TAILOR-MADE THERMOPLASTICS: PRODUCTION TECHNOLOGY AND QUALITY ASSURANCE OF A THERMOPLASTIC AIRCRAFT FUSELAGE SKIN SEGMENT

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ABSTRACT

The production of carbon fiber reinforced plastic (CFRP) parts for aircrafts is very time and cost intensive. To be able to compete with metal based technologies both the area of application as well as the production of CFRPs must be reconsidered.

For this reason the Center for Lightweight Production Technology (ZLP) at the German Aerospace Center (DLR) in Augsburg analyses the whole process chain along the production of CFRPs, starting from the choice of the material to the final assembly, on optimization potentials.

Process automation and optimization is demonstrated on the basis of an aircraft skin segment demonstrator produced out of carbon fiber reinforced thermoplastic (CFRTP) material. This material class offers alternative processing technologies compared to their thermoset counterparts. Technology solutions for each process step are developed like automated preforming, Out-of-Autoclave vacuum consolidation, combined laser and milling processing as well as automated dustless assembly.

An alternative production process for structural parts of aircrafts could be demonstrated using the advantages of thermoplastics.

1 INTRODUCTION

The structure of modern wide-body airplanes such as the Airbus A350 XWB and the Boeing 787 is primarily made out of carbon fiber reinforced plastics (CFRPs). The overall CFRP weight content for these aircrafts is 52% (A350 XWB) respectively 50% (Boeing 787) [1],[2].

Thermoset fuselage skins are mainly produced by gantry-mounted advanced fiber placement (AFP) machines and co-curing of stringers in a subsequent autoclave cycle. The carbon fiber material as well as the part production itself is still very cost intensive. Therefore the composite fuselage production needs to be improved to compete with metal production technologies of short-range aircrafts. An enabler for the breakthrough of composite material may be the class of carbon fiber reinforced thermoplastics (CFRTP). These materials offer potential for efficient processing and dustless assembly that need to be exploited. These high performance materials may enable an entirely new fuselage production and assembly process with pre-equipped subcomponents that are joined by welding technologies in the final assembly line (FAL).

2 AUTOMATED PROCESS CHAIN

The Center for Lightweight Production Technology (ZLP) of the German Aerospace Center (DLR) has developed a flexible process chain for the tailored production of thermoplastic composite structures from as-delivered material to final assembly [3].

The established flexible process chain is schematically illustrated in Figure 1.

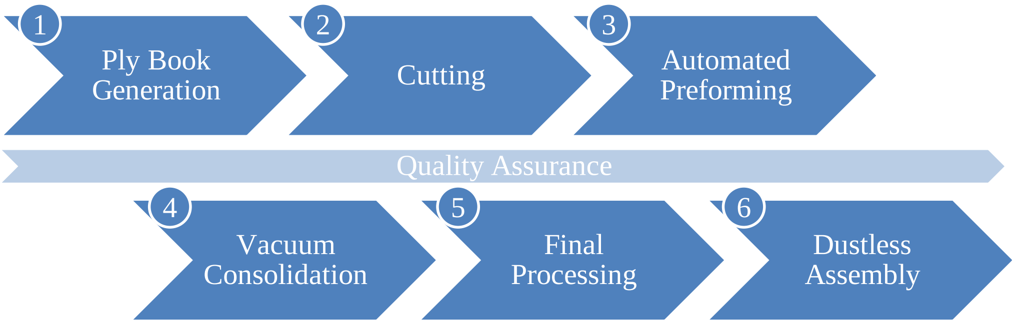


Figure 1: Schematic thermoplastic process chain

The process chain for CFRTPs starts with the generation of a ply book. The resulting geometries are cut and the plies are delivered to a robotic cell for further processing. An automated preform stacking is possible with the help of special developed camera detection and gripping system that is mounted on a robot. After the preforming process is finished the ply stack is consolidated by vacuum. Subsequent the consolidated part is trimmed to the final geometry. At the assembly step a dustless welding process can be used. All process steps are accompanied by quality assurance.

A typical curved skin segment of an aircraft fuselage serves as demonstrator for technology readiness along the described process chain. The chosen skin segment is located in section 16 of an aircraft (see Figure 2) and is based on the A320 geometry. The skin segment cuts the upper part of one window and the edges of 2 other neighbouring windows. This segment has dimensions of 940 mm x 580 mm with a radius of 2 m.

