HOW COBOTS BUILD TAILORED BLANKS: MATERIALS AND PROCESS QUALIFICATION FOR ADVANCED THERMOPLASTIC COMPOSITES

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ABSTRACT

Advanced carbon fiber-reinforced thermoplastics offer a great potential for aerospace applications by efficient and customizable processing via pick-and-place preforming and oven vacuum consolidation. However, omitting autoclave cycles and press-formed blanks bears the risk to produce parts with an insufficient degree of consolidation.

In order to assure reliability a cobot-based test stand was developed to automatically produce customized laminate stacks of reproducible quality with defined ultrasonic spot welds. The laminates are subsequently vacuum consolidated in an oven and inspected by water-coupled ultrasonic testing. Material and process qualification was carried out with different prepreg and semipreg materials.

The DLR Center for Lightweight Production Technology (ZLP) in Augsburg will give insight into the challenges and current work.

1 INTRODUCTION

The structure of modern twin-aisle airplanes such as the Airbus A350 XWB primarily consists of carbon fiber reinforced plastics. High volume clips and cleats as connecting elements between skin and frames are made of advanced thermoplastics. They are produced of pre-consolidated blanks, so-called organo sheets that are cut and thermoformed. Approximately half the preconsolidated material, i.e. the cut-off is scrap which impairs the fly-to-buy ratio. In addition, the organo sheets are typically supplied with a defined laminate building sequence of constant thickness. Design freedom in term of local thickness variations of the blanks is thus not given. On the other hand large parts are typically produced via costly autoclave processing. Both these production routes barely exploit the potential for cost-effective processing of thermoplastic composites.

The Center for Lightweight Production Technology (ZLP) of the German Aerospace Center (DLR) aims for efficient and customizable production technologies combining pick-and-place preforming with oven vacuum consolidation. Thereby enhanced design freedom at reduced material and energy consumption may be achieved.

This work presents an automated test bench[1] for the preforming of laminate stacks that is based on a patented downholder end-effector[2] mounted to a KUKA LBR iiwa. This cobot meets the requirements for human machine interaction (HMI), where workers and robots share the same workspace. The gripper is both used for the pick-and-place handling and prevents ply warpage during storage in the ply magazine. Thus the cobot produces customized laminate stacks that are spot welded by ultrasound and subsequently vacuum consolidated to tailored blanks.

Special focus is laid on the process data assessment and the degree of consolidation after oven vacuum bag processing as a measure of process reliability. Material and process characterization serves to quickly assess the respective applicability. All value adding production steps from as-delivered material to consolidated part may thus be assessed.

2 STATE OF THE ART

2.1 Ultrasonic Spot Welding in Automated Preforming

Ultrasonic systems are readily used for automation and high-volume production [3]. Weiland has discussed the advantages of ultrasonic spot welding for binder-based preforming of carbon fiber-reinforced plastics (CFRP) [4]. Benatar and Gutowski significantly influenced and established this technology for carbon fiber-reinforced PEEK [5–7].

At ZLP ultrasonic spot welding is applied in preforming to locally melt thermoplastic matrices by mechanical vibrations and thus bond laminate layers to one another. Heat is generated by a combination of intermolecular and surface friction within the material [3]. The preform is locally compacted while pressure is applied through the vibrating horn. Within the heat-affected zone (HAZ) flowing polymer chains diffuse and entangle across the interface of neighboring plies [7]. The main process parameters are thus weld pressure, time, amplitude and frequency.

Since the thermal conductivity along the carbon fibers is high energy dissipates in the reinforcement direction. This may results in a lengthening of the welding time which can cause detrimental overheating of the laminate below the horn and a penetration of the horn into the part [8]. Using a horn with a rather large surface at comparably lower contact pressures is recommended to avoid disruption of the fiber architecture [9], [10].

Studies have been carried out to establish weld parameters and assess their impact on the performance of advanced thermoplastics [11], [12].

2.2 Vacuum Consolidation

Pick and place preforming of locally fixed thermoplastic prepreg stacks requires a final consolidation step at processing temperatures up to 400°C to produce a part or blank. However, advanced thermoplastics compared to thermosets have far higher viscosity and their composite UD-prepregs and woven semipregs can have high levels of intrinsic porosity, also depending on the respective impregnation technology.

Typically, autoclave processing in inert atmosphere and external pressure is used to produce high quality thermoplastic composites with low void content [13–15]. In order to reduce processing costs so-called Out-of-Autoclave (OoA) processes are increasingly investigated as an alternative route.

Vacuum consolidation of advanced thermoplastic composites without additional pressure was first reported by Kempe and established at the Institute of Structures and Design of the German Aerospace Center [16–18]. Especially APC-2[1] CF-PEEK was used to cost-effectively produce high quality blanks and large parts such as an airplane rudder [19], [20].

Certain efforts have been made to establish vacuum consolidation in furnaces (a.k.a. oven vacuum bag) for different thermoplastic composite materials [21–27]. The parts are placed on a single sided mold and sealed under a vacuum bag. In terms of design freedom this route offers enhanced flexibility for parts and blanks of varying (local) thicknesses and adaptable build-up sequence of laminates since unique tooling is not required.

However, the displacement of intrinsic air is most vital in any thermoplastic consolidation process [28]. Zhang *et al.* have proposed a void removal mechanism based on single intralayer diffusion of entrapped gas volatiles encapsulated in melt impregnated UD-tapes (Cytec APC-2 AS4/PEEK) followed by gas evacuation along the permeable interlayers formed by the rough surfaces of the thermoplastic prepreg layers toward the laminate edges [26].

