DEVELOPMENT, MANUFACTURING AND TESTING OF CFRP ALUMINUM HYBRID STRUCTURES FOR AEROSPACE APPLICATIONS

Birte Höck (1), Thomas Link (1), Ulrich Glaser(1), Stefan Ehard (2), Enno Petersen (3), Günther Schullerer (1)

(1) MT Aerospace AG, Franz-Josef-Strauß-Str. 5, 86153 Augsburg, Germany

(2) Chair of Carbon Composites, Technical University of Munich (TUM), Boltzmannstr. 15, 85748 Garching, Germany

(3) German Aerospace Center (DLR), Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany

Abstract

Due to the request for lower weight and lower costs for future space applications, MT Aerospace (MT) is developing forward-looking manufacturing processes for a new generation of composite pressure vessels and structural launcher components. Together with the Chair of Carbon Composites (LCC) MT developed a manufacturing process for the in situ connection of aluminum profiles with carbon fiber reinforced thermoplastics (CFRTP). At the end of the project a cylindrical demonstrator was manufactured at LCC and tested afterwards at the German Aerospace Center (DLR).

The process is based on a Thermoplastic Automated Fiber Placement (TP-AFP) process where carbon fiber reinforced tape materials are directly joined with the aluminum substrates. Joining with the metal and consolidation of the laminate is realized in one process step, process cost and time consuming joining steps like bonding or riveting processes are avoided. Before joining, the interface areas of the aluminum profiles need to be pretreated to reach an optimal adhesion between the thermoplastic matrix and the aluminum alloy. During a study phase different surface treatments have been assessed concerning the joint strength and the influence of the surface treatment on the material properties of the aluminum. In the end of the study the best suited surface treatment was chosen for manufacturing of the test hardware.

To demonstrate the feasibility and performance of the joining technology on demonstrator level, a reinforced cylinder with integrated aluminum stringers and a skin made out of CFRTP has been designed and manufactured. The pre-dimensioning was performed using the MT software ODIN. Additionally non-linear buckling analyses have been performed. The cylinder has a diameter of 800 mm and a length of 1200 mm with a laminate thickness of one millimeter. At the inner surface 18 aluminum stringers are attached using the developed process. To increase the circumferential stiffness, three CFRTP stiffeners are wound on the outer surface.

After an ultrasonic testing and an inspection of geometrical surface imperfections by photogrammetry the demonstrator was tested under axial compression. During the test the deformations were recorded using the digital image correlation system ARAMIS. At the maximum load of 325 kN global buckling occurred. The failure load was in the predicted range and the buckling pattern correlates well to the prediction of the non-linear simulation. The evaluation showed that both before and after occurrence of the global buckling the axial strains in the skin and in the joining area are homogeneous. After unloading the buckling pattern was remaining in the demonstrator which is caused by the plastic deformation of the stringers. No separating of the stringers from the skin could be detected which indicates an excellent bonding quality between stringer and skin.

Based on the results of this study MT and TUM will continue working on the in situ joining of metals and CFRTP.

Keywords

Hybrid Structures, Thermoplastics, Aluminum, Buckling

1. INTRODUCTION

Due to the demand for lower weight and lower cost for future space structures, MT is developing forward-looking manufacturing processes for future launcher applications. To improve the technologies MT works in a strong network with several research institutes. Based on the experiences from previous projects [1], [2] with carbon fiber reinforced thermoplastics this project was setup to improve the manufacturing processes for structural applications.

Within this network a cylindrical structure made of CFRTP and integrated aluminum stringers has been designed, manufactured and tested. The requirements for this cylindrical structure have been derived from an interstage structure for Ariane 6.

From manufacturing point of view the main focus was on the evaluation of an adequate surface treatment and on the determination of optimized process parameters for joining the aluminum stringers with the CFRTP skin by TP-AFP with in situ consolidation. Additionally to the testing of the joining strength the tensile strength and stiffness of the aluminum substrates have been determined in order to investigate the properties after the thermal stresses caused by the treatment process.

After successful manufacturing the demonstrator has been tested under axial compression. Post-test investigations showed a promising connection of the aluminum stringers with the CFRTP skin.

2. DEMONSTRATOR DESIGN

The demonstrator design is derived from an interstage structure for Ariane 6. This structure connects the main stage with the upper stage. The inner diameter of the demonstrator is 800 mm while the length is 1200 mm. The material properties of the CFRTP were determined within previous projects [1], [2] while the material properties for the aluminum stringers have been determined using material samples which have been pre-treated with the thermal process necessary for the surface treatment of the stringer feet.