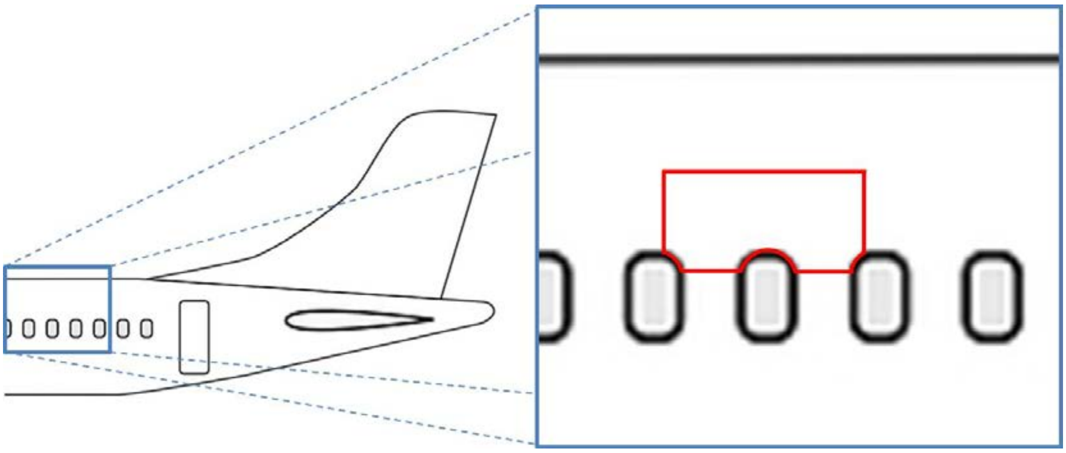


Figure 2: Schematic illustration and location of skin segment

In the following subsections the focus will be on the ply book generation and automated preforming, final processing and quality assurance along the described process chain.

2.1 Ply book generation and offline programming

The first step of the production process for the demonstrator is the generation of a ply book. The ply book was designed in *CATIA* V5 R23 *Composite Part Design (CPD)* and consists of 104 cut-pieces distributed over 32 plies. The cut-pieces are generated on basis of the size limitations of the material that is used. Unidirectional carbon fiber reinforced Polyetheretherketone (CF-PEEK) tape from TenCate (Cetex TC 1200) and unidirectional carbon fiber reinforced Polyetherketoneketone (CF-

PEKK) tape from TohoTenax (TPUD PEKK-HTS45) are used separately for skin segment demonstrators. Both tapes have a width of 12'' (304,8 mm). The layers are spliced to a width of 275 mm. This ensures a material security excess on both sides of the material of ~15 mm at the subsequent cutting process. The real geometry of the mould was scanned with a Leica T-Scan device mounted on a robot. Out of the resulting point clouds the mold surface was reconstructed in *CATIA's Quick Surface Reconstruction* (QSR), so that the ply book can be swapped onto the real surface geometry. This is important to ensure highest accuracy for the shape and laydown process of the cut-pieces (e.g. to reduce gaps and overlaps) [4].

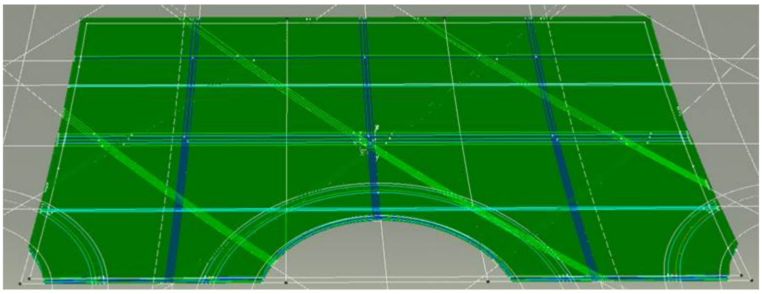
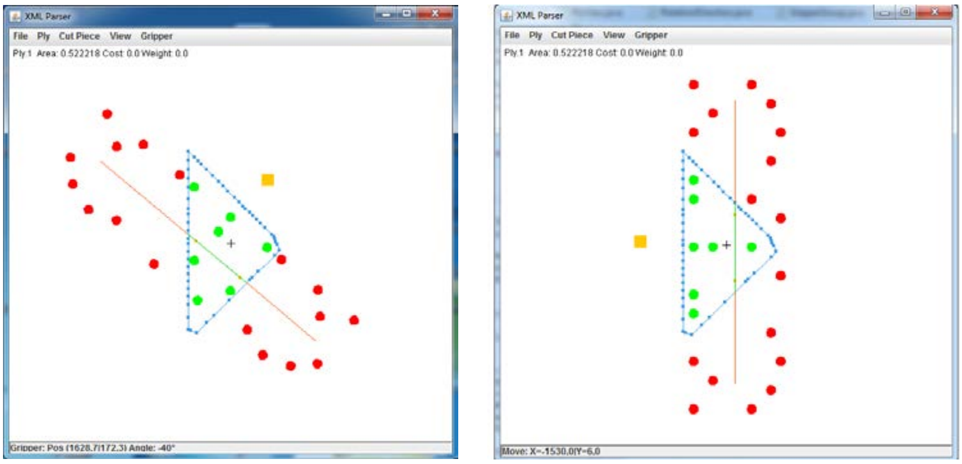


