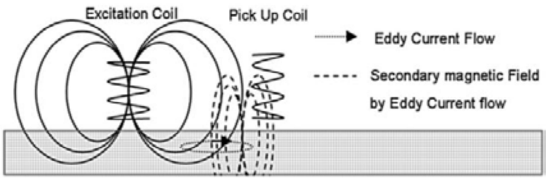

Fig. 3. Eddy current testing principle [12]

It is because of the mechanical rotations of the sensor pair that the method can be transferred to a synchronized series production using suitable kinematics. [12] presents the possibility of determining even the fibre orientation of complex freeform preforms by using industrial robots. First, the geometry is digitalized by using an optical measurement system. In doing so, the travel track for an eddy current sensor moved with the same kinematics is planned. The upstream time-consuming digitalization and the direct dependence of the robot-guided eddy current testing of the optical measurement data are a disadvantage of this method.

3. Scientific Approach

3.1. Concept

The continuous quality control of composite materials offers opportunities to circumvent the disadvantages of the presented eddy current systems: With the preliminary identification of possible critical zones or highly stressed points of the component possible ROIs are defined per se and must be controlled by the quality assurance. As a result, costly kinematics and travel track planning can be avoided if measuring equipment is used that enables an extensive and local examination of this ROI. The wiring of multiple sensor pairs in a defined formation (sensor array) offers the possibility to spatially shift the impedance measurement through selective activation of individual sensor pairs. This provides an alternative to the costly mechanical movement of the sensor over the component for characterizing the layer structure. Due to the comparatively low forces that act on the forming tool originating from the punch in an automated preforming process, this concept also offers the possibility to integrate the sensor array in an opening inside the tool itself as an in-process quality assurance measure and consequently to collect the relevant quality data directly during the process as well as to shorten the measurement time to just a few seconds.
The measurement of the impedance between two coils of which the result depends on the layer structure and frequency (3-32MHz in CFRP preforms [12]) can be controlled and analysed via a user interface on a test bench computer. When determining the measurement strategy, not only the measurement frequency but also the sequence of the controlled sensor pairs is determined. This is made possible by the use of a multiplexer.
Figure 4 shows the general structure of the eddy current testing system.

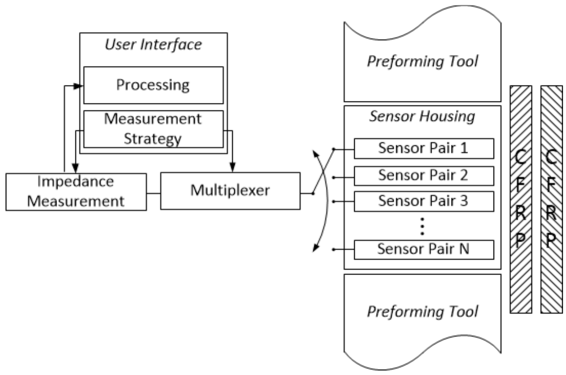

Fig .4. Eddy current sensor array principle

The implementation of the presented concept involves various factors: The determination of a suitable frequency range does not only depend on the utilized coil bodies but also on the state of the material during the preforming. This state can vary due to the application of different binders or temperatures and thus can influence the electrical behaviour of the object of investigation. Interactions between these factors and the maximum number of layers as well as the single layer structures also need to be taken into consideration. The design of the sensor should ensure that the coils are not influencing each other during operation. Here, it can principally be built on the state of the art in eddy current testing since the rigid eddy current arrays have already been tested in the context with other materials [20, 21]. Moreover, the targeted insertion of defects into semi-finished parts offers the possibility to characterize these defects and to use the data on the process side for controlling single preforming process parameters.

3.2. System design

In its prototypical realization the system design according to figure 3 consists of commercially available components. The impedance measurement system is conducted by a Solartron 1260A device, which is capable of automated measurement procedures and can be controlled by MATLAB routines via GPIB-USB connections. The measurement strategy can be characterized by a frequency sweep mode that can be operated within predefined frequency ranges. The order of measurements throughout all sensor pairs and their duration can be saved in a microcontroller, which is controlling the multiplexing unit. The possible arrangements and dimensions of excitation and pick-up coils must be determined in experiments under systematic variation of input parameters: The magnetic permeability of excitation and pick-up coils, the shapes and number of turns of the coils, their distance to the inspected material are expected to have strong interactions considering their influences on the measured impedances. The resolution of the measurement is restricted by the discrete amount of arranged coils and their dimensions. On the other hand the inspected continuously shaped material must be characterized with a high density of data in order to detect defects of critical sizes. Once the possible relative positions of the coils are determined, prototypical sensor arrays can be assembled in a resin casted housing and inserted in adapted preforming tools for the final evaluation about the applicability of this concept in serial production under real environmental influences.