For the pre-dimensioning the MT software ODIN has been used. To sustain the maximum load of 100 N/mm a skin thickness of one millimeter and 18 aluminum stringers on the inner surface as well as three circumferential stiffeners on the outer surface are necessary. For the load introduction at the end faces the wall thickness has been increased up to 5 mm. Therefore additional reinforcement layers have been placed between the single layers of the skin. Thus edge effects can be avoided and the buckling occurs between the circumferential stiffeners.

Non-linear buckling analyses have been performed in addition to the ODIN dimensioning. In a first step buckling-eigenvalue analyses have been conducted. The first three buckling patterns have been superpositioned and scaled to a maximum deformation of 0.1 mm. The resulting deformation has been added as a pre-deformation for the dynamic-transient analyses performed in the second step. FIGURE 1 shows the deformations of the demonstrator at failure load level. A pre-deformation amplitude of 0.1 mm results in a final failure load of 370 kN which represents an axial flux of 147.2 N/mm.

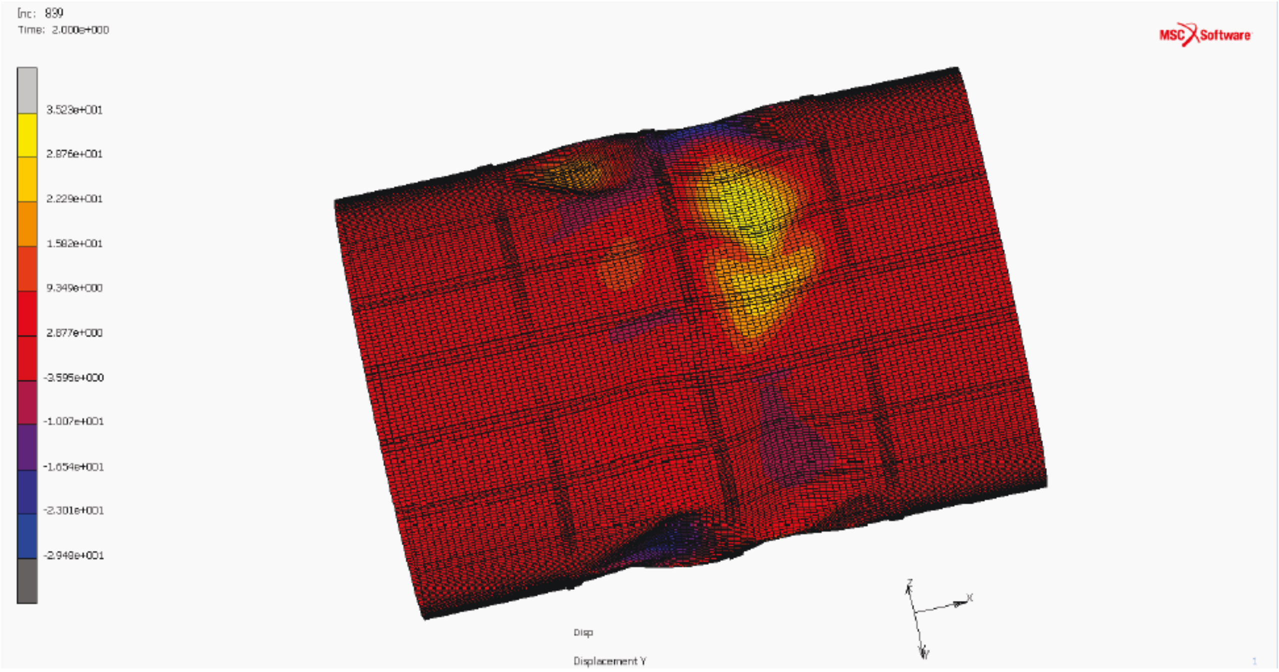

FIGURE 1. Deformations of the cylinder at failure load

3. MANUFACTURING

3.1 Thermoplastic Automated Fiber Placement

Thermoplastic Automated Fiber Placement is an automated process for joining and consolidation of pre-impregnated thermoplastic tape materials. During the process the substrate and incoming unidirectional reinforced tape are heated by a diode laser above the melting point of the thermoplastic matrix. Bond development and void content reduction is realized in the fusion zone under the cooled, flexible consolidation roller resulting in a fully consolidated laminate. This in situ consolidation requires an accurate temperature control during the layup process. A thermal camera measures the temperature distribution between incoming tape and substrate material. Laser power and laser angle are adjusted automatically to maintain the setpoint temperature and to achieve a homogenous temperature distribution in the fusion zone. By this closed loop control deviations in tape quality and changes regarding thermal properties can be compensated. The principle is shown in FIGURE 2.