[1] Aromatic Polymer Composite commercialized by ICI

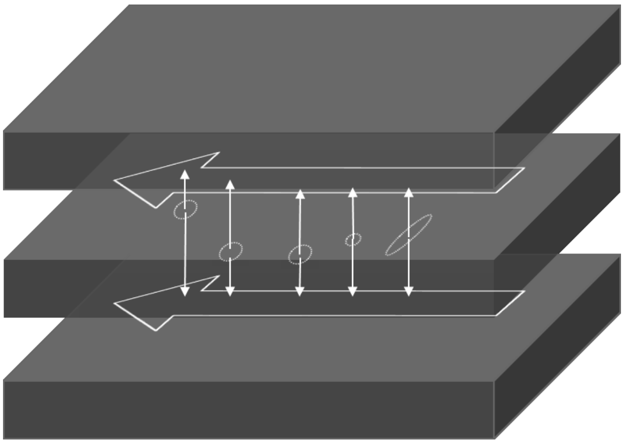

Figure 1: Schematic of void removal mechanisms [26]

2.3 Smart Automation

"*Most aerospace components are still laid-up by skilled labor, although considerable efforts are being made to automate or mechanize the process […]. Hand lay-up is very versatile because human hands make excellent grippers, eyes marvellous sensors, and the brain a powerful process control and quality control unit!*" [29]

Already in the 1995 the Institute of Robotics and Mechatronics of the German Aerospace Center (DLR) designed a small so-called lightweight robot (German: Leichtbauroboter, LBR) and conducted research on safety issues. Haddadin tackled one of the main challenges namely to allow human machine interaction or collaboration within the same shared workspace which, in terms of classical automation with common industry robots is usually ruled out [30]. In a joint approach KUKA then industrialized the DLR robot design and introduced the first LBR to the market in 2004. Within the framework of "Industrie 4.0" smart automation for mass-customization is often considered a basal necessity for the competitiveness of industrialized countries [31].

Aerospace industry in this sense is thus a prime example for the challenges of producing specifically designed products at rather small lot sizes. Even considering the high volume example of advanced thermoplastic composite usage in Aerospace, i.e. the thousands of clips and cleats within the structure of the A350 XWB, only roughly half are of identical design [32–35]. In addition, as high value industry performance and quality requirements simply have to be met. In this context, automation has always had convincing prospects in terms of reproducibility in production.

In this work, cobots are thus applied to fulfil the repetitive tasks of preforming laminate ensuring reproducibility. If need be the skilled worker is able to customize the stacking sequence and interfere should the process deviate from target.

3 EXPERIMENTAL SETUP

3.1 Cobot Test Bench

The cobot test bench was designed to produce laminate stacks for material processing qualification (see Figure 5). The basic requirements of the test bench are:

- Storage of pre-cut prepreg plies (305 mm x 305 mm | 635mm x 325 mm)
- Prevention of warpage of the impregnated plies
- Pick-and-place of single plies from the magazine to the vacuum plate
- Fixation of the laminate stack during the ultrasonic spot weld process

In order to meet these requirements the patented end-effector system is separated into the actual end-effector mounted to the robot and the downholder [1]. Function-integrated lightweight construction was employed to meet the limited load capacity of the KUKA iiwa 14 R820.

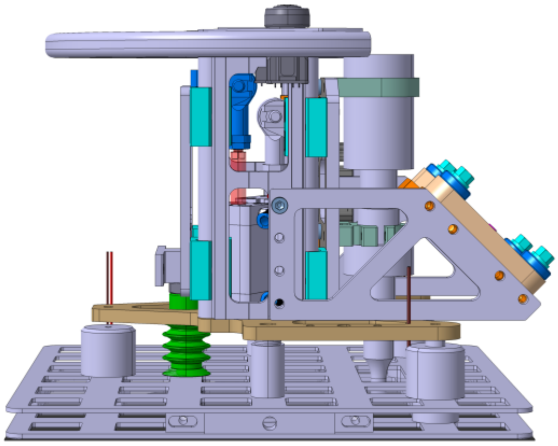

Figure 2: Side view of the downholder end-effector [21]

Apart from the fixation of the plies in the magazine and during the weld process the downholder also serves as gripping unit to move the plies. Vacuum is applied through channels within its glass fiber composite construction (see Figure 3). Thus the downholder ensures the correct positioning of each ply throughout the entire preforming process. Spot welding of the single plies to form locally fixed laminate stacks is realized by a lowerable sonotrode on a linear axis mounted to the end-effector. Accessibility of the sonotrode to the laminate is achieved by a pattern of quadratic cavities (25 mm x 25 mm) in the downholder. The downholder is connected to the end effector by permanent magnets, extended by electric coils to neutralize the magnetic effect and hence allow releasing.

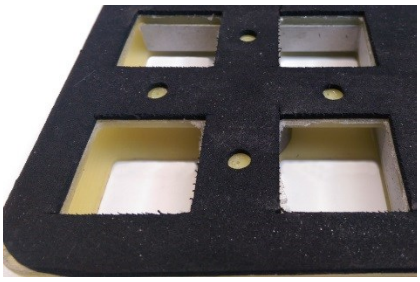

Figure 3: Foam rubber interface with perforation for the gripping of UD-prepregs

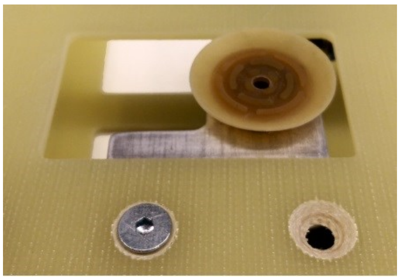

Figure 4: Vacuum cups grippers for semipregs with rougher surfaces

Fabric-reinforced semipregs have different handling requirements compared to UD prepregs. Especially solvent impregnated CF-PEI material with its rough surface and high inherent stiffness required a modification of the downholder gripping interface. Natural rubber vacuum cups (Schmalz SGP 24 NK-40 N016 [36]) with low shore hardness of 40 were chosen for air-tight form fitting to the rough surfaces (see Figure 4). An additional downholder was designed for the production of larger semipreg laminates.

