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MANUFACTURING AND QUALITY ASSURANCE OF LIGHTWEIGHT PARTS IN MASS PRODUCTION

Production-related preliminary damage and residual stresses have significant effects on the functions and the damage development in fiber composite components. For this reason, it is important, especially for the safety-relevant components, to check each item. This task becomes a challenge in the context of serial production, with its growing importance in the field of lightweight components. The demand for continuous-reinforced thermoplastic composites increases in various industrial areas. According to this, an innovative Continuous Orbital Winding (COW) process was carried out within the framework of the Federal Cluster of Excellence EXC 1075 “MERGE Technologies for Multifunctional Lightweight Structures”. COW is aiming for mass-production-suited processing of special semi-finished fiber reinforced thermoplastic materials. This resource-efficient and function-integrated manufacturing process contains a combination of thermoplastic tape-winding with automated thermoplastic tape-laying technology. The process has a modular concept, which allows implementing other special applications and technologies, e.g. integration of different sensor types and high-speed automated quality inspection. The results show how to control quality and improve the stability of the COW process for large-scale production. This was realized by developing concepts of a fully integrated quality-testing unit for automatic damage assessment of composite structures. For this purpose, the components produced in the COW method have been examined for imperfections. This was performed based on obtained results of non-destructive or destructive materials testing.

1. INTRODUCTION

In the area of mobility, the increasing shortage of natural resources and the accompanying increase in fuel costs as well as environmental constraints leads more and more to efficiency-enhancing activities. These include the development of sustainable production processes and the provision of lightweight components with high performance and functional density. Correspondingly, new lightweight design materials and structures have increasingly made their way into the aerospace and automotive sector in recent years. In particular, this relatively young group of fiber-reinforced composites (FRC) offers

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significant advantages due to high strength and stiffness, design features and properties as well as the ability for mass production. For example, the gain architecture can be adapted to complex and superposed stress conditions depending on the load, which leads to a high potential of lightweight design. Furthermore, in such structures, sensors and other similar objects can be integrated directly during their production.

The manufacturing processes for fiber composite components are increasingly being automated in order to improve efficiency and to ensure a constant quality of the products in high-volume production. These goals can be achieved by the use of thermoplastic fiber composites, because they allow short processing times (cf. [1]). For the automated production of fiber reinforced structures with thermoplastic matrix, processes such as winding, tape placement or continuous orbital winding (COW) are used. However, even these highly automated methods will not avoid the manufacturing-induced defects. These types of defects are often difficult to detect because they do not always have a clear impact on the studied structure. Moreover, not all production-related defects lead inevitably to restrict the functionality or failure. Generally, the defects cause a weakening of the material and can, at a defined size in combination with an unfavorable load, become the source of different fiber composite typical failure modes. Therefore, an inspection of composite structures is necessary, especially for safety-relevant components. Hence non-destructive testing methods (NDT) can be used to locate the critical defects in the fabricated structure and allow their evaluation.

The aim of this paper is the determination of requirements for a quality control system for thermoplastic fiber composite components, which are manufactured in the COW-process. For this purpose, the manufactured structures were examined with non-destructive and destructive testing methods, in order to locate, identify and evaluate the production-related defects. Based on the results appropriate NDT procedures for online monitoring were discussed. In conclusion, concepts for a quality module of the continuous orbital winding system with the focus on maintaining a high-production suitability were developed and evaluated.

2. DEFECTS IN FIBER-REINFORCED COMPOSITE COMPONENTS

In general, FRC structures contain hidden defects that are characteristic for the chosen manufacturing process (cf. [2–6]). Nevertheless, the manufacturing-induced defects do not necessarily lead to failure of the fabricated structure (DIN 55350). The pattern of damage in multilayer composite structures depends primarily on different forms of load (cf. [7]). Stiffness and strength properties of the composite components, the laminate lay-up and production-related pre-damage as well as internal stress states conditions of the workpiece also have an affect on the damage development. In most cases, the originating of different types of fiber composite failure modes is in the hidden material defects. These grow under load and influence each other until the structure fails. Figure 1 includes a schematic representation of the typical fiber reinforced composite manufacturing-induced defects and failure modes. The inhomogeneous structure of fibre-reinforced plastic (FRP) leads to the basic failure modes: fibre fracture (FF) and inter-fibre fracture (IFF).