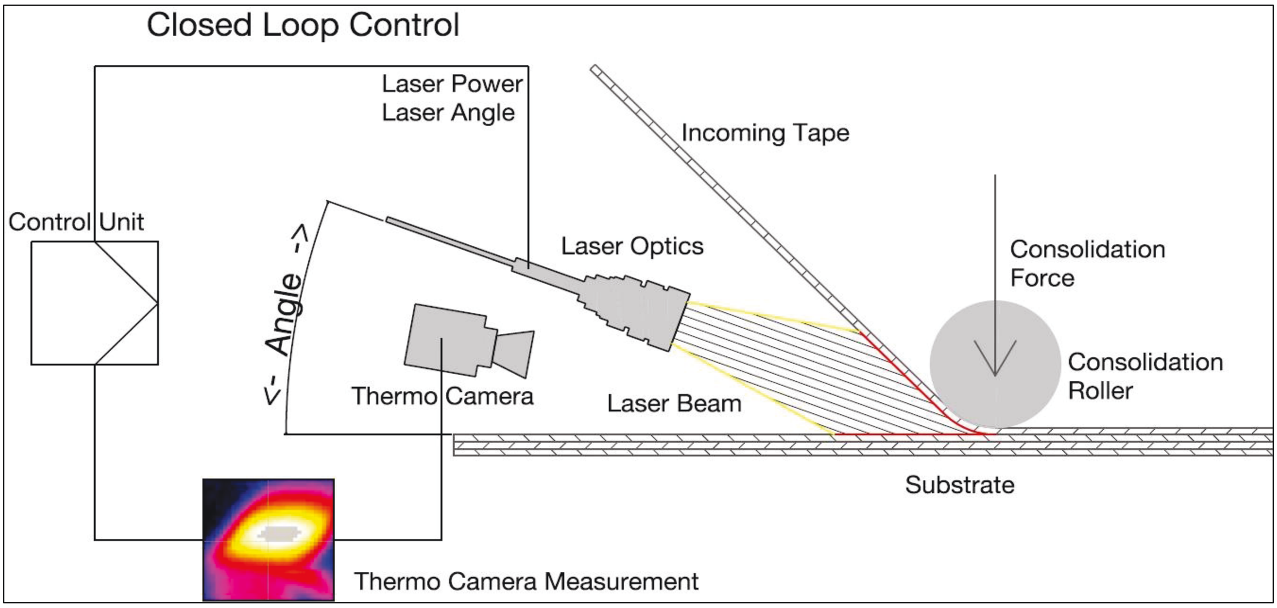

FIGURE 2. Principle of thermoplastic fiber placement [2]

Laser optics, consolidation roller, material coil, tape cutting unit and thermal camera are attached to the placement head. The placement head is moved by an industrial robot. The used single-tow winding head is produced by AFPT GmbH and was customized by Technical University of Munich (TUM) for fiber placement applications. By adjusting the tape guidance and spot size of the laser beam, the placement head allows processing tape widths in a range from ½” to 2”. The TP-AFP system is shown in FIGURE 3.

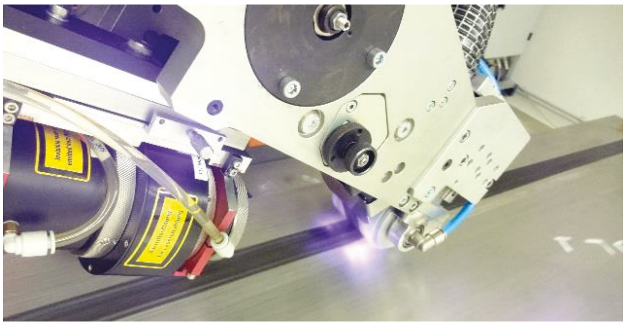

FIGURE 3. TP-AFP equipment at TUM

3.2 Surface Treatment

In order to achieve a sufficient joint strength between aluminum stringers and CFRTP a suitable surface treatment of the stringer feet is essential. The investigated surface treatments can be divided into three groups: mechanical, physical and chemical surface treatments. Additionally, the influence of a thermoplastic coating has been evaluated. Two different coatings have been analyzed, one is based on a PPS film and the other is an adhesive promoting polymer film with a lower melting temperature. To compare the different surface treatments peel tests have been performed. The tests showed different failure modes: Interlaminar failure in the CFRTP, adhesive failure between the CFRTP and the thermoplastic coating and adhesive failure between the thermoplastic coating and the aluminum surface.