Figure 3: Ply book for skin segment designed in *CATIA CPD*

In order to enable further steps in the automated production, the ply book was enriched with additional information concerning the relations between points on the plane cut-pieces and the draped cut-pieces. To this purpose, a grid of 2D-points with mesh size 10 mm was created on the plane cut-piece. Subsequently, every such point was mapped to its associated point on the draped cut-piece under the producibility of the respective cut-piece. All this was done automatically by a catvba-script which exported the results together with the other ply book information in an XML-file.

For the determination of the grip- and droppoints (i.e. the end-effector positions, where the plane cut-piece has to be gripped and the cut-piece has to be dropped into the mold) a proprietary offline programming tool was developed. There the user gets a suggestion from the system how to place the gripper on the plane cut-piece. Depending on the quality of the suggestion, one can alter the position of the gripper according to the own view. Based on the gripper position the tool calculates the vacuum suction devices which have to be activated, the positions where the cut-pieces have to be welded, and the final gripper position for the placing process. The system tries to place the gripper on the cut-piece in order to optimize both the number of vacuum suction devices on the cut-piece and the number of suction devices near the corners of the cut-piece. Often the system finds good solutions; however, in some cases a human expert has to correct the positions by hand.

The screenshots in Figure 4 may illustrate this: in both pictures, the big orange square indicates the tool center point of the gripper. The green full circles correspond to vacuum sucction devices placed on the cut-piece. The cut-piece is depicted as a blue, in this case triangular shape. The little squares on the edge line stem from the vertices exported from CATIA. As red full circles the vacuum suction devices are illustrated that are out of the cut-piece and therefore do not need to be activated. Furthermore, the line segment illustrates the linear axis along which the ultrasonic welding unit can be moved. The feasible position in the interior of the cut-piece is illustrated in green and in red for the exterior one. Finally, the small orange squares on the linear axis show where the welding takes place.



Ply 1 Area: 0.522218 Cost: 0.0 Weight: 0.0

Gripper: Pos (1628.7/172.3) Angle: -40°

Ply 1 Area: 0.522218 Cost: 0.0 Weight: 0.0

Move: X=-1530.0/Y=-6.0

Figure 4: Screenshots from the offline programming tool for gripper positioning

The configuration from the left picture of Figure 4 was suggested by the system. It places seven vacuum suction devices on the cut-piece, as well as the human-made solution from the right picture. For reasons of better reachability and a lower amount of necessary motions during the placing process in this case the second solution if preferable to the computed one. Here a lot of further research for integrating those and related issues into the automated gripping system is ongoing work.

2.2 Cutting

Subsequently all ply geometry information resulting from the generated ply book are imported in a special nesting software. Here an optimization of the material utilization takes place. As output a nesting sequence is generated and transmitted to the cutter. A vacuum matrix gripper is able to grab and transport the plies to a mobile drawer storage. An algorithm was developed to reduzed the necessary grabbing action to increase the efficiency of this process step [4], [5].

2.3 Automated preforming

After delivering the plies to a robot cell via the mobile drawer storage unit the preforming step takes place.

Here a robotically pick & place end-effector detects, grips and drops the cut-pieces out of the drawers storage unit into a mold (see Figure 5). The end-effector mainly consists of a cut-detection camera, a vacuum generation and distribution system (vacuum pump, valve cluster and suckers on spring followers) and a welding unit (ultrasonic generator with horn on a pneumatic drop unit sitting on a linear axis). All cut-pieces are detected and laid down automatically in the ply book’s lay-down order.

The most outstanding feature of this process is that all robot motions are generated automatically. Since the real cut-piece position and orientation is determined dynamically by the computer vision system the robot’s motion is directed by an external MES (Manufacturing Execution System) that passes both the coordinates for gripping (determined by the camera system) and for dropping (determined previously by inversing the draping simulation) to the robot main program. Thus very complicated ply books can be laid without much programming or operating effort of the robotic system. The preforming technology works for 2D and 3D preforms with low draping rates with marginal shearing.

