INNOVATIVE AND EFFICIENT MANUFACTURING TECHNOLOGIES FOR HIGHLY ADVANCED COMPOSITE PRESSURE VESSELS

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ABSTRACT

The currently ongoing development project at MT Aerospace (MTA) deals with a cost efficient manufacturing process for space structures. Thermoplastic fibre placement, which was identified as one of the most forward-looking technologies, promises advantages such as shorter cycle times and a high level of automation. In addition to the manufacturing method, research activities on non-destructive inspection methods and on acoustic emission analysis are performed. The analysis of the components will also be improved using advanced modelling approaches. The capability of the processes and methods will be shown on the basis of a scaled solid rocket motor casing.

1. INTRODUCTION

Due to the demand for lower weight and lower cost for future space structures, MTA is developing a forward-looking manufacturing process for a new generation of composite pressure vessels. To improve the technology a co-operation with several research institutes was established, with MTA as the leading company. Within this co-operation, MTA is responsible for the engineering activities and works closely together with the research institutes. The Institute for Carbon Composites (LCC) is primarily responsible for the manufacturing technology, while the German Aerospace Center (DLR-ZLP) is improving the non-destructive inspection (NDI) method. The Institute of Physics (AMU) is performing the material characterisation and acoustic emission (AE) analysis.

To demonstrate the application of the processes and methods for pressure vessels, two technology demonstrators, based on a strap-on booster design, will be manufactured, inspected using ultrasonic testing and tested in a burst pressure test, which will be accompanied by acoustic emission analysis.

2. DESIGN AND ANALYSIS

2.1 Design

The two demonstrators which will be built in the framework of the programme have a diameter of 1.3 metres in the cylindrical area. The pole opening in the dome measures 0.35 m in diameter. Each demonstrator has only one dome and an integrated skirt. For the burst test the demonstrators will be connected to each other using an aluminium ring and a bolted joint. The laminate of the demonstrators consists of the cross layers which carry the axial loads and the hoop layers which carry the circumferential loads. For both the segment joints at the end of the cylinder and the skirts, reinforcements are required. Therefore additional plies will be applied in a defined stacking of 0°, ±45° and 90° layers. The skirt includes the hoop-layers of the pressure vessel. The gusset between the dome and the skirt will be filled with an elastomer during the manufacturing process.

Figure 1 shows the demonstrator assembly for the burst test. The pole opening of the short demonstrator on the bottom will be closed with a blind cover, while the long demonstrator on the top will be closed with a cover which includes the pressure ports. Steel bolts will connect the aluminium ring to the demonstrators. The skirt of the short demonstrator is dimensioned to support the whole assembly.