With the chemical surface treatment no significant joint strength could be achieved. An enlargement of the surface area by mechanical or physical surface treatment is helpful for the in situ connection of the stringers with the CFRTP skin. However, it has been found that the use of an additional polymer coating on the pre-treated surface is beneficial for enhancing the joint strength. The polymer film with a lower melting temperature showed poor results especially at elevated temperatures. Etching, abrasive blasting, and laser treatment in combination with the PPS coating delivered highest joint strengths in the range of adhesively bonded joints. In terms of reproducibility a laser treatment resulting in a micro-structured surface delivered the best results. Since this surface treatment is a very fast method it has an economic benefit also.

Besides enhancing the joint strength the thermoplastic coating has also the function to conserve the pre-treated surface and to isolate the aluminum from the carbon fibers. Furthermore, it gives the opportunity to adapt the optical surface properties to the laser assisted fiber placement process.

For the coating four different processes have been assessed. Based on previous experiences [3], [4] a vacuum bagging of the polymer film and aluminum substrate on a heated plate was used. This process delivers a sufficient wetting of the polymer on the aluminum surface and a high joint strength after debagging. The disadvantage of the process is, that the aluminum suffers from the temperature cycle and the high melting temperature in case of the PPS polymer used in this project. To avoid decreasing material properties of the aluminum a second coating process has been developed. This process is characterized by melting the thermoplastic film and pressing the cold aluminum on the molten thermoplastic film. Thus the aluminum is not suffering from a long temperature cycle. Additionally powder coating with a laser as heat source and flame spraying process have been tested.

To compare the different coating processes single lap shear tests have been performed. The samples using the powder coating and flame spraying processes have been damaged during preparation and showed adhesive failure between coating and aluminum. The coating of the aluminum on a heated plate under vacuum delivers the highest lap shear values with a good reproducibility. The lap shear values from the samples manufactured using the press process were also found suitable.

Due to the size and shape of the aluminum stringers, the vacuum bagging process has been used for coating the pre-treated substrates.

3.3 Fiber Placement Process for Stringer Connection

After determining a suitable surface pre-treatment and coating process, the process parameters have been optimized by TUM for the joining step. Based on process parameters from previous projects [2] for standard TP-AFP layup, the main parameters were varied for the placement of the first layer. The main parameters are the placement velocity, the angle of the laser optics and the process temperature.

The investigated variations of the process parameters showed only a small impact on the resulting shear strength. For a medium temperature setpoint an increase of the placement velocity leads to a lower lap shear strength. By increasing the setpoint temperature higher lap shear strength were observed. For further investigations the parameter set with a medium temperature setpoint and a high placement velocity was not taken into account. For three representative parameter sets the fracture surfaces have been compared. The first parameter set delivered the highest lap shear strength values and is characterized by a high temperature setpoint and a high velocity. The second set has a medium temperature setpoint and velocity while the third set of parameters is characterized by a high temperature setpoint and a low velocity. The performed peel tests showed mixed mode failure between aluminum and thermoplastic film for the first parameter set. The other two parameter sets showed adhesive failure between thermoplastic film and CFRTP. During sample preparation it was also found that a high placement velocity has a positive influence on the process stability. Thus the first parameter set has been chosen for the demonstrator manufacturing.

3.4 Demonstrator Manufacturing

The surface treatment of the aluminum stringers and demonstrator manufacturing was conducted by TUM. For the demonstrator manufacturing a tooling made of glass-fiber reinforced plastic (GFRP) has been designed. It consists of two aluminum plates at the end faces and 18 GFRP segments which are connected to the aluminum plates. Between the single segments there are cavities for the stringers, see FIGURE 4.

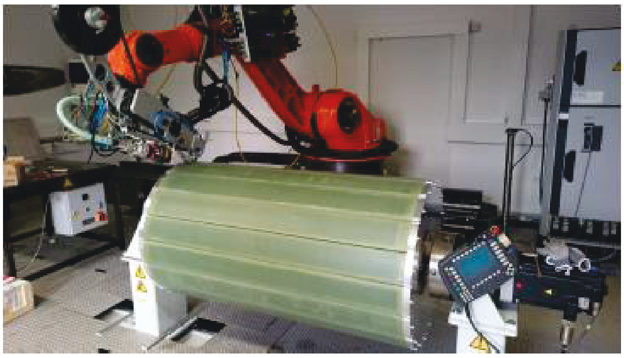

FIGURE 4. Tooling for demonstrator manufacturing at TUM

The demonstrator manufacturing is subdivided into six steps:

1) Preparation of the stringers: as explained in chapter 3.2 the stringer feet need to be structured via laser treatment and are subsequently coated with a thermoplastic film.
2) Preparation of the tooling and assembly of the stringers in the cavities: the tool segments have been cleaned and treated with a release agent. After fixing the single segments at the end plates the stringers have been positioned in the cavities.
3) Placement process for the first layer: the process parameters for the first layer are differing from the process parameters of the following layers since the thermal and optical properties of tooling and stringers are different. The process parameters have been determined during the parameter optimization as explained in chapter 3.3.
4) Placement process of the following layers of the skin: for the following layers a standard placement process has been used. The process parameters have been established and tested during previous studies [2]. The placement process is explained in chapter 3.1. Additionally, reinforcement layers at the edges of

the cylinder have been added between the single layers of the skin.