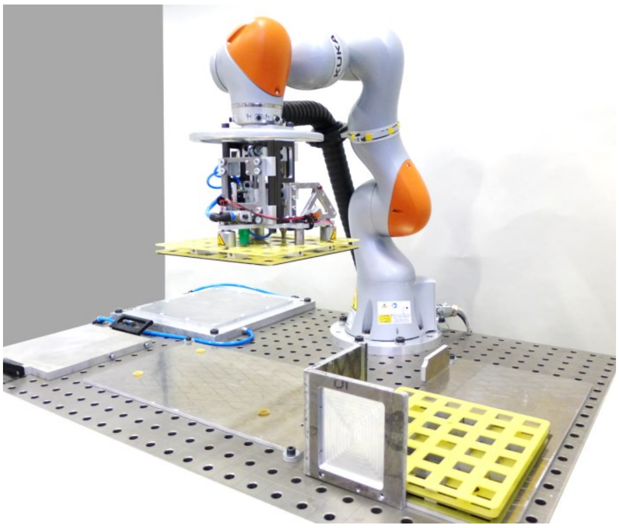

Figure 5: Cobot-based automated preforming with the down holder end-effector

3.2 Sample Preparation

A main goal of the investigation was to probe the applicability of vacuum consolidation for different prepreg materials.

305 mm by 305 mm cross-ply laminate stacks of 14 UD-prepreg layers (TenCate TC1200 PEEK AS-4 [37] as well as 635 mm by 325 mm TenCate Cetex TC1000 Premium CF-PEI of 6 ±45° layers were produced.

The laminates were welded with a titanium stepped horns of 10 mm diameter. A Branson ultrasonic welder of type DCX S 40:0.8 H 40 kHz power supply with a titan solid mount gold booster was used.

Branson's amplitude reference guide [38] recommends an amplitude range for PEI from 42 – 60 µm and for PEEK 42 – 72 µm. The amplitude can be calculated by multiplying the converter output with the booster and horn gain along with a setup value between 10-100 %, which in the case of a 40 kHz converter (with 8 µm) and a setup value of 100% yields:

$$A = 8\,\mu\text{m} \times 1.5 \times 5 \times 1 = 60\,\mu\text{m}$$

In order to optimize the processing parameters for the vacuum consolidation CF-PEI laminates were heat treated at different dwell times and temperatures according to a face-centered cubic design of experiment (DOE). Three different levels of applied temperature (310°C, 330°C, and 350°C) and dwell time (5min, 22.5 min, 40min) were used to investigate the degree of consolidation.

Figure 6 shows the bagging setup for vacuum consolidation. A polyimide separation film (UPILEX-125S) coated with release agent (MIKON 705) is set atop and below the laminate. A desized glass filament fabric (FAW = 200 g/m²) covers the separated part. Metal caul sheets that provide uniform surface finish are covered with glass fabric (FAW = 300 g/m²). The outer polyimide vacuum foil (KAPTON 200HN) is fixed to the tooling with high temperature silicone sealant tape (A-800-3G). Glass fabric tape (FAW>1000g/m²) is applied as edge breather around the laminate. The vacuum bag is connected to the rotary vane pump outside the furnace via corrugated metal hoses.

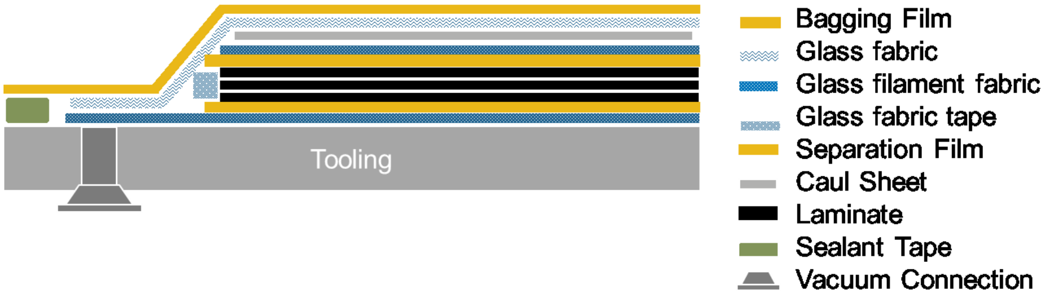

Figure 6: Vacuum bag setup for the consolidation of CF-PEI semipreg

In addition, a resource-optimized vacuum bag setup was probed for the consolidation of CF-PEEK UD-Tapes (see Figure 7). The glass fabric tape edge breather (FAW > 1100 g/m²) was replaced by a stainless steel metal wire mesh. The incompressible 2 mm thick mesh has a porosity of 60 % and an effective cross section of 3.6 mm²/cm at the cutting edges with low drag to improve air flow. Atop the separation film a non-woven fiberglass breather (AIRWEAVE UHT 800) allows good transition between the laminate and vacuum film at any given radius so that no wrinkles in the vacuum film are imprinted on the part surface.

CF-PEEK prepregs were heat treated at temperatures above 380°C for 35min.

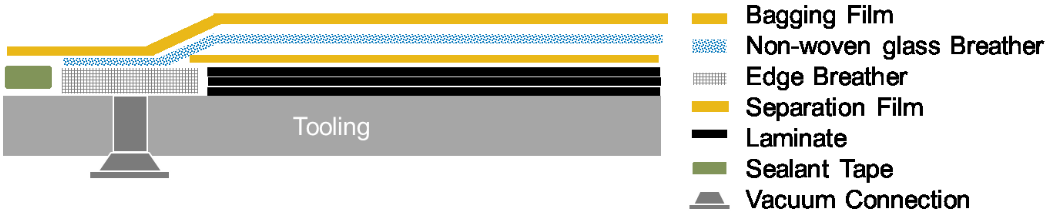

Figure 7: Resource-optimized vacuum bag setup for the consolidation of UD-Tapes

All laminates were vacuum consolidated in a Nabertherm N1500/45HA oven that fulfils AMS 2750 E. The process parameters were measured during the oven process for in-line process monitoring.