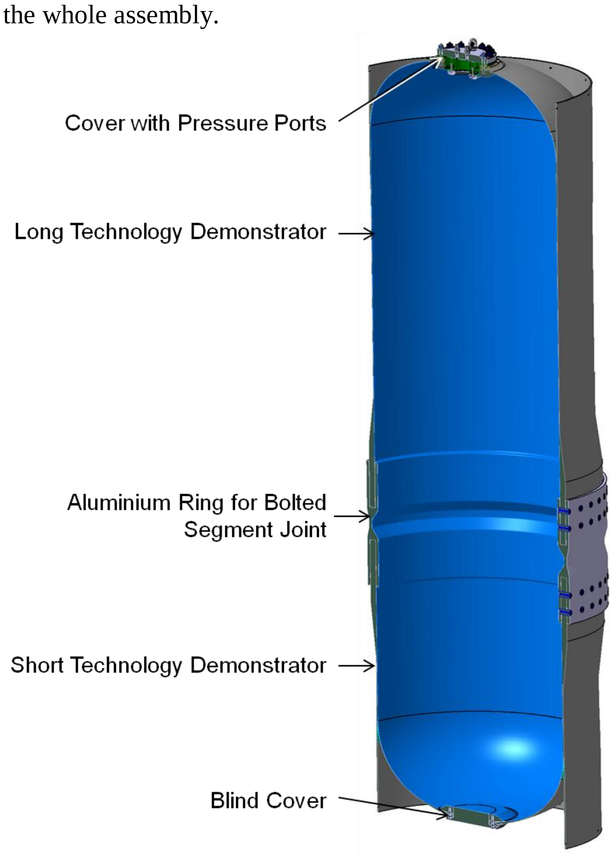

Figure 1: Demonstrator Assembly for Burst Test

2.2 Material Characterisation and Breadboard Testing

For the verification of the pressure vessel design the material used must be characterised. Therefore, an extensive material characterisation programme was performed measuring tension, compression and shear properties. Additionally inter-laminar properties such as the apparent inter-laminar shear strength and the strain energy release rates under mode I and mode II conditions were determined. Accompanying thermal, chemical and physical properties were evaluated.
The material characterisation was carried out in close collaboration with the manufacturing process development. In an iterative procedure coupons have been manufactured with varying process parameters. These have been tested for critical material properties and their results have been correlated to the process parameters. With the best process parameters most of the material properties could be increased as shown in Figure 2. Especially the tensile strength parallel to fibre was enhanced by about 40 %. Beyond this increase, the standard deviation of the values has been decreased significantly, which is another indicator of an improved laminate quality.

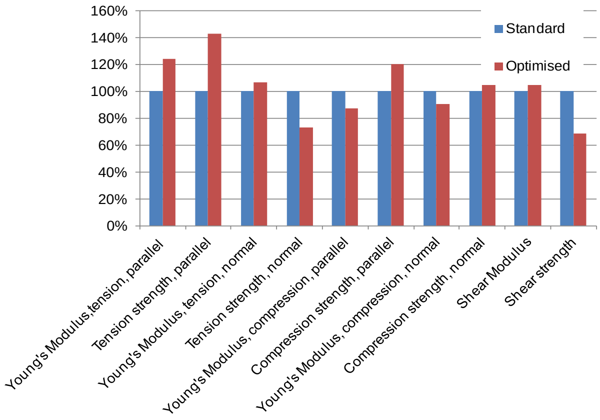

Figure 2: Comparison of Material Properties

Besides the material characterisation on a coupon level, breadboards like bearing test specimens were manufactured and tested. The bearing test campaign uses laminates with three different thicknesses. The test results demonstrated that there is no significant influence of the specimen thickness on the bearing strength of the laminate.
To investigate the bonding between the thermoplastic matrix material and elastomers, single lap shear specimen were fabricated and tested. The test methodology follows testing of two CFRP face sheets with the elastomeric layer instead of an adhesive between them. The bonding between the elastomer and the thermoplastic polymer was set up during the fibre placement process. The failure occurred inside the elastomer, which indicates suitable compatibility and joining on the coupon level without the requirement of additional adhesives.

2.3 Analysis

The material properties which were determined after the process optimisation were used for both the preliminary dimensioning and the finite element analysis (FEA). The preliminary design of the composite demonstrators was established according to the net-theory using analytical tools, while the detailed analysis was performed using the software Abaqus. In contrast to common low fidelity modelling approaches, each composite layer of cross- and hoop layers and skirt lay-up is discretised with at least one individual element row, i.e. local effects at the end of skirt reinforcement layers can be investigated. The distribution of winding angles and layer thicknesses along the meridian is consequently considered according Clairaut´s equation. With this approach the interaction between the pressure vessel and the skirt is reproduced accurately and a high resolution of ply stress results is achieved.
With the analysis it was shown that the failure under pressurisation can occur in different areas at the same pressure level. Thus the design is well-balanced.
Additionally to the first ply failure analysis, a last ply failure analysis was performed in collaboration with LCC. The FE model uses continuum shell elements for each layer of the pressure vessel. Between the single layers, cohesive elements are added, which allow the consideration of delaminations. Thus the influence of the crack propagation during the pressurisation of the vessel on the global load capacity can be considered. The use of the described model allows a realistic burst pressure prediction. Furthermore the full lightweight potential of the composite material can be tapped.