5) Placement of the circumferential stiffeners: Three circumferential stiffeners with 1” in width were added on the outer surface. The stiffeners have been manufactured by winding 90° layers.
6) Trimming and demolding: For trimming the edges a milling spindle motor has been attached to the robot which normally operates the placement head. With this setup the edges of the cylindrical demonstrator have been cut directly on the tooling. The demolding was carried out in vertical position. After dismounting the end face plate on the top side the single segments were removed to the top.

FIGURE 5 shows the demolded demonstrator in front of the manufacturing facility. After an ultrasonic inspection which showed a good connection of the stringer feet to the skin the demonstrator was ready for the test preparation.

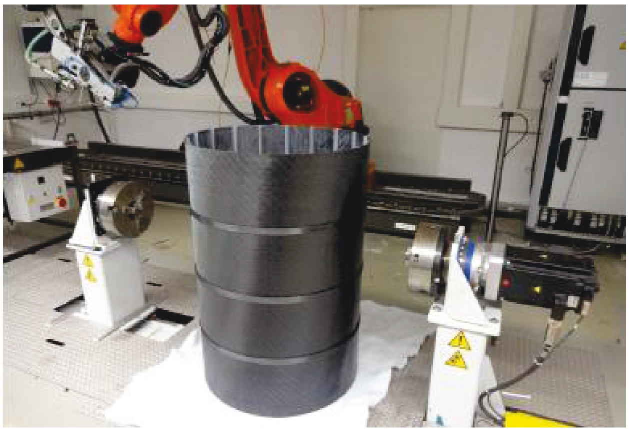

FIGURE 5. Finished demonstrator at TUM

4. TESTING

A compression test was conducted to validate the manufacturing process and to investigate the experimental load carrying capacity of the hybrid structure. Therefore, the manufactured specimen is tested in the buckling test facility of the DLR in Braunschweig. The considered test procedure is described in the literature [5], [8] and was considered for several tested structures in the past [6], [7]. FIGURE 6 shows the test set-up with the measurement systems.