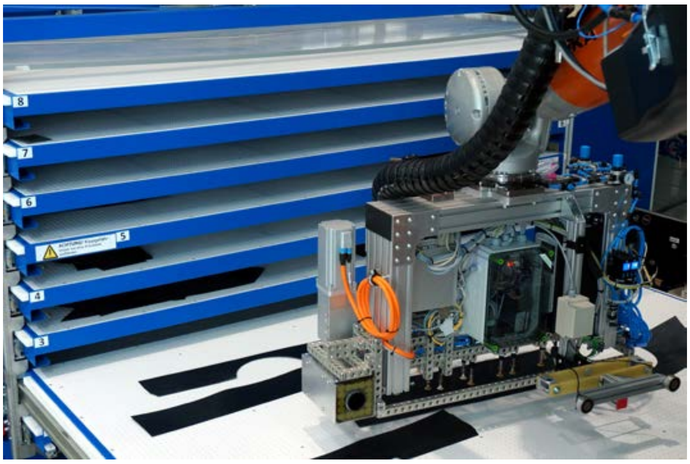


Figure 5: Automated picking process out of a drawer storage unit

This automation routine is repeated until all plies are placed on their predefined positions and thus the preform is finished. During the process data about robot positions, drive temperatures, vacuum pump status and welding are collected for further process improvement.

2.4 Vacuum consolidation

Pick and place preforming of the spot welded skin preform requires final consolidation. Especially for the production of larger aerospace structures vacuum consolidation on a heated tooling has proven to be a cost-effective alternative to autoclave processing [6], [7].

Recently, certain efforts have been reported to establish vacuum consolidation of advanced thermoplastic composites in standard oven equipment without additional pressure. In this context, volatile removal and successful consolidation without porosity remains one of the main challenges [8–15].

Particularly for this kind of materials processing qualification an automated test bench and quality assessment routine has been setup [16].

The preform of the locally welded fuselage skin is vacuum bagged and consolidated at 380°C in a hot air oven (NABERTHERM N1500/45HA) for 30min. Heating and cooling rates were set to 5 K/min. For enhanced process control the part temperature is regulated by the furnace with a thermocouple (type N) within the preform.

Figure 6 shows the bagging setup for vacuum consolidation with its auxiliaries.

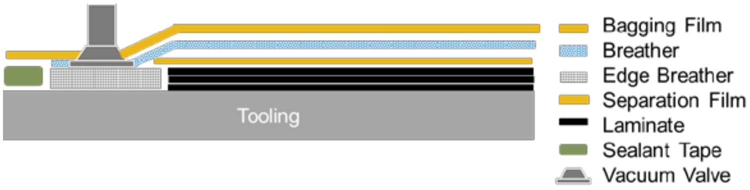


Figure 6: Bagging setup for oven vacuum consolidation

The vacuum setup was adapted to leave the curved preform unaffected on the tooling. A polyimide separation film (UPILEX-125S) coated with release agent (MIKON 705) is set atop the laminate. The non-woven fiberglass breather (AIRWEAVE UHT 800) allows good transition between laminate and vacuum film at any given radius so that no wrinkles in the vacuum film are imprinted on the part surface. The outer polyimide vacuum foil (KAPTON 200HN) is fixed to the tooling with a high temperature silicone sealant tape (AIRTECH A-800-3G). As edge breather a stainless steel wire mesh

(Topmesh TM3-QM 500) picture frame was used that provides improved air flow compared to standard glass fabric tape. The vacuum bag is connected to the rotary vane pump outside the furnace by two vacuum valves (VAC VALVE 409 SS HTR) and corrugated metal hoses.

2.5 Final processing

Subsequent to the consolidation step the resulting CFRTP part must be trimmed to its final geometry.

For the final processing a cell constructed during the course of the FlexiCut project [17] is used. The design and construction of the cell are the result of the cooperation of various companies and research institutes [18]. The task of the FlexiCut cell is a combined laser and milling machining of cured CFRP parts with the aim of a more economical finishing. The idea is a very fast and rought processing by laser followed by a milling finishing. Due to this application time and cost (for milling tools) can be reduced.

The principle of such a combined finishing process by the example of a CF/PEEK component is described in this subsection. The layout and components of the FlexiCut cell is shown in Figure 7.