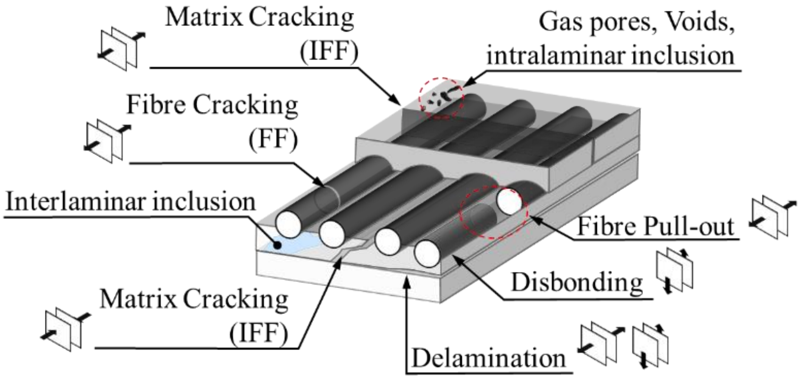

Fig. 1. Production-related defects and failure modes of FRP, based on [2, 3]

Characteristic for the reinforcing component is the fibre fracture (FF), which occurs on exceeding the maximum load. The fibers break under tensile load or buckle in the micro range under pressure load. The failure of the matrix (IFF) leads to brittle fracture in the matrix material or along the fiber/matrix interface. The IFF cracks in the matrix may tend to initiate failure (FF) of fibre filaments in adjacent lamina and possibly initiate delamination (cf. [2]). This delamination can grow and separate the region between two adjacent ply matrix cracks as illustrated in Fig. 1. This kind of interlaminar IFF cracks can also be formed by low-velocity impact.

3. MANUFACTURING PROCESS: INNOVATIVE CONTINUOUS ORBITAL WINDING (COW)

The innovative Continuous Orbital Winding (COW) allows a continuous and large-scale production of closed structural components made of long fiber reinforced thermoplastics. The highly efficient and automated production technology has been designed, developed and implemented in the form of a pilot plant within the framework of the federal excellence cluster MERGE Exc1075 in subarea A2. The method allows producing structural components with concave and convex surfaces, in which segment with different cross-section and different lay-up can be designed. COW is a result of merging thermoplastic tape placement and inverted winding process. These technologies are briefly explained below.

The thermoplastic Winding [8, 9] closed rotationally symmetric shaped parts are produced with continuous fiber reinforcement. This is a limited continuous and mostly automated process, in which a multi-layered arrangement of high-strength filaments takes place in the direction of stress. This allows manufacturing load-oriented composite structures construction with a high degree of lightweight, high specific structural strength and stiffness (cf. [10]). In the thermoplastic winding process, a fiber-reinforced thermoplastic tape is placed on a rotating core (cf. Fig. 2a). Consequently, the winding core defines the component geometry, whereby a distinction is made between a reusable or lost core (liner). The position of the tape guide elements (yarn eye) and the rotation speed of the winding core are coordinated with one another and changed in a timed, whereby a characteristic winding pattern is created (cf. Fig. 2b).

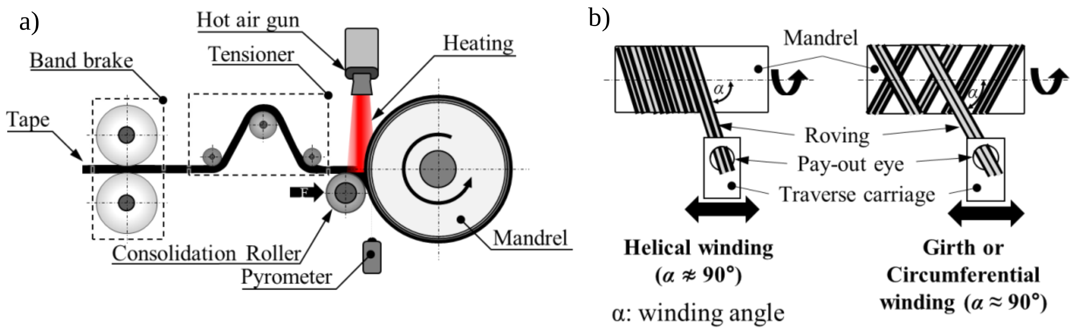

Fig. 2. Schematic diagram of a winding system (a) and the a characteristic winding pattern (b) based on [1, 8]

The tape is heated directly before the depositing point and the matrix material selectively melted (cf. [11, 13]). As a result, similarly as in case of welding process, the liquid thermoplastic matrix of the tape connects to the matrix material of the underlying tape layer. The consolidation and compaction is usually done via the retraction force associated with the thread tension. Additionally a consolidation roller can be used to improve the properties of a product.

The thermoplastic tape placement is an automated process, which allows the precisely positioned layers of plastic tapes on curved or flat structures. Generally, continuous unidirectional fiber reinforced thermoplastic tapes are also used here. For placement of the thermoplastic tape, a special placement head is used, which includes among others a consolidation roller, material storage as well as extraction, cutting and heating devices (cf. Fig. 3). On the way to the consolidation roller, the tape is heated up to polymer melt temperature with a heating device before reaching the deposition point. Then the tape is placed on the mould surface or on a previously placed tape layer and pressed with a consolidation roller. The roller compress the entrapped air voids in the low-viscosity tape material and assists in flattening of tape surface irregularities.