3. MANUFACTURING

3.1 Manufacturing Process and Equipment

Thermoplastic fibre placement is based on the principle of plastic welding of pre-impregnated thermoplastic carbon fibre reinforced tapes.
During the process a 4 kW diode laser serves as a heat source. Simultaneously substrate and incoming unidirectional reinforced tape are heated up to the melting point of the thermoplastic matrix and consolidated under pressure, which is induced by a cooled, flexible plastic roller. Ovens, specifically autoclaves for laminate curing, are unnecessary.
Laser optics, a consolidation roller, a material coil, a tape cutting unit and a thermo camera are attached to the placement head produced and customised by AFPT GmbH. The placement head allows processing tape widths of one and two inches. Each tape width requires an individual laser optics system. The process used at LCC’s manufacturing facility is shown schematically in Figure 3.

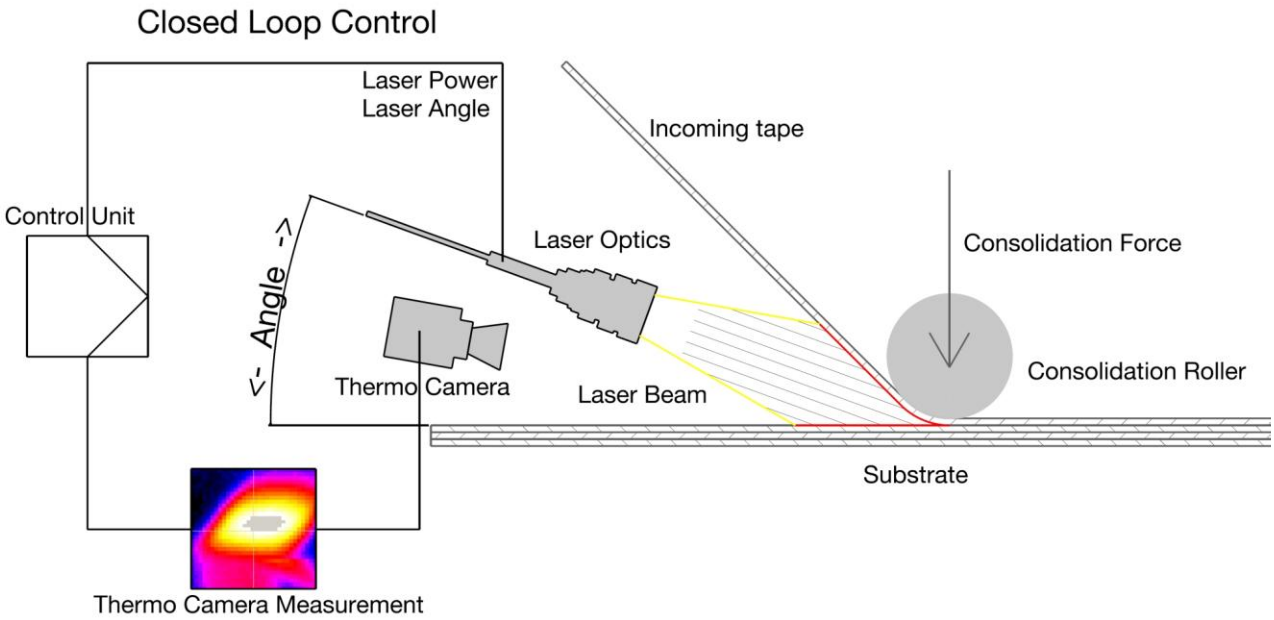

Figure 3: Principle of Thermoplastic Fibre Placement (Source: LCC)

The placement head is moved by an industrial robot. Its movement is controlled by special software, ensuring highest placement accuracy and avoiding collisions of placement head and produced part. Through an in-line temperature measuring laser, the power and angle of incidence are adjusted instantaneously. Thus fluctuations in tape quality and changes regarding geometry or thickness of parts can be compensated. Furthermore, continuous data logging enables the evaluation of the process. Figure 4 illustrates the temperature distribution between incoming tape and substrate during the laying process.

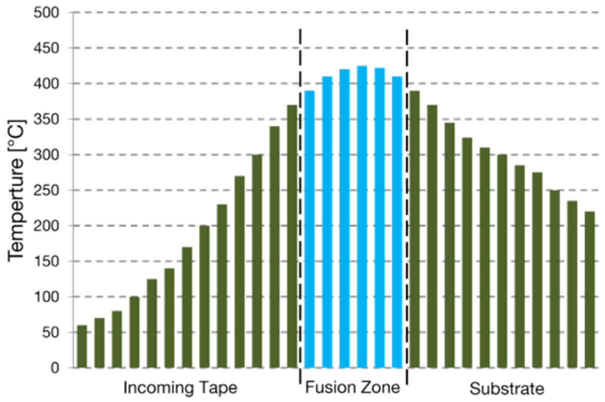

Figure 4: Temperature Distribution during Fibre Placement (Source: LCC)

3.2 Process Development

During the process development several specific steps have been performed, increasing process security, process stability and laminate quality regarding the highest requirements on mechanical properties.