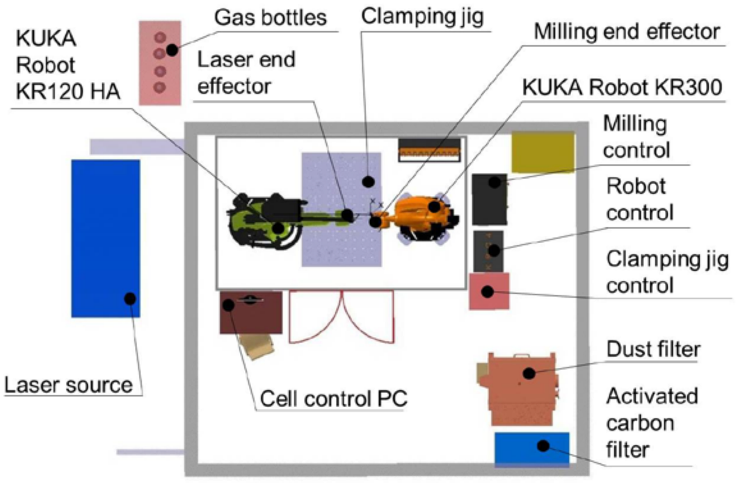


Figure 7: Layout of the FlexiCut cell

The process chain of the final processing step is shown in Figure 8 (according to [19]). First, the component is fixed on a clamping jig in a defined position. Subsequently, using a laser tracker, the part is referenced to a coordinate system. Based on this coordinate system the positions in the coordinate systems of the laser and the milling robot will be derived. These positions are used as input for the path planning done in *DELMIA*. The resulting programs had to be corrected marginally by hand and tested thoroughly at low speed without active laser or milling device.

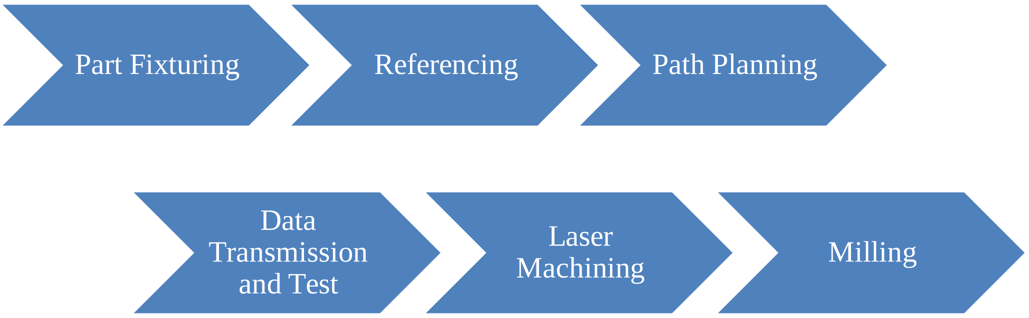


Figure 8: Schematic process chain of the final processing step

After successful dry running test the laser trimming is performed. For this operation a KUKA robot

KR 120 HA with a Trumpf laser source (TruDisk2001) and a Trumpf laser end-effector (Beo D70) is used. The Yb:YAG laser source is generating a wave length of λ =1.03 µm and 2 kW continuous laser power. A cone-shaped laser bundle with a sharply defined focal point is emitted. The position of the focal point relative to the CFRTP part is an important parameter for the process result.

The cutting quality depends on different influencing factors. The feed rate and the position of the focal point has been observed to be the main influencing quantitative factors.

The optimum feed rate and focal positions were determined by tests on flat test plates. In order to use these results for the laser processing of 3D parts it is crucial to guarantee a high control over the velocity and the position of the focal point also on 3D paths.

The influence of the laser processing on the thermoplastic samples can be seen in Figure 9. The images show microsections of the laser cutting edges. The laser hit the samples from the upper side of the images. In the dark reagion the PEEK matrix is degraded by the laser. At the brighter area the thermoplast matrix was melted by heat transferred from the cutting zone. A typical cone shaped geometry of the heat-affected zone can be seen. Delaminations of the first respectively last ply is obseved at samples made out of unidirectional prepreg material. For samples made out of fabric material no delamination was observed.

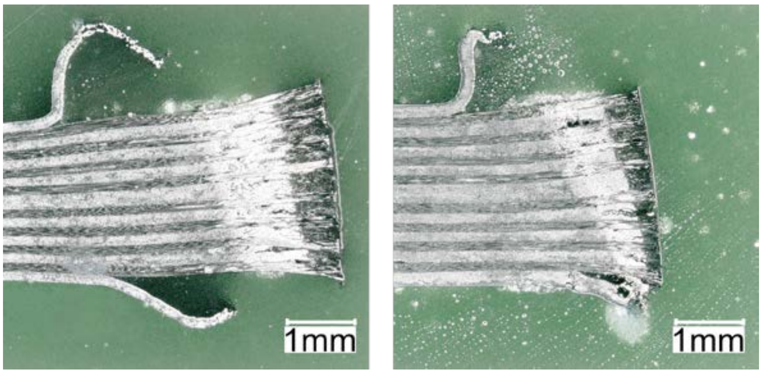


Figure 9: Laser trimmed CF/PEEK samples. One cut at low speed (left) and a two-time cut at higher speed (right)

The sample on the left image of Figure 9 was cut by laser with a speed of 3 cm/s. By enhancing the speed up to 6 cm/s and a two-time cut the heat-affected zone could be reduced significantly. At the second laser cut the focal point was lowered in relation to the material removal due to the first laser cut.