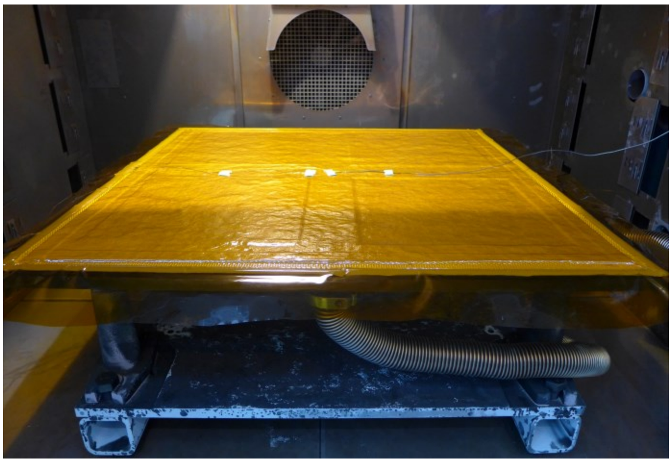

Figure 8: Vacuum consolidation setup in the furnace

3.3 Quality Assessment

The degree of consolidation of the organo sheets was characterized by water-coupled ultrasonic testing (WCUT) using the pulse-echo method. An Olympus Omni Scan MX2 with a phased array module (OMNI-P-PA32:128), a 5MHz PA-probe with 64 elements (5L64-NW1), a wedge (SNW1) and a 2-axis encoding manual scanner (GLIDER 36 × 36) were used for the measurements.

4 RESULTS

4.1 Vacuum Consolidation

CF-PEI

Figure 9 illustrates a representative pressure and temperature profile during the vacuum consolidation for CF-PEI. Thermocouples were placed in the top, middle and bottom of the laminate (marked in grey lines). The furnace temperature was regulated by the charge temperature sensor on top of the vacuum bag (yellow triangles). The pressure is measured at the vacuum pump inlet and depicted as grey circle scatter diagram. Above the glass transition temperature of CF-PEI (T_g = 217°C) the temperature gradient decreases until the processing temperature is reached.

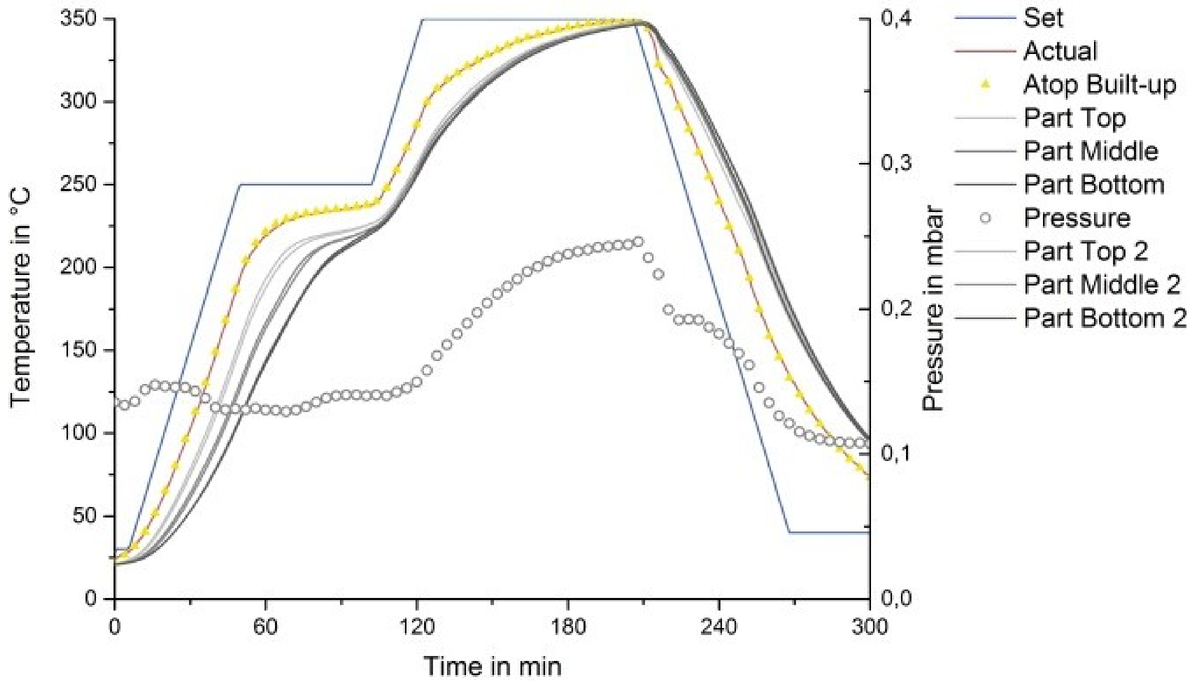

Figure 9: Temperature and pressure profile of a CF/PEI laminate during vacuum consolidation

Table 1 lists the measured process parameters, i.e. temperature, dwell time, and pressure for the produced CF-PEI laminates. In contrast to temperature and time that are regulated by the furnace, pressure is an uncontrollable factor. The vacuum level is primarily relevant during the consolidation phase, i.e. above the glass transition temperature of PEI. Only above this temperature the pressure during the vacuum consolidation was evaluated (p_{avg}). In addition to the pressure measurement during the consolidation, the leak tightness before (p_{pre}) and after (p_{post}) the oven process was recorded by measuring the pressure increase 60 seconds after the vacuum pump is switched off. The higher the pressure increase after this period of time the higher the leakage current thus indicating low leak tightness.