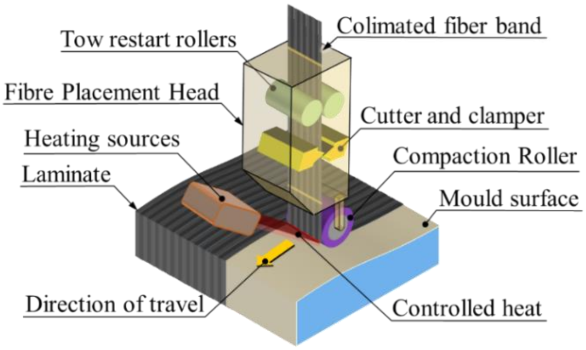

Fig. 3. Thermoplastic tape placement, components of a placement head, [1, 11, 12]

The transport of the tape can be made via motorized feed rollers or by the relative movement of the pressing unit. Contrary to the winding technique is here the application of the tape discontinuously. Thereby a variable lay-up configurations and local reinforcements are possible.

Similar to the tape laying process, placement heads are also used in the COW process (cf. Fig. 3 and 4). They are used in the so-called winding units (cf. Abb. 4a). Usually a several of this units are used in the manufacturing process, because each of the units contains a placement head (cf. Abb. 4b). The head is mounted on a rotating disk and surrounds the core structure, applying the tape (online consolidation).

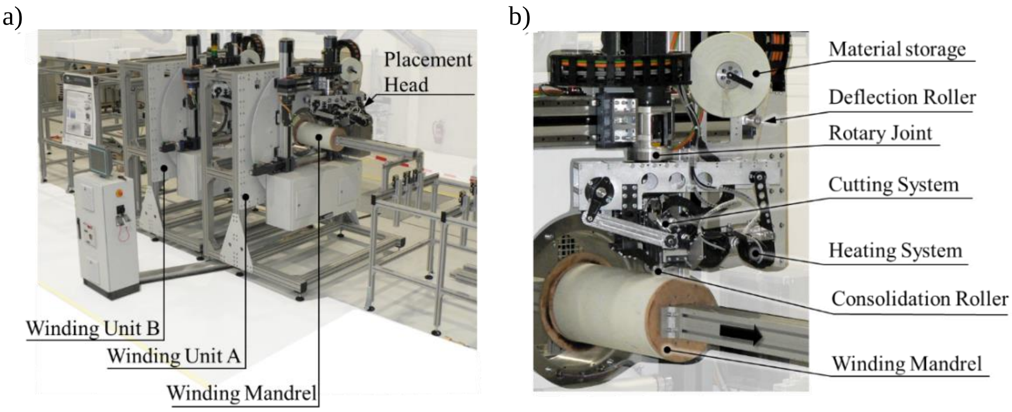

Fig. 4. Orbital winding units (a) and orbital placement head (b)

Figure 5a shows the mechanism for moving the placement head and the movement of the placement head along a cross-sectional profile (Fig. 5b).

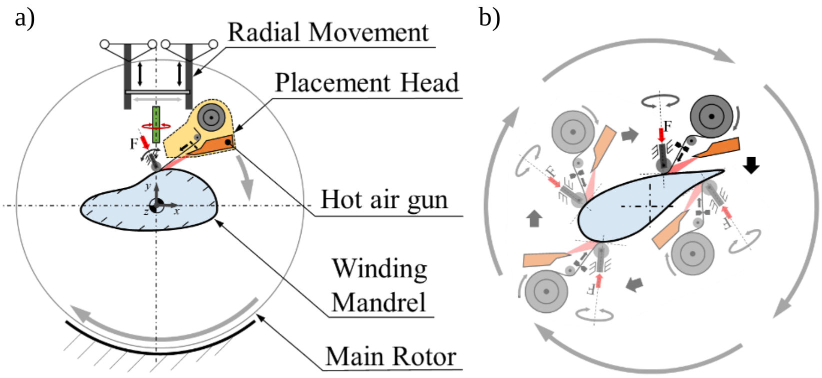

Fig. 5. Mechanism for moving the placement head (a) and movement of the placement head along a cross section profile (b), [12, 13]

The winding mandrel moves through the winding units at a constant speed. In this way, an endless structural component is manufactured along the mandrel path, which has a variable lay-up realized by the individual winding units (cf. Fig. 4 and 5). The continuous production facilitates the synchronization of different parts of the entire process chain. Additional elements, such as sensors or actuators can be introduced into the composite structure direct in the manufacturing process, as shown in [12, 13]. After the core structure has passed all the winding units, the produced structure is stored and the manufacturing process ends. The result, a near-net shape semi-finished product or a closed structural component, that can be directly further processed. Some key features of the continuous orbital winding process are summarized in Table 1 and compared with the thermoplastic winding and the tape placement.