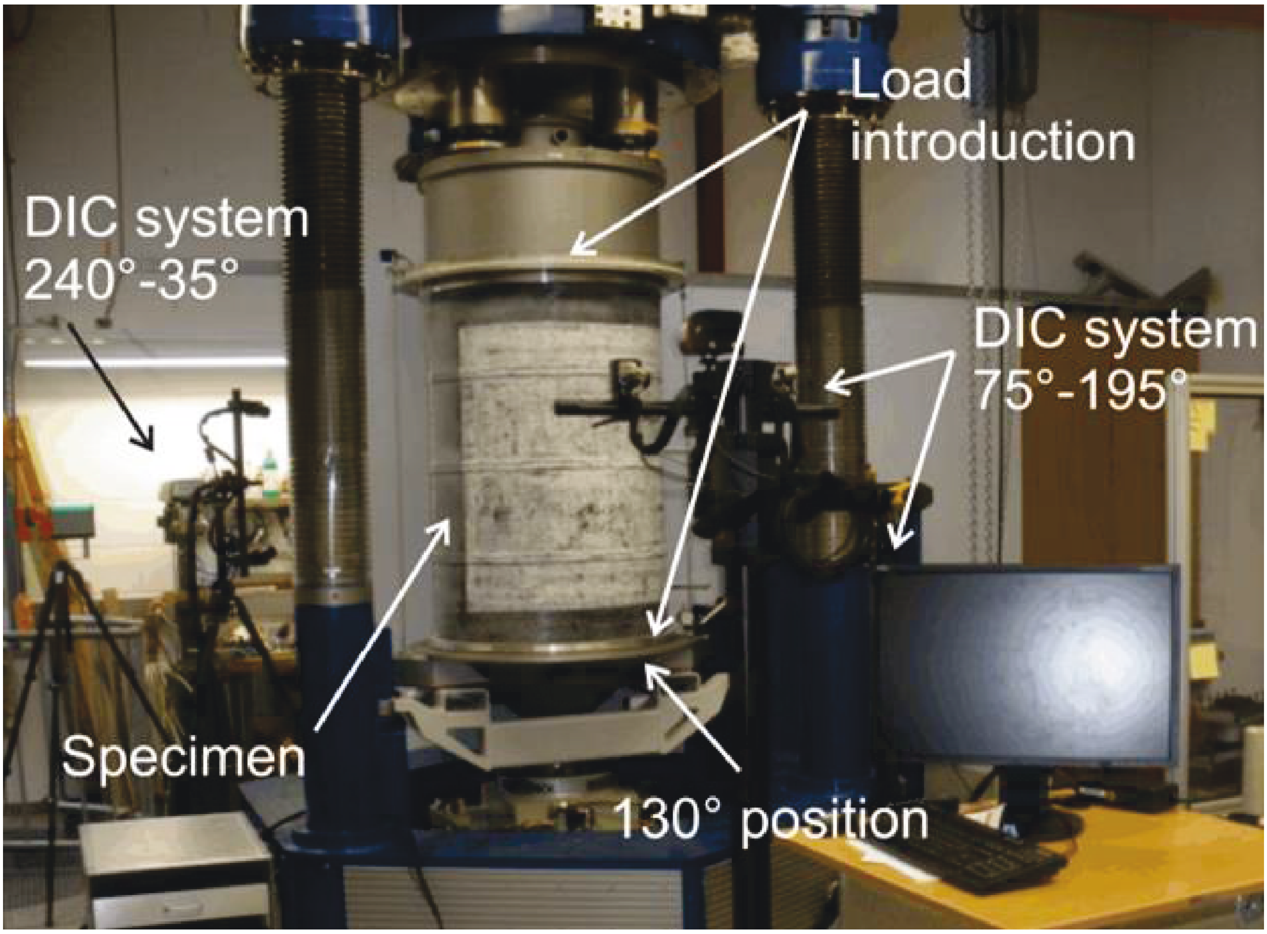

FIGURE 6. Test set-up at DLR

4.1 Test Preparation

To assure an ideal axial compression load scenario it was necessary to use potting of the specimen's top and bottom into load introduction elements as depicted in FIGURE 7.

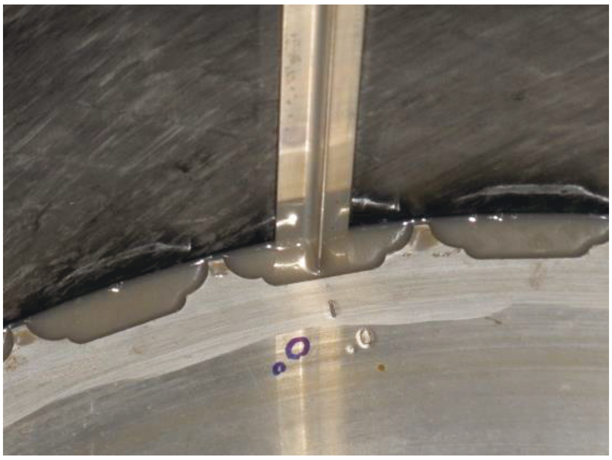

FIGURE 7. Potting of the specimen into the load introduction elements

After curing of the potting for the load introduction elements, the surface was scanned by the 3D sensor system ATOS from the GOM company. Herein, the influence of the load introduction elements weight and the potting was included. The obtained geometrical imperfection pattern was used to identify interesting locations for the optical measurement during the test.

At all, the specimen showed a nearly homogenous surface. However, a skin field with the maximum imperfection of about 1 mm negative amplitude was identified, what is depicted in FIGURE 8. The inspection showed, that this imperfection was not caused by the winding process but by the misalignment of one tool segment.

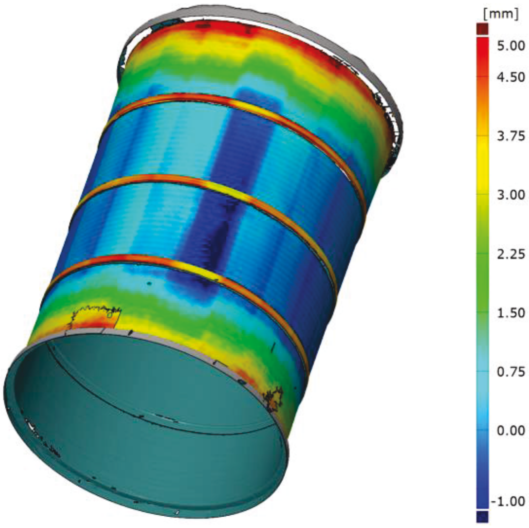

FIGURE 8. Scan of surface imperfections with largest imperfection in skin field from 120°-140°

Further, the measuring equipment as the Digital Image Correlation (DIC) system Aramis was carefully arranged. The specimen was installed in the test apparatus after which the strain gauges have been connected to recording system. The application of speckle patterns was required for the DIC. One speckle pattern was applied between 75° and 195° and over the height of the vertical inner skin fields. Hence, the by the surface scan identified skin field with the highest imperfection was set to the focus of the DIC measurement. On the contrary side the speckle pattern was applied over the whole height and between 240° and 35°.