Label	T_{set} °C	t min	p_{avg} mbar	p_{pre} mbar	p_{post} mbar
VK_PEI_#1	310	5	0.16	9.1	13.0
VK_PEI_#2	310	22.5	-	9.1	8.2
VK_PEI_#3	310	40	0.16	16.0	7.9
VK_PEI_#4	330	5	0.16	6.4	16.0
VK_PEI_#5	330	22.5	0.53	6.5	170
VK_PEI_#6	330	40	0.20	7.1	7.6
VK_PEI_#7	350	5	0.21	7.3	7.9
VK_PEI_#8	350	22.5	0.19	7.1	5.8
VK_PEI_#9	350	40	0.10	0.6	1.5

Table 1: Process parameters for the vacuum consolidated CF-PEI laminates [24]

CF-PEEK

Figure 12 shows the pressure and temperature profile during the vacuum consolidation for CF-PEEK UD cross-ply laminates. The furnace temperature was regulated by the charge sensor atop the vacuum bag (yellow triangles). Above the melt temperature of CF-PEEK (T_m ~ 343°C) the temperature gradient over part thickness decreases (grey lines). The laminates are consolidated at temperatures above 380°C for 35min. In accordance with Cogswell [39] a drying step of the laminate stack was carried out at 150°C furnace temperature for 30 min. No greater change of the pressure levels during the drying step is measured. Once furnace temperatures of 240°C and part temperatures of 200°C are reached the pressure rises to about 0.2 mbar. The surface is rougher compared to samples consolidated with caul sheets.

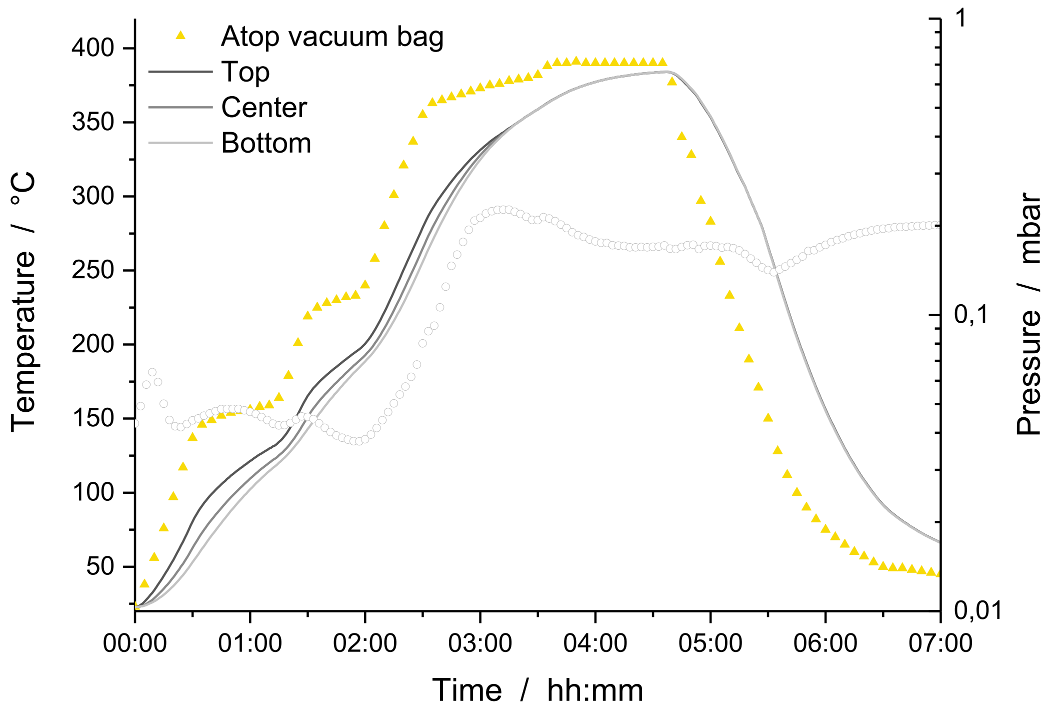

Figure 10: Temperature and pressure profile of a CF-PEEK laminate during vacuum consolidation

Figure 12 indicates the pressure rise during the leak test after the vacuum source has been turned off, both prior and after the vacuum consolidation. After consolidation the pressure rises from 0.2 mbar to 9.3 mbar within the first minute. The dashed line indicates a pressure rise of 5 mbar within the first minute which serves as process quality requirement. The leak tightness is obviously weakened during consolidation.

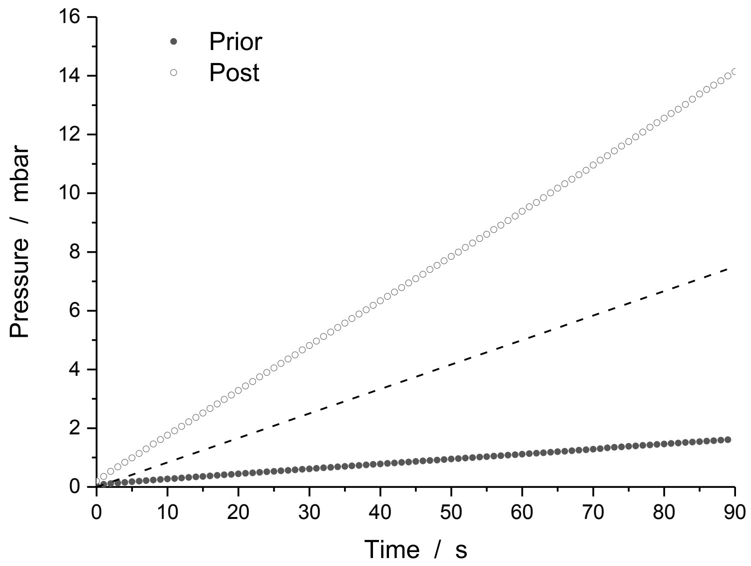

Figure 11: Pressure rise during leak test

4.2 Consolidation Quality

Finally the organo sheets were tested via water-coupled ultrasonic testing (WCUT). The measurement yields a colored C-Scan picture of the back-wall echo attenuation. Blue colors indicate echo amplitudes below 50%. Between yellow and red the amplitude lies within 50% to 100%, showing the areas with back-wall echo attenuation lower than 6 dB. These areas are considered to be of sufficient quality according to the AITM 6-4005 test method [40].