Table 1. Properties of selected manufacturing processes for fiber-reinforced thermoplastics components

	Winding technology [11, 13, 14]	Continuous Orbital Winding	Thermoplastic Tape Placement [11, 13, 15]
PROCESS	Continuously for part of finite length	Continuously for continuous production	Discontinuous
COMPONENTS	Most rotationally symmetrical or curved structures with convex and closed surface	Complex rotation-asymmetrical structural components; convex and concave surfaces	Any
CONSOLIDATION	About tension	Pressure unit (thrust)	
PLACEMENT PATH	Geodetic	Any (angle and tape length)	
FIBRE ORIENTATION	10° to 88° without tools (depending on the bandwidth)	0 ° to +/-90° without tools (depending on the bandwidth)	Any
FIBER POSITIONING	Layers		Any (local get lost)
PRINCIPLE OF MOVEMENT	Rotation of the winding core	Rotation of the placement head	Motorized rollers or relative movement of the clamping unit
AXES OF MOTION	y-z, x, y, z red. Translat.	y-z, x, y, z red. Translat.	x, y, z
PROCESSING	UD-reinforced tapes (tapes), but also mat or cloth tapes		
TAPE WIDTH	up to 30 mm	up to 40 mm	
WIDTH OF PLACEMENT MATERIAL	Constant (invariable)	Constant per unit of winding (invariable)	Depends on placement head
PROCESS SPEED	up to 670 mm/s	up to 400 mm/s per winding unit (several sites at the same time)	Up to approx. 1000 mm/s per placement head
TAPE POSITIONING	Layers		Any
FEATURES	▪ High accuracy and good reproducibility		
	▪ Largely automated	▪ Full automation ▪ Near NET-shape component production with minimal waste	
	▪ Economical		▪ Complex geometries

4. NDT for QUALITY

The COW provides a high accuracy and good reproducibility. However, similar to other established manufacturing process, defects cannot be avoided. Therefore, a quality control of produced components should also be done here. For this, especially imaging non-destructive testing (NDT) are considered for the investigation of composite structures. They map directly the position and geometry of the defects, which is essential for their evaluation. In addition, a link with the industrial image processing allows to automate the inspection process in a high degree. Efficient image processing algorithms in combination with powerful computing devices also provide to a high speed and accuracy in detecting defects. Fig. 6 shows a schematic overview of the different imaging NDT techniques and their detection capability depending on the size and location of the defects. Often the manufacturing-induced defects are difficult to detect and their effect on the structure is hard to prove. The size, position and type of defects, are here crucial. Therefore, the quality control should be carried out by NDT procedures, which are matched to the process-specific defects.

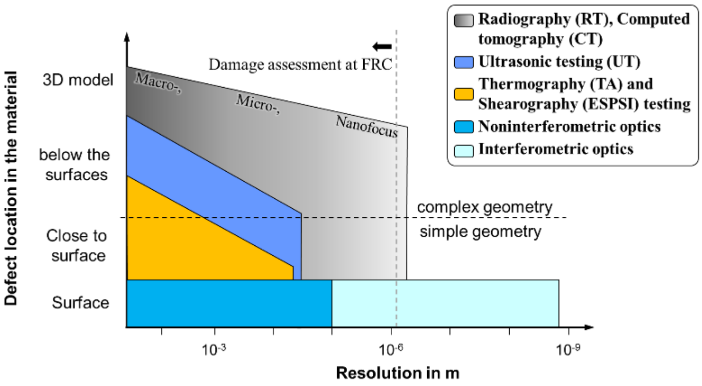

Fig. 6. Schematic compilation of imaging NDT depending on the fault location and resolution, based on [15]

4.1. REQUIREMENTS FOR THE NDT

The manufacturing process and its products were analyzed to define the manufacturing conditions and the quality of the manufactured item. For the preliminary investigations, simple composite structures were produced in the Continuous Orbital Winding (see Fig. 5) process by used Polytron® tapes (PP-GF60).

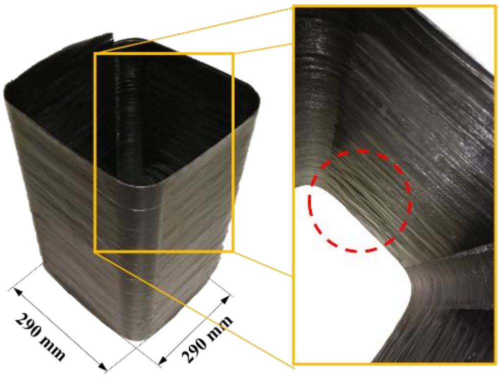

Fig. 7. Composite structure with defects (delamination) produced in the COW process

4.1.1. PRODUCTION CONDITIONS

The processing temperature in the COW process was investigated by the infrared camera FLIR T430 as well as sensors integrated in the hot air gun and the winding structure. The tape was heated up to polymer melt temperature (160-170°C) using a hot air heating. The aim was to monitor the temperature in the placement location (see Fig. 8a). The temperature profile, captured online by the sensor integrated in the winding structure during the winding process of the first layer, shows a maximum temperature of 210°C (see Fig. 8b, 8c).