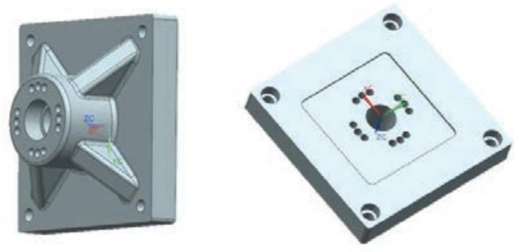

Fig .5. CAD model of an eddy current sensor array housing

Figure 5 shows a possible housing that can be inserted in flat areas of preforming tools: The centre of this housing is characterized by numerous predefined counterbores, which are used to position both excitation and pick-up coils. The closed side of the housing is oriented towards the CFRP in order not to short-circuit the coil arrangement, which is also why the housing should also have electrically insulating properties. Industrially available methods of 3D printing enable the use of plastics with the required electrical properties and simultaneously can be used for more complex housing designs with convex or concave shapes that are used in the preforming process. Holes in the flat corners of the housing allow the attachment to the preforming tool with screws. Caps for the screw heads allow even surfaces that have no negative effects on the preforming quality. The variant of the housing that is depicted in Figure 4 shows a centralized wide bore for a large excitation coil, which is serially connected to each of the eccentrically positioned pick-up coils during the measurement process. Other possible arrangements of coils include their collocation in matrix-like shapes with the disadvantage that there is no central excitation coil and therefore involve an increased effort in the programming of the multiplexing scheme as there are more connecting/disconnecting steps to be done during the measurement.

3.3. Data processing

Due to the high variety of CFRP structures that are characterized by e.g. stack structure, layer types, the measurement routine requires a preceding referencing method that creates a comparable measurement dataset, which contains all characteristic information about the tested material which is free of defects. According to [19], polar histograms that result from the fibre orientation analysis of flat cross-ply laminae with eddy current techniques may have characteristic shapes that indicate the fibre orientations throughout the CFRP stack by accordingly aligned lobes that can be seen in Figure 6.

The use of CFRP shapes for reference purposes can be realized with the use of an industrial CT and the statistical evaluation of fibre orientations throughout the CFRP stack. The tested material can be draped on materials with representative shapes and a low density such as Styrodur. An advantage in the use of this material is its machinability which allows the creation of reference shapes that may represent the preform and therefore allow the calibration of sensors with shapes other than simply flat sensor arrays.

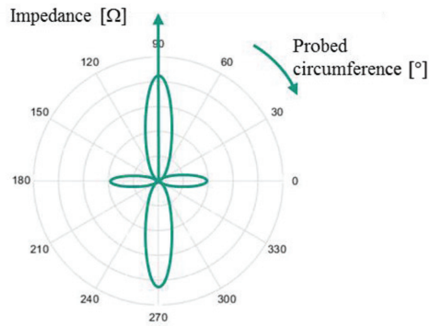

Fig. 6. Schematic reference measurement [19]

After the comparison of the reference CT scan and the measurement that is conducted with the eddy current sensor, a serial application of this measurement system requires the definition of specification limits that allow the definition of tolerances in production and their surveillance. The definition of specification limits can be conducted according to the state of the art in statistical process control and varies due to the expectancy value (target fibre orientation), the standard deviation of the process and the number of measurements. The visualised polar histogram with according specification limits is depicted in Figure 7.

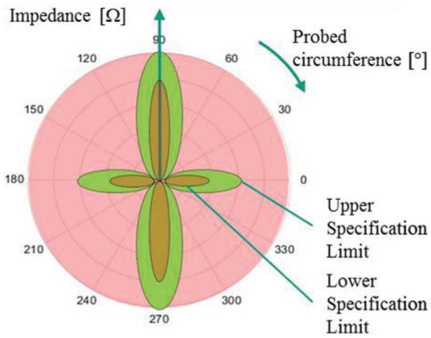

Fig. 7. Definition of specification limits based on reference measurement

After the determination of specification limits the process integrated measurement can be conducted under consideration of inevitable process variations in serial production. The signal sequence can be evaluated by means of statistical significance that leads to a comparison between the specification limits and the actual signal that may be used in an automated production system for the detection of interior defects in CFRP structures that is exemplary illustrated in Figure 8.

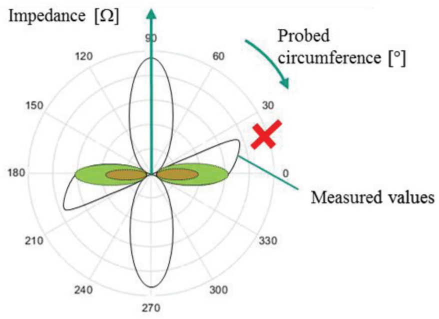

Fig. 8. Quality information about the inspected area

4. Conclusion

CFRP materials gain more and more importance in automotive serial production of lightweight structures. In order to fulfil the quality requirements in the application of this immature production technology it is necessary to develop quality assurance systems that are capable of being integrated into production processes under consideration of restrictions resulting from automatization, short measurement times, required space and handling steps. Most nondestructive testing methods only partially respect these restrictions and therefore show drawbacks that may be compensated with the adjusted eddy current testing method that was presented in this publication.

The introduced concept includes both the required hardware components and the necessary data processing steps for a robust application in serial production. Future work will focus on the systematic experimental estimation of the influences and interactions of system parameters on the measured impedances. Hereupon the assembly of the eddy current sensor array will be performed with characteristic preform shapes.

Acknowledgements

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