CF-PEI

Each produced blank is labelled according to
Table 1 along with the area percentage of sufficient back-wall echo above 50 %. The consolidation quality as measured by WCUT was found to be insufficient for CF-PEI prepregs. Figure 12 illustrates the WCUT measurements for CF-PEI organo sheets at different levels of dwell time and temperature. Despite increasing temperature and time the area percentage of sufficiently good consolidation reached a plateau at approximately 37%. Merely the consolidation quality near the laminate edges was improved with increasing temperature. Up to five centimeters from the edges were affected by the improvement, while an oval area within the center remained comparable constant. The resulting absence of back-wall echo indicates insufficient void removal from the center area. Additional thickness measurements showed a correlation between back-wall echo and the organo sheet thickness. The well consolidated areas were thinner compared to areas of insufficient quality. In contrast to temperature, an increase in dwell time yielded little or no significant improvement of the consolidation quality.

Organo sheets with higher pressure levels and reduced vacuum tightness (
Table 1) such as sample PEI_#5 show higher back-wall echo attenuations (Figure 12).

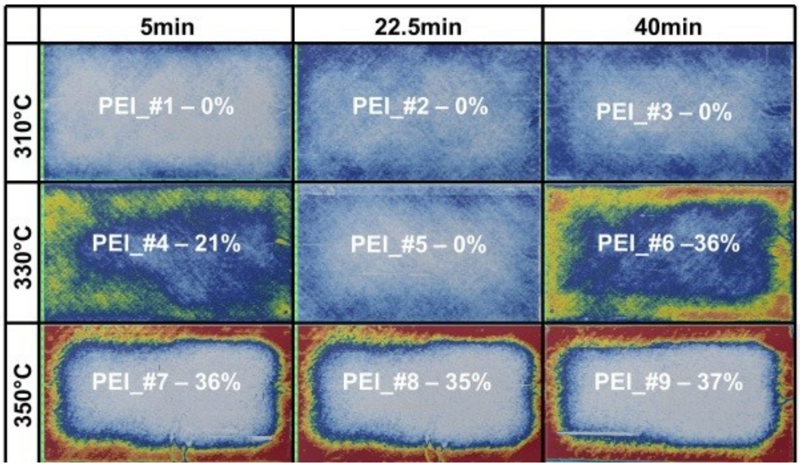

Figure 12: C-Scan of the back-wall echo attenuation for CF-PEI at different design points. [28]

CF-PEEK

Figure 13 shows the WCUT measurement of a CF-PEEK cross-ply laminate. Areas of insufficient consolidation quality (blue) alternate with sufficiently good consolidated areas (orange and red).

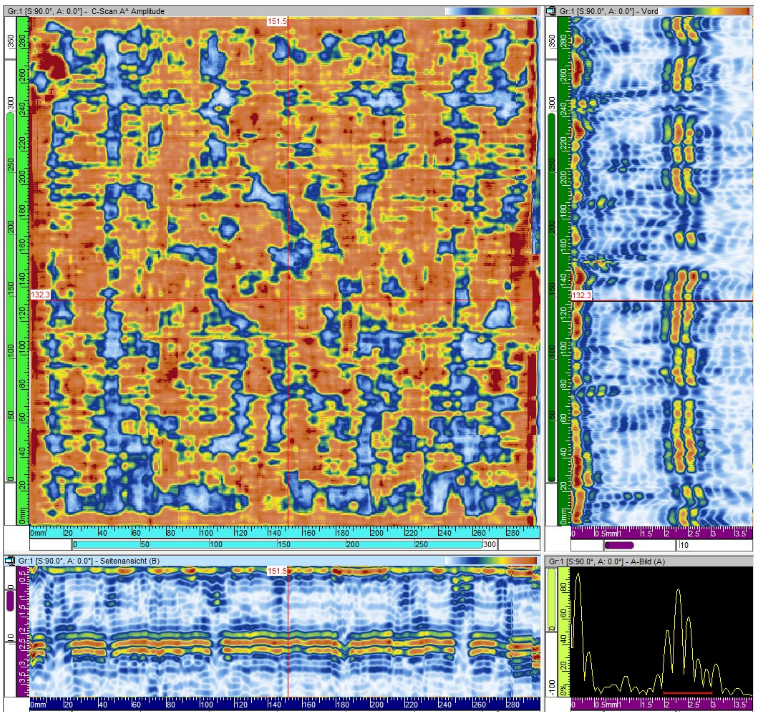

Figure 13: WCUT A-, B-, C-Scan and D-Scan of a CF-PEEK UD laminate

5 DISCUSSION

Solution impregnated semipregs like CF-PEI typically show bubbles at the surface where the solvent evaporates. Voids exist between the warp and weft where impregnation with polymer is reduced. [41]

Design of experiment was used to evaluate different levels of dwell time and temperature to define processing parameters that render samples of minimized void content. The WCUT results served as an input parameter for the evaluation and revealed that a temperature increase impacts the close-to-the-edge back-wall echo approximately linear and over eight times higher as an increased dwell time [28]. This results from the sharp reduction of melt viscosity of PEI at higher temperatures [42] allowing quick autohesion between neighboring plies with intimate contact at the edges. However, after the edges are sealed no further improvement in consolidation quality is reached. With the edges sealed volatile removal of trapped air becomes a diffusion driven process. According to the impregnation model of Hou *et al*. a pressure of 2 MPa is required to provide void contents below 0.5% [43]. Consequently, only pre-consolidation of CF/PEI appears to be achievable via vacuum consolidation [24], [25].

Compared to the CF-PEI samples the difference in consolidation between center area and border is less pronounced. Void volatile removal is not yet sufficiently realized.

The measured leakage currents vary between 0.6 to 16 mbar indicating difficulties in achieving reproducible vacuum tightness. Sources for leakages are manifold such as leaks within the vacuum connection, perforation of the vacuum bag or weakened tack of the sealant tape due to contaminations. Most of these sources of error can be minimized or eliminated prior to consolidation. However, during the oven cycle an oxidation process of the sealant tape occurs partially leading to cracks and in consequence to low leak tightness. Organo sheets with significant higher post pressures (e.g. PEI_#5) showed approximately three times higher average pressure values during the vacuum consolidation and reduced consolidation quality. The average vacuum level measured during the heat cycle with a sensor close to the pump are always comparably low and only allow limited deduction on the leak tightness.