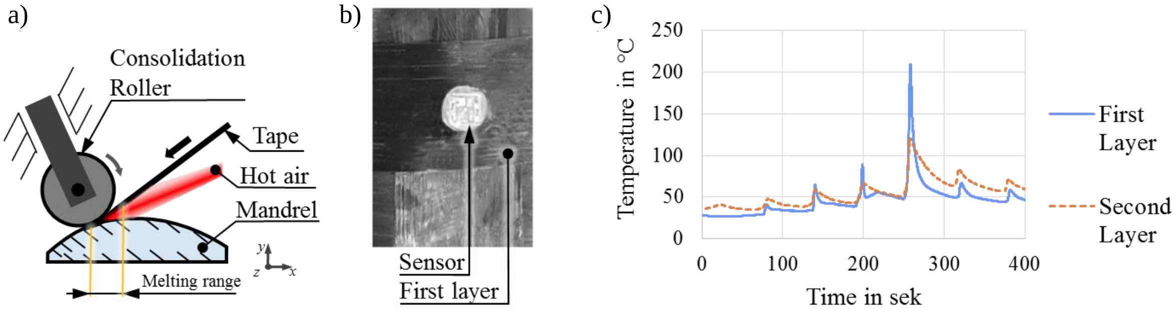

Fig. 8. The placement location (a) and the integrated temperature sensor (b) with the temperature profile for two layers (c)

The IR camera captured a maximum temperature of 150°C near the processing field (see Fig. 9b, 9c, 9e). The camera register with an accuracy of ±2 °C.

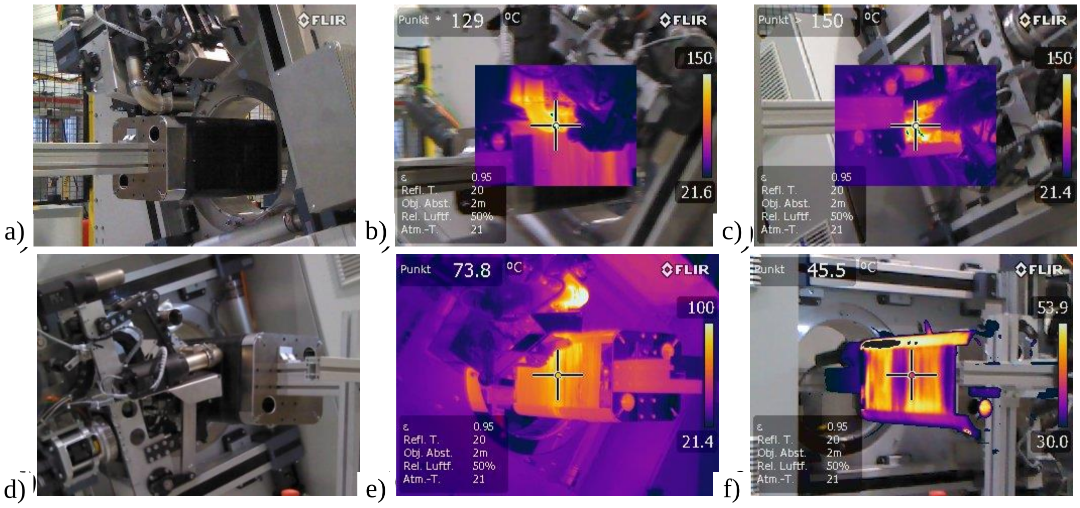

Fig. 9. Continuous Orbital Winding (a, d) and the processing temperature (thermal images: b, c, e, f)

The temperature in the molten area could not be measured, because of the placement head position. So the thermal imaging camera was used to search for areas where the online consolidation was made incorrectly (cf. Fig. 9e, 9f). However, only about 40% of the identified defects was correct. Further validation of localized defects was performed using an ultrasound examination (cf. Fig. 10).