4.2 Test Results

The load was applied with a constant speed of 0.5 mm/min. FIGURE 9 shows the force - displacement curve. A maximum force of 325 kN was reached at an applied axial displacement of 1.53 mm. A sudden force drop occurred without any preceding stiffness decrease. Further, with increasing displacement, also the force increased again. During loading in the post-buckling regime strong cracking noise as typical for CFRP failure was recognized.

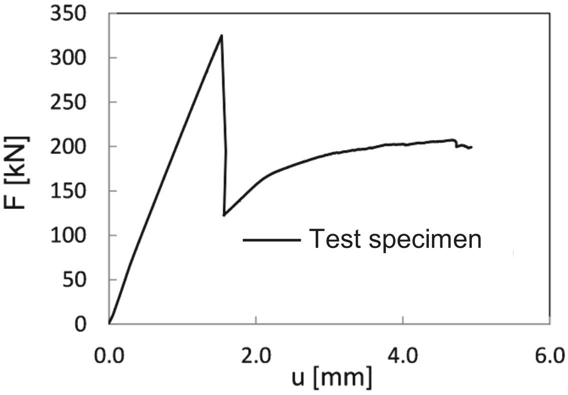

FIGURE 9. Force-displacement curve

At the maximum load buckling took place suddenly and a pattern of radial displacements as visualized by the DIC in FIGURE 10 occurred between the inner frames. Hereby, the single buckles extend over the skin fields braced by the stringers. Hence, the buckling type was identified as global buckling. The thickened regions outside the frames did not show any buckling, what was revealed by the second Aramis system.

In the nonlinear regime after the maximum load was reached the buckling pattern stood constant. However, its amplitude increased.

The strains recorded by the gauges, show a sudden change in the skin fields caused by the out-of-plane deformation. On the stringers a sudden increase of the longitudinal strain could be observed at the initiation of buckling. After buckling the slope was decreasing till a plateau is reached.

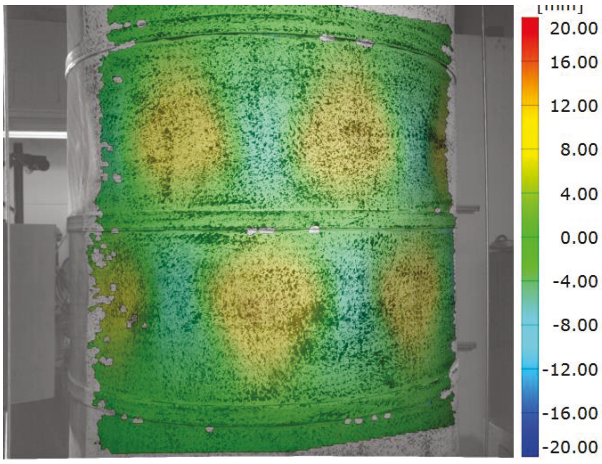

FIGURE 10. Radial displacement visualized by DIC between 130° and 40° at 325 kN

A conservative (w.r.t. machine capabilities) maximum failure load of 370 kN has been calculated, based on the assumption of minimum imperfection of 0.1 mm. As the real imperfection was higher, see chapter 4.1, the measured test failure load of 325 kN is fitting well into the expected range. FIGURE 11 shows the demonstrator after testing. The buckling pattern shows a high correlation to the buckling pattern determined within the dynamic-transient analyses as it is shown in chapter 2.

FIGURE 11. Demonstrator after testing

4.3 Posttest Investigation

After unloading the specimen still showed the buckling pattern, as the skin is fixed to the plastically deformed stringers. The deformation of the demonstrator is shown in FIGURE 12.

FIGURE 12. Plastically deformed demonstrator

At some positions damages in the skin are visible like it is shown in FIGURE 13.