As a consequence, a quality requirement of 5 mbar/min was defined for future vacuum bagging configurations.

6 CONCLUSION AND OUTLOOK

A cobot test stand was setup to produce laminates of reproducible quality for materials processing qualification of various carbon fiber-reinforced thermoplastic materials. The test stand with downholder end-effector automatically stacks plies and fuses them by ultrasonic spot welding. The weld parameters can be monitored and adapted depending on the respective materials.

The laminates were then heat treated in an oven vacuum consolidation process. In addition to in-line process monitoring, the consolidated blank quality is assessed by water-coupled ultrasound (WCUT).

It was found that this OoA-technology without additional external pressure strongly depends on the vacuum tightness of the vacuum setup. Degradation of sealant tape may impair part quality.

Certain materials such as CF-PEI semipreg appear to only allow pre-consolidated via this route and require final pressurized consolidation.

CF-PEEK UD-Tape were vacuum consolidated with a resource optimized vacuum bag setup allowing a partial reutilization of breather auxiliaries and faster handling times. The general utilization could be shown. However, the achievable consolidation quality may still be improved.

Currently CF-PEKK UD-Material from Toho Tenax is being investigated concerning its applicability for future aircraft fuselage applications [44]. At reduced processing temperatures the degradation of auxiliaries may be positively influenced. In addition, a sealant tape especially designed for high temperature oven processes will be tested.

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REFERENCES

[1] M. Engelschall, P. Gänswürger, and F. Fischer, "Entwicklung und Konstruktion eines MMI-Endeffektors zur automatisierten Lagenpaketerstellung thermoplastischer Faserverbundwerkstoffe," Deutsches Zentrum für Luft- und Raumfahrt (DLR).

[2] M. Schönheits, A. Schuster, P. Gänswürger, F. Fischer, and M. Beyrle, "Niederhalter, Effektor und Verfahren zum Herstellen eines Lagenaufbaus aus flächigen thermoplastischen Faser-Matrix-Halbzeug-Lagen," U.S. Patent 10 2015 116 302.0.

[3] A. Yousefpour, M. Hojjati, and J.-P. Immarigeon, "Fusion Bonding/Welding of Thermoplastic Composites," *Journal of Thermoplastic Composite Materials*, vol. 17, no. 4, pp. 303–341, Jul. 2004.

[4] F. Weiland, "Ultraschall-Preformmontage zur Herstellung von CFK-Luftfahrtstrukturen," Institut für Verbundwerkstoffe, 2012.

[5] A. Benatar, "Ultrasonic Welding of Advanced Thermoplastic Composites," Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, 1987.

[6] A. Benatar and T. G. Gutowski, "Methods for fusion bonding thermoplastic composites," in *Composites*, 1986, vol. 18, no. 1, pp. 35–42.

[7] A. Benatar and T. G. Gutowski, "Ultrasonic welding of PEEK graphite APC-2 composites," *Polymer Engineering and Science*, vol. 29, no. 23, pp. 1705–1721, Dec. 1989.

[8] C. Ageorges and L. Ye, *Fusion Bonding of Polymer Composites: from basic mechanisms to process optimisation*, 1st ed. Springer London, 2002.

[9] S. S. Volkov and Y. V. Kholopov, "Technology and equipment for ultrasonic welding of polymer based composite structures," vol. 28, pp. 145–155, 1998.

[10] S. S. Volkov and Y. V. Kholopov, "Technology and equipment for ultrasound welding structures made of polymer-based composite materials," *Welding International*, vol. 12, no. 5, pp. 400–403, Jan. 1998.

[11] J. Dorsch, M. Kühnel, and F. Fischer, "Experimentelle Ermittlung der Prozessparameter zum automatisierten Ultraschall-Heften von Carbonfaserverstärkten Thermoplast-Lagen," Deutsches Zentrum für Luft- und Raumfahrt (DLR), 435-2013/32, Sep. 2013.

[12] Y. Mezakeu Tongnan and F. J. C. Fischer, "Untersuchung zum Einfluss von Ultraschallheftstellen beim Preforming auf die Organoblechqualität carbonfaserverstärkter Hochleistungsthermoplaste," Deutsches Zentrum für Luft- und Raumfahrt (DLR), Augsburg, Germany, DLR-IB-BT-AU-2016-75, Apr. 2016.

[13] A. Lystrup and T. L. Andersen, "Autoclave consolidation of fibre composites with a high temperature thermoplastic matrix," *Journal of Materials Processing Technology*, vol. 77, no. 1–3, pp. 80–85, May 1998.

[14] I. Fernández, F. Blas, and M. Frövel, "Autoclave forming of thermoplastic composite parts," *Journal of Materials Processing Technology*, vol. 143–144, pp. 266–269, Dec. 2003.

[15] J. Denault and M. Dumouchel, *Advanced Performance Materials*, vol. 5, no. 1/2, pp. 83–96, 1998.

[16] G. Kempe, "Duroplastische und Thermoplastische Faserverbundwerkstoffe - Vorteile - Eigenschaften - Verarbeitung und Anwendungsgebiete beider Werkstoffgruppen," in *Faserverbundwerkstoffe mit thermoplastischer Matrix*, vol. 529, W. J. Bartz and E. Wippler, Eds. Renningen, Germany: Expert-Verlag, 1997, pp. 44–74.

[17] G. Kempe and H. Krauss, "Manufacturing Processes and Molding of Fiber-reinforced Polyetheretherketone (PEEK)," in *ICAS PROCEEDINGS 1986*, 1986, no. ICAS-86–4.6.1.