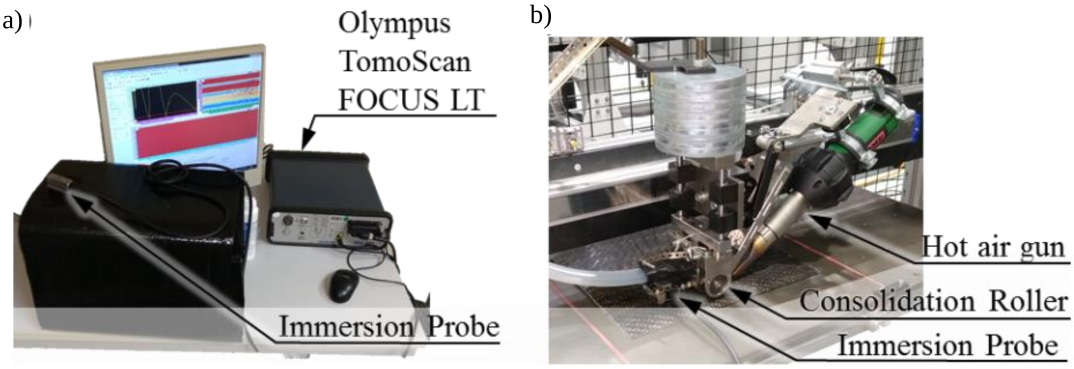

Fig. 10. Ultrasonic testing by phased array technique (a) as well as an experimental device set-up with a simplified tape placement head and immersion probe (b)

For this purpose a phased array technique device (TomoScan FOCUS LT) with a 10 MHz immersion probe (10L64-I1) was used. Additionally, an experimental device was built to verify the possibilities of ultrasound online monitoring in the processing of thermoplastic tapes (cf. Fig. 10b).

4.1.2. THE MANUFACTURING-INDUCED DEFECTS

In most cases, it was possible to detect both gas pores and not fully welded areas in the fabricated structures. The formation of gas pores in the matrix component cannot always be avoided in the proceedings of the COW. This type of defects occurs during the consolidation process. At high speed, during the pressing process, air can be introduced under the placed tape with molten matrix, which then forms voids in the solidified thermoplastic. Fig. 11 illustrates micrograph of a cross section of the manufactured structure with delaminated areas and air voids.

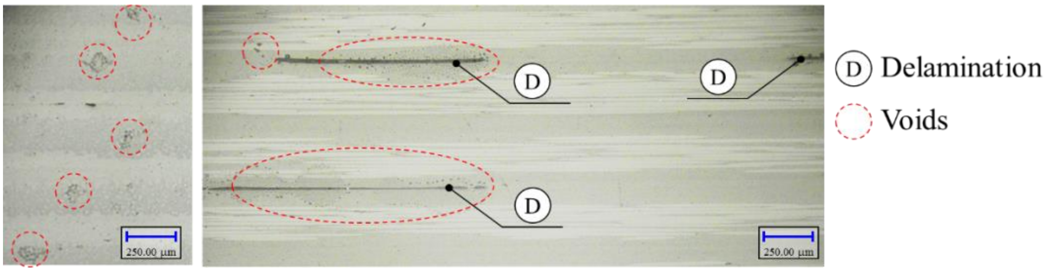

Fig. 11. Microsection of composite structure with delaminated areas and air voids

The faulty consolidation was the result of wrong-defined process parameters like temperature, speed and pressure force of the consolidation roller. The used hot-air heating system could not always ensure the constant melt of the thermoplastic matrix. This problem can be usually found in the case of first layers placement, because there is a large influence of the mandrel on the heat distribution (cf. [16, 17]). The resulting defects are to be regarded as delaminations, which are a special form of inter-fibre fracture (cf. Fig. 5b). The fracture occurs in the interface between two adjoining tape layers (adhesion failure). In most cases, the growth of delaminations under load is done abruptly, because crack-stopping mechanisms are missing. This leads to the separation of the region between two adjacent tape layers and in the extreme case, it comes even to separation of the entire outer layer. The interlaminar cracking minimizes bending and torsional stiffness and can lead to buckling of the composite structure under pressure load in the laminate plane. An overview of the production-related defects and the resulting effects on the fiber composite components is given in Table 2.

Table 2. Away error in the COW method and its effects

Production-related defects	Frequency	Impact
Air voids	+++	Reduction in compressive strength (||) and the interlaminar shear strength with a volume fraction of pores by more than 10%
Damaged filaments	+	Reduces the tensile strength (||) and the compressive strength (||)
Delamination	++	Reduction of the interlaminar shear strength of 50%
Delamination due to impact	+	Can a reduction in over 50% of the compressive strength (||) lead
Thermal residual stresses	+	Predominant degradation of interlaminar shear strength
+: single defects sporadically available, ++: frequently present, +++: many available, || : Stress in the fiber direction		

5. SYSTEM OF QUALITY CONTROL

5.1. SELECTION OF NON-DESTRUCTIVE TESTING METHOD

The design of a quality assurance system focuses on the production conditions of the monitored process and their influences. In this case, differences in material and process parameters are investigated primarily. In the COW-process the structures are made by using fiber reinforced thermoplastics. Therefore, a non-destructive testing method should be selected that allows to detect the typical process-specific as well as FRC defects and directly reflects their position and geometry. The procedure should also provide a test speed up to 400 [mm / s], so as not to limit the speed of the process. Moreover, the objects to be investigated can have concave and convex surfaces and varying cross-sections. The wall thickness is almost constant. The processing temperature can reach locally up to 240°C and the melting temperature of the winding areas is up to 170°C by processing of PP-GF60. In addition, the test method should be economically viable even for small series. Accordingly, the following NDT methods could be used for the quality control of the structures produced in the COW process: radiography (RT), computed tomography (CT), ultrasound (UT), thermography (TA), Shearography (ESPSI) and Visual inspection (VT). A comparison of these imaging techniques includes the Table 3.