Due to the vast range between glass transition temperature (T_g) and melting temperature of the semi-crystalline thermoplastic tape material, the matrix tends to bond to the consolidation roller as soon as the roller reaches temperatures exceeding T_g of the matrix system. This phenomenon causes tear out of fibres on the laminate, decreasing the mechanical properties of the part. Therefore, advanced water- and air-based cooling systems have been developed and successfully integrated in the manufacturing process.

Moreover, process optimisation loops have significantly contributed in improving the produced laminate integrity and its mechanical properties while also considerably reducing time-consuming process interruptions. The influence of process parameters like placement speed, distance of laser optics, consolidation pressure, consolidation roller material, roller cooling, roller diameter, laser power, winding pattern and angle of incidence of the laser have been examined. To evaluate the effects of these parameters on laminate quality and to characterise the processed material itself, various tests have been performed as described in chapter 2.2.

With the process parameters developed in the optimisation programme, the technology demonstrators were manufactured. Figure 5 shows the long demonstrator, which was accomplished by end of 2013.

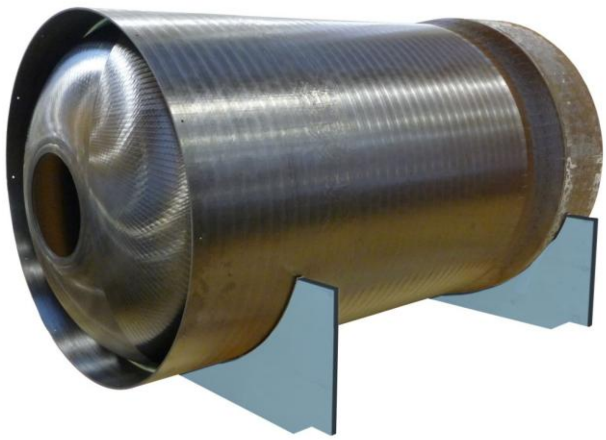

Figure 5: Technology Demonstrator

Furthermore, the process parameters for the realisation of hybrid connections between thermoplastic carbon fibre tapes and elastomeric rubber materials have been studied. The single-lap shear tests described in chapter 2.2 showed the suitability of the process for hybrid connections.
Besides the already successfully performed optimisation steps of the fibre placement process there is still potential to improve the technology. The empty drives of the placement head can be further optimised and its paths shortened to increase the laying performance. Moreover, in future applications several tapes could be processed simultaneously and the placement speed can be accelerated to reduce the production time. Furthermore, the tape producers are working on better ways of impregnating carbon fibres with thermoplastic matrices to further improve the tape quality. Additionally, increasing the tape length is one of the focal points of the tape suppliers. Finally, the process stability of thermoplastic fibre placement shall reach a level where process surveillance is reduced to a minimum to decrease labour costs significantly.

4. NON DESTRUCTIVE INSPECTION

To ensure the quality of the laminate coupons, breadboards and pressure vessels were inspected using air-coupled ultrasonic testing in reflection mode. There were a number of driving reasons for the choice of this test method and scenario. A very specific reason is the geometry and the accessibility for inspection. In this particular case it would have been possible to access the structure from both sides, even this would still be challenging. Looking forward to the future scenario, a NDI method that allows a single sided testing was sought. Besides, the goal was to achieve a testing with the highest amount of automation and therefore a throughput that would serve industrial needs. In order to fulfil all requirements, the decision has been made for air coupled ultrasonic inspection by using a slanted setup, with both sender and receiver on one side in order to induce lamb waves within the laminate. The chosen set-up is shown in Figure 6.