[18] G. Kempe and N. Bürkle, "Economic Manufacturing Techniques for Continuous Fibre-Reinforced Thermoplastics in Aircraft and Automotive Applications," in *Advanced Technology for Design and Fabrication of Composite Materials and Structures: Applications to the Automotive, Marine, Aerospace and Construction Industry*, G. C. Sih, A. Carpinteri, and G. Surace, Eds. Dordrecht: Springer Netherlands, 1995, pp. 349–363.
[19] G. Kempe and L. Häberle, "Vacuum Consolidation Technique As a Cost Effective Manufacturing Technology for Continuous Fibre Reinforced Thermoplastics," in *International Workshop on Thermoplastic Matrix Composites*, 2003.
[20] M. Feiler, W. Dudenhausen, L. Häberle, and G. Kempe, "A new vacuum consolidation technique for cost effective production of a thermoplast CFRP rudder," in *18th Technical Conference of the American Society for Composites*, 2003.
[21] F. Fischer, Y. Mezakeu Tongnan, M. Beyrle, T. Gerngross, and M. Kupke, "Characterization of Production-induced Defects in Carbon Fiber Reinforced Thermoplastic Technology," in *7th International Symposium on NDT in Aerospace*, 2015, no. BB 156.
[22] R. Jarczyk, L. Meis, T. Neitzel, K. Edelmann, and A. Miaris, "Forming the Future: Structural Applications for Fibre Reinforced Thermoplastics in Next Generation Airframes," in *Proceedings of the 17th European Conference on Composite Materials ECCM 17*, 2016.
[23] D. Zhang, D. Heider, S. G. Advani, and J. John W. Gillespie, "Out of Autoclave Consolidation of Voids in Continuous Fiber Reinforced Thermoplastic Composites," in *SAMPE 2013*, 2013.
[24] T. Stefani and F. Fischer, "Process Evaluation of the Automated Production of Thermoplastic Organo Sheets," Deutsches Zentrum für Luft- und Raumfahrt.
[25] F. Fischer, M. Beyrle, A.-H. Thellmann, M. Endrass, T. Stefani, T. Gerngross, and M. Kupke, "Corrugated Composites: Production-Integrated Quality Assurance in Carbon Fiber Reinforced Thermoplastic Sine Wave Beam Production," *Advanced Manufacturing: Polymer and Composites Science*, 2017.
[26] D. Zhang, D. Heider, and J. John W Gillespie, "Void Reduction of High-performance Thermoplastic Composites Via Oven Vacuum Bag Processing," *Journal of Composite Materials*, Mar. 2017.
[27] D. Zhang, D. Heider, and J. John W. Gillespie, "Volatile Removal during Out of Autoclave Processing of High Performance Thermoplastic Composites.," in *CAMX - 2014*, 2014.
[28] J. B. Cattanach and F. N. Cogswell, "Processing with Aromatic Polymer Composites," in *Developments in Reinforced Plastics—5*, Springer Netherlands, 1986, pp. 1–38.
[29] A. A. Baker, S. Dutton, and D. Kelly, *Composite Materials for Aircraft Structures, Second Edition*. AIAA, 2005.
[30] S. Haddadin, "Towards Safe Robots: Approaching Asimov's 1st Law," RWTH Aachen, 2011.
[31] B. für Bildung und Forschung (BMBF), "Industrie 4.0 - Innovationen für die Produktion von morgen." Bundesministerium für Bildung und Forschung (BMBF), Referat Forschung für Produktion, Dienstleistung und Arbeit, 53170 Bonn, Apr-2014.
[32] K. Edelmann, A. Miaris, M. Ulrich, T. Neitzel, and T. Frese, "Thermoplastische Bauteile entstehen im Minutentakt," in *Fachtagung Carbon Composites*, 2014.
[33] A. Deterts, A. Miaris, and G. Soehner, "Serial Production of Thermoplastic CFRP Parts for the Airbus A350 XWB," in *ITHEC 2012*, 2012, pp. 29–30.
[34] A. Miaris, K. Edelmann, and M. von Hayek Boelingen, "A350 XWB: Thousands of thermoplastic composite parts in an FRP aircraft," in *SAMPE 2014*, 2014.
[35] A. Miaris, K. Edelmann, and S. Sperling, "Thermoplastic Matrix Composites: Xtra complex, Xtra Quick, Xtra Efficient Manufacturing advanced composites for the A350 XWB and beyond," in *20th International Conference on Composite Materials*, 2015.
[36] Schmalz, "Flat suction cup (round) SGP 24 NK-40 N016," 2017.
[37] TenCate, "Technical Data TenCate Cetex TC1200 PEEK Resin System, 2014." Jul-2015.
[38] B. U. Corporation, "Technolog TL-2: Amplitude Reference Guide." Branson Ultrasonics Corporation, 2013.
[39] F. N. Cogswell, *Thermoplastic Aromatic Polymer Composites: a study of the structure, processing, and properties of carbon fibre reinforced polyetheretherketone and related materials*. Butterworth-Heinemann, 1992, pp. 1–10.

[40] AIRBUS, "Ultrasonic pulse-echo inspection of carbon fibre plastics," Airbus S.A.S Engineering Directorate, Blagnac, France, AITM6-4005, 2011.
[41] M. Neitzel, P. Mitschang, and U. Breuer, Eds., *Handbuch Verbundwerkstoffe*. Carl Hanser Verlag GmbH & Co. KG, 2014, pp. I–XXI.
[42] H. P. Zepf, *Faserverbundwerkstoffe mit thermoplastischer Matrix*. Expert-Verlag, 1997.
[43] M. Hou, L. Ye, H. J. Lee, and Y. W. Mai, "Manufacture of a carbon-fabric-reinforced polyetherimide (CF/PEI) composite material," *Composites Science and Technology*, vol. 58, no. 2, pp. 181–190, Jan. 1998.
[44] M. Beyrle, F. J. C. Fischer, C. Frommel, A.-H. Thellmann, T. Stefani, M. Kühnel, A. Schuster, P. Dreher, R. Glück, T. Gerngross, and M. Kupke, "Tailor-made Thermoplastics: Production Technology and Quality Assurance of a Thermoplastic Aircraft Fuselage Skin Segment," in *21st International Conference on Composite Materials*, 2017.