Table 3 shows that although shearography offers good detection capability, it can only be used to a very limited extent under the prevailing process conditions. However, during the production process, the load condition changes on each lap of tape placement head around the core structure. In addition, the vibrations of the COW units significantly affect the shearography measurement. Thus, the defects are represented in the online tests as noise, which prevents a reliable assessment (see [18]).

Table 3. Characteristics of selected Imaging NDT techniques

Features		NDT					
		RT	CT	UT	TA	ESPSI	VT
Detection ability	FB	+	+	+	+	++	-
	Zfb	-	+	+	++	++	+
	Delamination	+	+++	+++	++	++	+
	Pores	+	+++	+	+	++	-
	Inclusions, such as such as protector, etc.	+	+++	+++	+	++	-
Suitable for online process monitoring		++	+	+++	++	-	+++
Test speed		++	++	+++	++	++	+++
Procurement and operating costs		+++	+	++	++	++	+++
+++: very good, ++: good, +: restricted: not measurable							
RT: Radiographic testing; UT: ultrasonic testing; ESPSI: Shearography CT: X-ray computed tomography; TA: Activ thermography; VT: Visual testing							

Similar restrictions apply for computed tomography and, on a smaller scale, to X-ray inspection. In this case, vibration of the examined object, although allow the imaging of the defects, but with a limited resolution (unsharp). In addition, the CT is associated with significant procurement and operating costs, because in addition to the tomograph an adequate protection against radiation should be considered.

The analysis of the test procedure showed that the ultrasonic (UT), thermography (TA) and Visual inspection (VT) are suitable for online monitoring of continuous orbital winding. However, visual inspection can not detect the defects in the structure. In consequence, the concepts are worked primarily for the UT and TA tests.

5.2. CONCEPTS

In order to ensure the quality of the structures produced and to minimize losses in production, the idea of online monitoring should be followed. For this purpose, two concepts of the quality assurance system were developed.

The *concept I* provides for the use of an ultrasonic testing with phased array technology. This should be the inspection operation in an additional winding unit, where an ultrasound testing system with water supply device is mounted next to the tape placement head (cf. Fig. 12). For the examination is the Olympus RollerFORM probe (see [19]) provided. The coupling medium is sprayed through a nozzle in the form of a thin layer of water before the test probe. The tape placement head should be here limited to the consolidation module. In combination with the separate control of the test module the hot air heating and the consolidation roller can be used for correction (heat and pressure) of localized defects, such as delaminations.

The position and number of the ultrasonic test modules can be defined as in the manufacturing process. Accordingly, the test time – after each tape layer or at the end of the process – can be arbitrarily designed. In addition, a feedback loop of the unit to the line control can be used for an online optimization of process parameters.

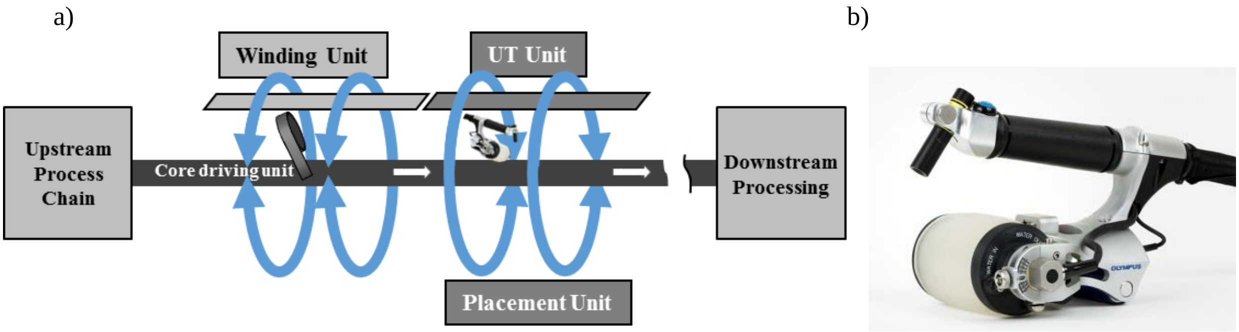

Fig. 12. Concept I (a) and the special test probe Olympus RollerFORM (b), [19]

The *concept II* is based on a thermography test. For image acquisition, a thermal imaging camera is used with a refresh rate of up to 500 Hz (depending on the process speed). Similar to the *concept I*, the test procedure is carried out in a separate unit, in which instead of the tape placement head an IR camera is mounted (cf. Fig. 13).