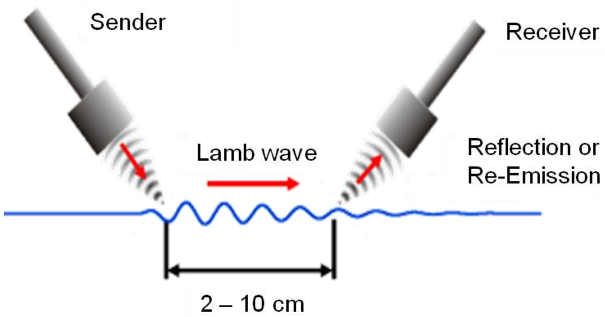

Figure 6: Air Coupled Ultrasonic Inspection in Slanted Reflection Mode (Source: DLR)

The method is common practice in laboratory environments, but has not yet made the step towards industrialisation. For this, a number of tasks have to be carried out.

1. Development of a robotic end-effecter to carry the probes
2. Integration of the air coupled ultrasonic inspection system with the robot control and the evaluation software
3. Development of an automation scenario
4. Development of the visualisation and evaluation software for complex 3D geometries

In Figure 7, the outcome of the development of a robotic end-effecter is given. It is able to carry two probes (shown in green), is independently adjustable in 4 axes for both probes and is flexible to be mounted in different ways onto the robot, using the adapter plate (shown in orange).

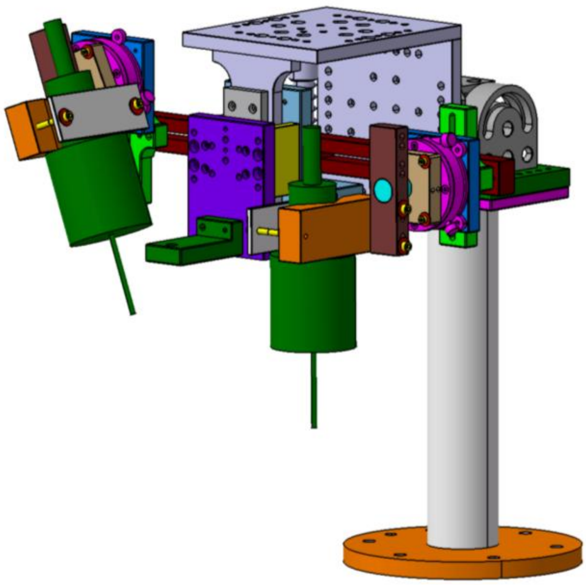

Figure 7: Highly Flexible End-Effecter Prototype (Source: DLR)

The integration of the inspection system and the robot control turned out to be crucial. This is necessary to precisely relate the measured data to the corresponding location at the part in order to allow further analysis of the NDI results. This integration has been performed using industrial bus technology named EtherCAT. This, in combination with the technology packages of the robot control, allows a precise measurement with a constant distance between the demonstrators and the end-effecter.
The entire automation scenario, including robot and end-effecter, turntable and demonstrator, has been brought into a simulation environment. This has been used to investigate reach, accessibility and collision avoidance. It finally led to robot programmes that are used to perform a fully automated inspection. Figure 8 shows the automation scenario using a turntable to rotate and move the pressure vessel in combination with an industrial six axis robot with a mounted end-effecter.

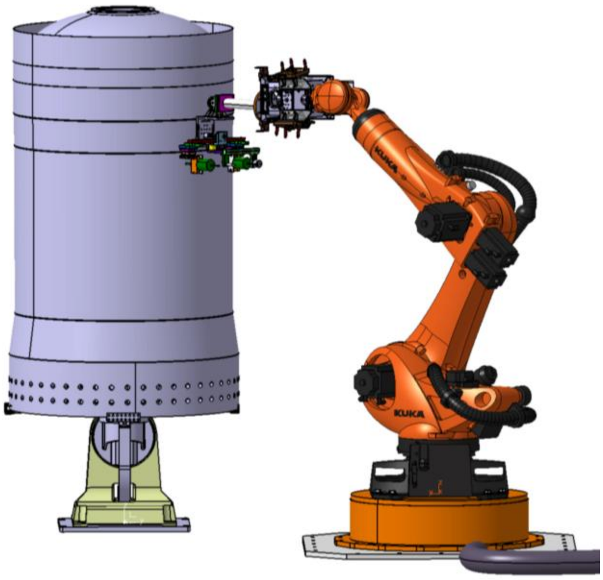

Figure 8: Automation Scenario (Source: DLR)

Finally the visualisation and evaluation software have to be adapted. The commercial software based on Labview has been improved to allow B-Scan and C-Scan analysis on complex 3D geometries, for this specific ultrasonic signal.