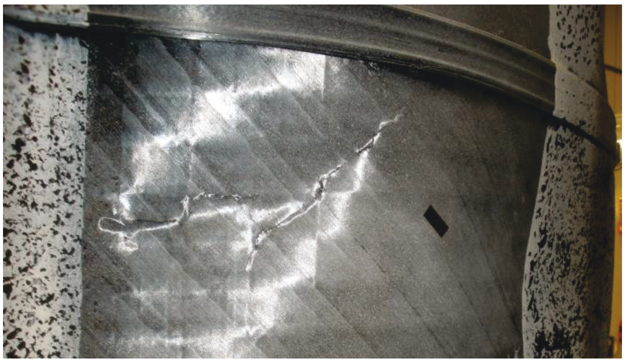

FIGURE 13. Damage in the skin

The stringer connection to the skin has been analyzed after testing by micrographs. In the cross-section shown in FIGURE 14 also cracks in the CFRTP skin can be seen. The joining of the stringers and the skin is still intact. This observation was supported by an ultrasonic inspection of the tested cylinder which also showed that the stringer to skin connection is still functional.

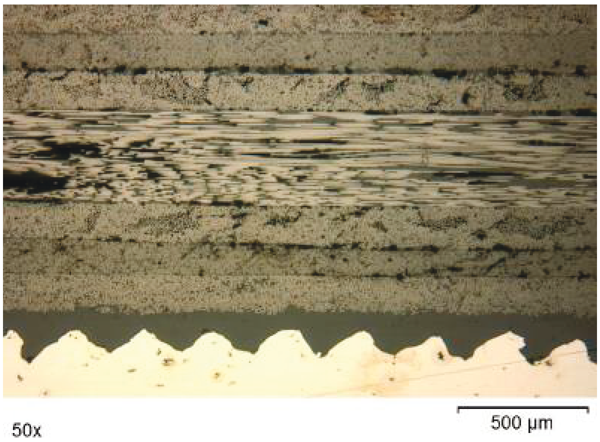

FIGURE 14. Cross-section of the stringer connection

5. CONCLUSION

During the project a suitable surface treatment for aluminum was developed to prepare the material for an in situ joining with carbon fiber reinforced thermoplastics. A laser structuring and a subsequent coating with a thermoplastic film lead to high joining strength values. By manufacturing and testing the reinforced cylindrical structure the load capacity of the joining was demonstrated successfully. However, since the melting temperature for the thermoplastic material used within the study is very high additional optimization steps for the coating process of the stringer feet should to be conducted to reduce the thermal stresses for the aluminum.

The development show promising results for a cost efficient manufacturing process for structural components for future launcher applications. The process can be transferred to other thermoplastic materials which offers a wide range of opportunities.

6. REFERENCES

[1] B. Höck, M. Regnet, S. Bickelmaier, F. Henne, M. Sause, T. Schmidt, G. Geiss. Innovative and efficient manufacturing technologies for highly advanced composite pressure vessels. European Conference On Spacecraft Structures, Materials And Environmental Testing, Braunschweig, Germany, (2014).

[2] F. Henne, S. Ehard, A. Kollmannsberger, B. Hoeck, M. Sause, K. Drechsler. Thermoplastic In Situ Fiber Placement for Future Solid Rocket Motor Casing Manufacturing. SAMPE Europe SETEC 14 - Efficient composite solutions to foster economic growth, Tampere, Finnland, (2014).

[3] S. Ehard, E. Ladstätter, M. Jürgens, L. Bortolotto, N. Remer. Development of a hybrid tail rotor drive shaft by the use of Thermoplastic Automated Fiber Placement. ECCM 17 - 17th European Conference on Composite Materials, Munich, Germany, (2017).

[4] S. Ehard, A. Mader, E. Ladstätter, K. Drechsler. Thermoplastic Automated Fiber Placement for manufacturing of metal-composite hybrid parts. Euro Hybrid Materials and Structures 2016, Kaiserslautern, Germany, (2016).

[5] R. Degenhardt, A. Kling, K. Rohwer, A. C. Orifici, R. S. Thomson, Design and analysis of stiffened composite panels including post-buckling and collapse, Comput. Struct.86(9), (2008), p.919–929.

[6] R. Khakimova, R. Zimmermann, D. Wilckens, K. Rohwer, R. Degenhardt, Buckling of axially compressed CFRP truncated cones with additional lateral load: Experimental and numerical investigation, Compos. Struct.157, (2016), p.436–447.

[7] E. Petersen, C. Hühne, Potential of cross section varying Ω stringer made of carbon fibre reinforced plastics

[8] R. Zimmermann, H. Klein, A. Kling, Buckling and postbuckling of stringer stiffened fibre composite curved panels: tests and computations, Compos. Struct.73(2), (2006), p.150–161.