Also the delamination length of the first and last ply could be reduced by this process otimization.

For the finishing milling step a KUKA robot KR 300 together with a milling control and a milling end-effector provided by MAPAL GmbH is used. The milling step is necessary to remove the heat-affected zone resulting from laser processing. Here the main influencing factors for the cut quality are the geometry of the milling tool, the feed rate and the cutting speed which in turn depends on the rotational speed of the milling tool. Due to the high strength of the carbon fibers a PCD-tool is used. Good milling edge quality is achieved with a feed rate of 0,08 cm/s and a rotational speed of 10000 min^{-1}.

The efficiency of the above-described process depends on different factors. These factors include, for example, the current and anticipated array of products, the cost structure in production, developments on the sales market and so on. With appropriate framework conditions and an adaptation of the above-described prototype robot cell, cost savings in the final processing can be achieved.

2.6 Dustless assembly

Subsequent to the final processing step the assembly of different thermoplastic parts can take place.

Thermoplastic composites offer a great potential for using dustless and composite compatible joining technologies. Due to the meltability of thermoplastic polymers under elevated temperatures, thermoplastic welding technologies can be used for part assembly [20], [21].

Commonly used joining methods for fiber composites like riveting and bolting are dealing with fiber interruptions. They can be substituted by a welding process, generating an areal and closed high-strength connection with simultaneously high potential for automation [22]. In this case the material-compatible component and joining zone design maximizes the connection properties. Besides other advantages the abolition or reduction of bolts and rivets leads to a significant weight reduction. Furthermore the dustless joining offers the possibility of pre-equipping composite structures with systems. A decentralisation of system integration from the final assembly line to different panel pre-equipping work stations reduces the manufacturing bottleneck at the final assembly.

Welding of carbon fiber composites can accordingly be used during panel manufacturing to assemble skins with stringers, clips and frames as well as for closing a longitudinal or circumferential joint of a pre-equipped aircraft barrel. For these tasks different thermoplastic welding technologies have to be developed to ensure fast and reproducible assembly. In thermoplastic welding, automation is an enabler for the controlled and repeatable quality of the welding task. At the DLR, Institute for Structures and Design (BT) Stuttgart and Augsburg, scientists are working on the realization of different automation approaches for welding of thermoplastic composites. In this context, a promising technology at DLR is for example the electrical resistance welding of CF/PEEK clips onto a CF/PEEK plate (see Figure 10).

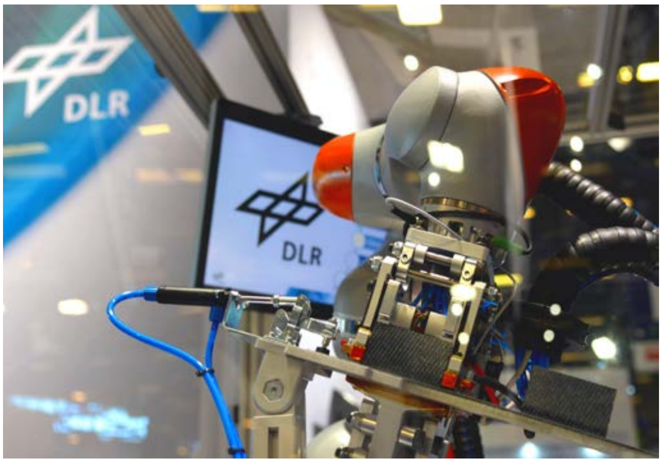


Figure 10: Automated and quality ensured resistance welding of a CF/PEEK clip onto a plate [23]

The state of the art stainless steel welding element developed by C. Freist [24] was modified. For applications in aviation a multifunctional end-effector could be used for process monitoring, automated gripping, positioning and clamping. As a result of these efforts we obtained an increase in reproducibility and accuracy of the welding process.

2.7 Quality assurance by air-coupled ultrasonic testing

Quality assurance accompanies the complete process chain. In this this subsection the inspection of large parts with inaccessible geometric boundary conditions by air-coupled ultrasonic testing (ACUT) is discussed.

Water-coupled ultrasonic testing (WCUT) has been part of quality assurance in aerospace and automotive industry for many years and high-end systems have been developed [25]. ACUT on the other hand is not applied to the same extent until today. However, facilities for transmission measurements exist in industry. For instance, Airbus Helicopters Germany, München has established a facility for ACUT in transmission only, in 2011 [26]. Reflection mode is available only on laboratory scale like at Stuttgart university, where it is used for fatigue monitoring of composite tubes [27]. From a physical point of view, one main reason for this is the much greater mismatch of acoustical impedances between air and trandsducer-/ specimen material compared to the usage of a liquid couplant. This leads to very low transmittance of ultrasound through such interfaces in the order of 0.01 % as compared to about 10 % in the case of WCUT. Other reasons for the widely spread usage of WCUT is the better resolution that can be achieved due to higher frequency (shorter wavelength) that is used and the phased array technique that is available.