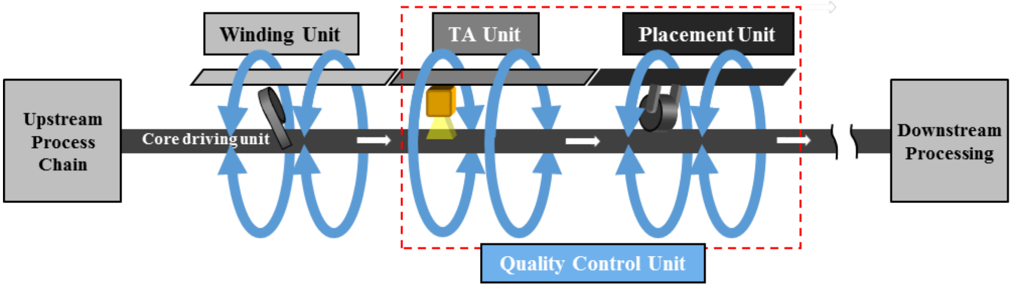

Fig. 13. Concept II

The test should be done immediately after the tape has been placed in the previous winding unit. In this way, the consolidation process can be directly tested and the introduced heat can be used to detect defects. However, an examination on several tape layers requires an additional heat source and will require more time. A subsequent placement unit limited to the consolidation module can be used for a correction of localized defects, such as delaminations. A feedback loop from the TA unit to the system controller can be used to optimize the process parameters, like temperature.

Both concepts were rated based on a decision matrix, which is shown in Fig. 14. During the evaluation, the essential criteria for the COW procedure were defined and their mutual relation determined. In this way, the most important criteria were identified, such as cost (K6) and delamination detection (K3). Due to the decision matrix, the weighting of the decisive criteria was taken into account accordingly, which indicated the advantage of the first concept.

Features	╳	**K1**	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	Q_i	**Concept**		
										I	II	I_i
Detection of pores	K1	╳	0.5	0	0	0.5	0.5	0	1	1	2	3
Detection of Inclusion like protective layer residues etc.	K2	0.5	╳	0	0.5	0	0.5	0	1	3	2	3
Detection of delaminations	K3	1	1	╳	0.5	0.5	0.5	1	3	3	2	3
Detection of impact damage	K4	1	0.5	0.5	╳	1	0.5	0	3	3	3	3
Different laminate structure or wall thickness and notches	K5	0.5	1	0.5	0	╳	0.5	0	2	3	1	3
Speed	K6	0.5	0.5	0.5	0.5	0.5	╳	0	2.5	3	3	3
Cost	K7	1	1	1	1	1	1	╳	6	2	3	3
									Z	47.5	46.5	55.5
									d [%]	85.59	83.78	100.00

Evaluation of the mutual relation of the criteria:
0: no relation *0.5: one-sided relation/dependency*
1: bilateral relation
Rating: *1: limited* *2: good* *3: very good*
Calculation: $Q_i = \sum K_i$ $Z = \sum_{i=1}^{7} K_i \cdot B_i$ $d = \frac{Z}{3\cdot\sum_{i=1}^{7} Q_i}$

Fig. 14. Decision matrix for concept evaluation

6. CONCLUSION

The Continuous Orbital Winding (COW) process closes the gap between established production methods, such as the thermoplastic filament winding or tape placement. This has been confirmed by summarizing the basic features of these production processes and comparing them with the characteristics of the COW process. In particular, offers the COW process a high degree of automation and allows the production of complex, rotationally asymmetric structural components with concave surfaces as well as a continuous production, which facilitates synchronization of different parts of the entire technological chain. This also allows integrating the automated quality control into the production process. Accordingly, the test procedure for an on-line monitoring, adapted to the production process and the manufactured structures, was discussed. Various imaging NDT methods such as tomography (CT), ultrasound (UT), thermography (TA) and shearography (ESPSI) are very useful for the localization of manufacturing-induced defects. Generally, the ultrasound and thermography testing showed the best efficiency for an on-line monitoring of continuous orbital winding. The identified defects have been evaluated with regard to the error frequency and the influence on the residual behavior of the component. It has been shown that delamination occurs most often in the first layers of structures produced by the COW method. In order to reduce the number and size of defects two concepts for process-integrated quality control modules were presented and evaluated with regard to the criteria, which are important for the manufacturing process. The studies have shown that the best results have been achieved by the concept of online monitoring using ultrasound method with phased array technology.

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