5. BURST PRESSURE TESTING

5.1 Acoustic Emission

Several microscopic types of failure exist in CFRP, which ultimately result in complex macroscopic failures. The relevance of the various failure mechanisms to the composites integrity and stability depends on the application and type of loading. In order to understand the individual contributions of these failure mechanisms, it is vital to record their evolution as a function of loading. In the past, various authors used acoustic emission analysis to detect the onset and position of microscopic failures occurring in fibre-reinforced materials and many attempts have been made to distinguish between different types of failures [1-5]. Various authors suggest distinguishing between fibre breakage and matrix cracking based on the significant contributions at high frequencies (fibre breakage) or low frequencies (matrix cracking) of the acoustic emission signals [1-3, 5, 7]. However, a significant shift of the weight of frequency distributions as a function of the distance between the acoustic emission source and the sensor position occurs [5, 6]. To overcome this problem, parameter-based pattern-recognition techniques can be applied to form more complex decision criteria to detect and separate clusters of acoustic emission signals originating from different microscopic failure mechanisms [2-5, 7].

In this project, a method of source identification is followed based on finite element modelling of the acoustic emission source, the signal propagation and the signal detection process. This was established throughout a series of publications [5, 8, 9]. Here the basis for distinguishing different microscopic failure mechanisms are the orientation of the crack surface displacement (in-plane or out-of-plane) and the elastic properties of the cracking medium (i.e. matrix or fibre).

In the framework of this research programme, acoustic emission analysis was carried out during mechanical testing of laboratory size specimens and small structural parts. The aim was to transfer approaches developed on a laboratory scale to test conditions as envisaged for the proof testing of the fabricated pressure vessel. It could be demonstrated that, within reasonable signal propagation distances, the pattern recognition approach was found to yield valid results [10]. At the same time new strategies were developed to simulate acoustic emission signals in hybrid structures of the anticipated scale of ~metres[9].

Many attempts have been made to apply acoustic emission in combination with burst pressure testing. Typical configurations comprise quality monitoring during autofrettage, repetitive testing or proof testing [11-13]. In the test configuration, the focus is on the recommendations of ASTM E 1067 comprising loading-unloading cycles. As demonstrated previously, the Felicity-Ratio calculated during such loading-unloading cycles approaches a critical value shortly before ultimate rupture occurs [13]. Based on the previous experience on the laboratory scale, the aim of the project is to predict the critical Felicity-Ratio of the pressure vessel based on critical Felicity-Ratios previously measured on sample level.

6. CONCLUSION

The aim of the research activities on the thermoplastic fibre placement is to develop a cost efficient manufacturing process. Therefore the focus is on process optimisation and automation. The results of the performed development are very promising.

The process parameters have been optimised, resulting in a higher laminate quality and enhanced material properties. Furthermore, hybrid connections with thermoplastic CFRP and elastomers were manufactured successfully. The demonstrators were produced without significant interruptions due to facility failure, which demonstrates the process stability already reached during the short period of the project.

Additionally a robotic end-effecter for the automated non-destructive testing was manufactured and tested with success.

The acoustic emission analysis of CFRP structures made a big step forward, especially in terms of distinguishing different types of microscopic failure in large structures. This helps to increase the quality monitoring of proof pressure tests, which are required for each pressure vessel during series production.

The manufacturing process still offers a high potential for improvement. To make the step towards industrialisation, the robot movements and the placement speed shall be accelerated to reach a higher process performance. Also the use of a multi-tow placement head and tapes with a higher thickness and a longer length would help to increase the lay-up rate of this manufacturing process.

Moreover, for series production, the reproducibility of the NDI results must be verified.

Besides the verification of the design and analysis approach, the transferability of the acoustic emission analysis approach developed on sample level to the pressure vessel will be shown in the final burst pressure test, which is planned for August 2014.

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