However, ACUT does also have advantages: It is completely non-contact, so one does not have to care about flux of liquid couplant, contact pressure between transducers and the surface of the specimen, firm contact on uneven and rough surfaces as well as moisture on electronics and corrosion. One can also abstain from expensive infrastructure like immersion tanks, tubes, water conditioning and other preventive measures that have to be taken in order to secure the robotic system from water damage. Therefore the cost efficiency of ACUT is potentially superior.

There are two different modes for ACUT, through transmission and single-sided [28]. The pulse-echo mode is not possible since the echo is overlaid by the incoming pulse.

At DLR, the single-sided mode was implemented in order to inspect a 2.3 m long pressure vessel (see Figure 11 a). By slanted incidence of ultrasound, Lamb waves are excited in the laminate which can be detected on the same side they are excited from (see Figure 12 a). The Lamb wave's amplitude and time-of-flight is affected by flaws in the laminate which can thereby be detected. In the vessel laminate a porosity amount of 2 – 4 % was detected. Consequently an inspection by WCUT would be impossible due to the scattering of the short-wavelength which results in an unexaminable structure.

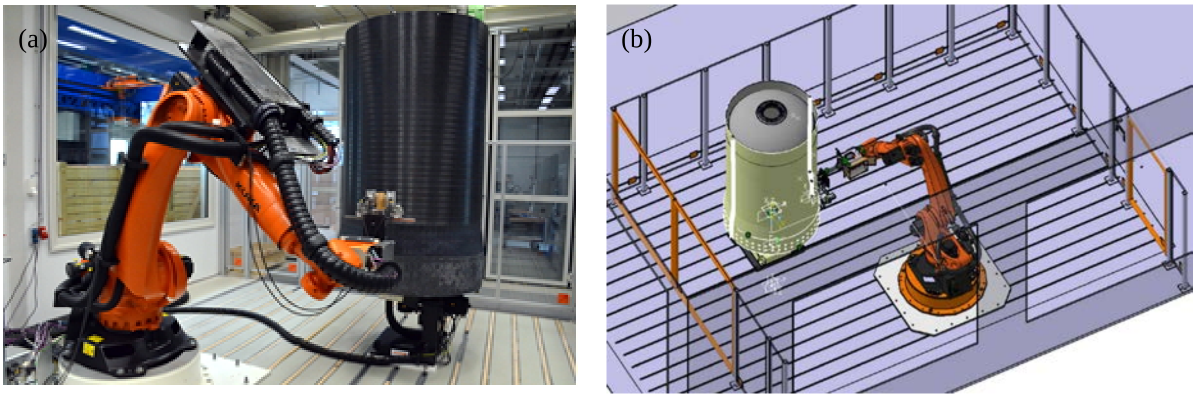


Figure 11: (a) Automated quality assurance of a pressure vessel (b) Offline programming of the inspection task in *DELMIA®*

The through transmission technology is currently only possible by using a C-frame. This inspection technique is not suitable for large specimens like fuselages due to interfering contours. Therefore the through transmission technology by cooperative robots will be part of ongoing work. Until this technology is ready the single-sided mode will be used for the inspection of the skin segment demonstrator.

For the ACUT quality assurance of the vessel a KUKA KR120 R2700 extra HA robot, possessing six axes and a particularly high repetition accuracy was used. The ultrasonic transducers were mounted on a special end-effector that allows reproducible adjustment of the excitation angle (see Figure 12 a). The ACUT device provides interfaces for integration and communication with the robot control unit. It can be triggered by the robot controlling unit path-equidistantly. This triggering is realized with a high pulse repetition frequency (PRF) up to 250 Hz. This means that the transducers send ultrasonic pulses on-the-fly, every 2 mm for instance, on the programmed path.

Offline programming (OLP) was performed using *FASTSURF®* in conjunction with *DELMIA®*

(see Figure 11 b). Thereby a 2 mm × 2 mm measurement grid on the pressure vessel was realized with a path velocity of 230 mm/s. By simultaneously monitoring the ultrasonic data together with its respective positions during the scanning procedure, three-dimensional C-scans mapping the geometry of the inspected body, could be obtained. The subsequent data processing and evaluation were performed using *MATLAB®*. Figure 12 b shows the result of result of a 64 kHz amplitude-C-scan of an automatically examined part.

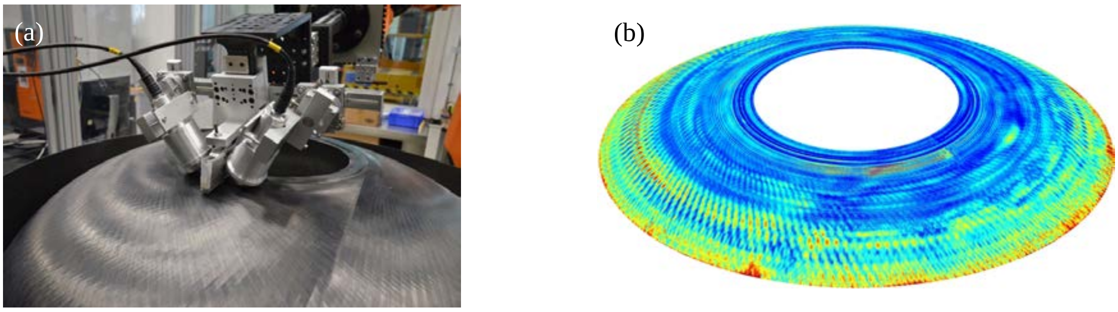


Figure 12: Measurement with a robot mounted ACUT end-effector (a) and resulting 3-D C-scan (b)

The single-sided ACUT quality assurance method shows high potential for the examination of large parts with complex geometries like aircraft skins or where only one-sided accessibility is possible.

3 CONCLUSIONS AND OUTLOOK

The complete process chain of a thermoplastic fuselage skin segment was investigated regarding its automatization and optimization potential. Along this chain several automated solutions has been established. An automated ply book generation and pick and place process for the preform was realized. Due to automation the preforming step can be done more efficient and also with a higher reproducibility. Therefore the production time and error sources can be reduced. Further research will be done by implementing a collision free path planning algorithm into the automated preforming process [29].

By the optimization of the vacuum bagging setup the preparation time as well as the total costs (by recycling parts of the auxiliary materials) was reduced.

With the combination of laser and milling an alternative final finishing process was demonstrated. With optimal process parameters good cutting edge quality can be achieved. However by processing complex geometries with extreme curvatures a large heat-affected zone was observed. Therefore the laser processing of complex geometries and its parameter optimization is ongoing work.

An automated dustless assembly step by an electric resistance welding process with integrated process monitoring was realized. In this way connections with reproducible quality can be achieved.

With the single-sided ACUT method a non-contact quality assurance method was tested on large composite parts by using a robot mounted end-effector. Therefore the single-sided mode may also be suitable for aircraft skin segments or other pre-equipped structural parts with only one-sided accessibility.

All open research and optimization issues will be addressed at another demonstrator with the size of a quarter shell.

It could be demonstrated that CFRTPs offer the possibility for automated and quality assured production for structural parts. By the consequent usage of the advantages of thermoplastic materials, like dustless assembly, this material class may be able to win the competition against established metal based technologies for structural components of short-range aircrafts.

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Thermoplastic composites provide real answers to remedy these limitations, as they are: thermoformable and heat-weldable: the thermoplastic material softens when the composite parts are heated. These can then be shaped or welded (a process easy to control, avoiding the use of adhesives).Â EliumÂ®: resilience of a composite, recyclability of a thermoplastic. To meet the challenge of thermoset composites that cannot be remelted or recycled, Arkema's R & D recently developed EliumÂ®, the only liquid thermoplastic resin on the market that can be processed in the same way as liquid thermoset resins with the same manufacturing processes: the parts obtained have mechanical properties identical to those of thermoset parts, with the added benefit of. Stelia Aerospace has developed a full-scale thermoplastic fuselage demonstrator to allow an internal evaluation of the use of high performance thermoplastics - as opposed to thermosets â€“ within a next generation single aisle aircraft. The demonstrator featured all the typical characteristics of a primary fuselage airframe those being thin skin, lightning protection, stringers and frames, to allow a detailed evaluation of these technologies in a true industrial environment. Stelia Aerospace has invested several millions in their Arches Box TP Research & Technology project (2015-2017) within In contrast with thermoplastics, thermosetting plastics (also referred to as thermosets) remain in a permanent solid state after curing. Polymers in thermosetting materials cross-link during a curing process that is induced by heat, light, or suitable radiation. This curing process forms an irreversible chemical bond.Â Cooling: The mold is slowly cooled while the mold remains in motion to ensure that the skin of the part does not sag or collapse before fully solidifying. Part removal: The part is separated from the mold, any flashing is trimmed away. Rotational molding requires less expensive tooling than other molding techniques as the process uses centrifugal force, not pressure, to fill the mold.