SAFE AND SOUND THERMOPLASTICS: QUALITY ASSURED ULTRASONIC WELDING IN FUSELAGE SKIN PRODUCTION

Frederic J.C. Fischer[1], Alfons Schuster[1], Mark Willmeroth[1], Roland Glück[1], Manuel Engelschall[1], Lars Larsen[1] and Michael Kupke[1]

[1]Institute of Structures and Design (BT), Center for Lightweight Production Technology (ZLP),
German Aerospace Center (DLR), Am Technologiezentrum 4, Augsburg, Germany
Email: frederic.fischer@dlr.de, Web Page: http://www.dlr.de/bt

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Abstract

Future single-aisle commercial aircrafts are considered to be produced of advanced thermoplastic composites. To this end flexible yet fully-automated production technologies are required in order to assure quick ramp-up, high production rates but also customization of high quality parts.

At the Center for Lightweight Production Technology (ZLP) fully-automated patch-preforming has been established for individualized lay-up of variable ply books, such as of a fuselage skin. Ultrasonic spot welding is used to weld each cutpiece to the subjacent stack. In this study, we shall describe the routine for weld parameter determination and monitoring. In-line quality assurance to minimize production variabilities along the process chain is a self-evident requirement that is pursued in a consequent manner.

1. Introduction

Carbon fiber-reinforced thermoplastics (CFRTPs) are a promising candidate for future single-aisle aircrafts components. In order to compete with low-cost metal based solutions highly effective and flexible production technologies are required. With automated production of high-performance thermoplastic structures one may exploit the material properties as well as the benefits of weldability.

These days, high volume thermoplastic composite parts such as the Airbus' A350 clips are produced of pre-consolidation blanks, so-called organo sheets that are cut and thermoformed in a hot press. Premium AEROTEC, together with the Institute for Composite Materials (IVW) and the DLR Center for Lightweight Production Technology (ZLP) in Augsburg recently demonstrated the applicability of hot press molding and resistance welding for the production of a thermoplastic rear pressure bulkhead for the A320 family at ILA in Berlin [1], [2]. It should be noted, that the degree of producible geometries by molding is limited by the size of the available hot press and the nature of the fiber-reinforcement, with the use of UD-tapes being limited by their negligible drapability.

Larger parts, such as fuselage panels have been demonstrated, e.g., by Fokker (TAPAS 2) and Stelia (Arches Box TP) by thermoplastic automated fiber placement (AFP). Often, AFP parts still require additional final consolidation, in an autoclave or an oven.[3–5]

Both these production routes only partially exploit the potential for flexible, yet cost-effective processing of thermoplastic composites.

At ZLP an entire process chain for thermoplastic composites from as-delivered material to part assembly has been setup, with an integrated production line in aerospace industry relevant environment (e.g. [6]). An efficient and customizable production process combining pick-and-place patch preforming with oven vacuum consolidation has been developed which provides enhanced design freedom as net-shape local reinforcements can be easily added in this single-side tooling approach.

In this context, ultrasonic welding for ply fixation is a crucial step during patch preforming. The respective processing pressures and induced energies should ideally be limited in order to prevent detrimental down-stream effects, e.g., by irreversible disruption of the fiber architecture for instance by too strong local compaction under squeeze flow.

Ultrasonic welding offers the possibility of in situ process monitoring, allowing process optimization by quality assessment [7], [8]. Thus, in this work, special focus is laid on advanced process data acquisition as a measure of improving the overall process reliability.

2. Experimental

2.1 Use-Case

An aircraft skin segment with typical single-aisle radii within the cylindrical section was chosen as use-case (see
Figure **1**). The laminate lay-up was adapted from the all-composite Airbus twin-aisle design of the A350. Toward the window cut-out the thickness increases from 2.2 mm to 5.6 mm with the applied 12 K material. The segment has a length of 950 mm and a width of 600 mm.

The thermoplastic composite material used in this work was 12inch wide UD-tape, more precisely carbon fiber-reinforced CF/PEKK from Toho Tenax (Tenax® -E TPUD PEKK-HTS45).

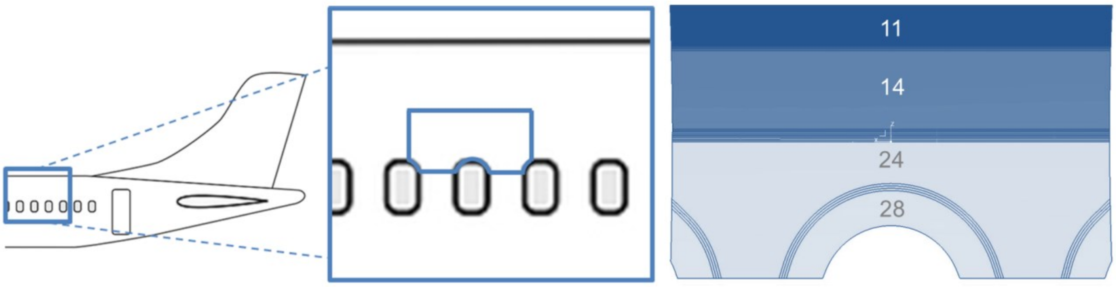

Figure 1. Fuselage skin segment with increasing laminate thickness toward the window cut-out

2.2 Automated Preforming

In patch preforming net-shape individual cut pieces are gripped, then transferred and stacked in the curved mold (see Figure 2). Developed by Schuster [9], a fully-automated camera-based ply detection hereby tracks and places the single cut pieces according to the defined ply book's lay-down order.

As a core feature of this system, all robot motions are generated automatically depending on the particular cut-piece position and orientation. An external MES (Manufacturing Execution System) passes both the coordinates for gripping and for dropping to the robot main program. Thus comparalbly complex ply books may be laid without efforts for robotic programming. For the preforming of UD-tapes this process is applicable for rather low draping rates. [10]

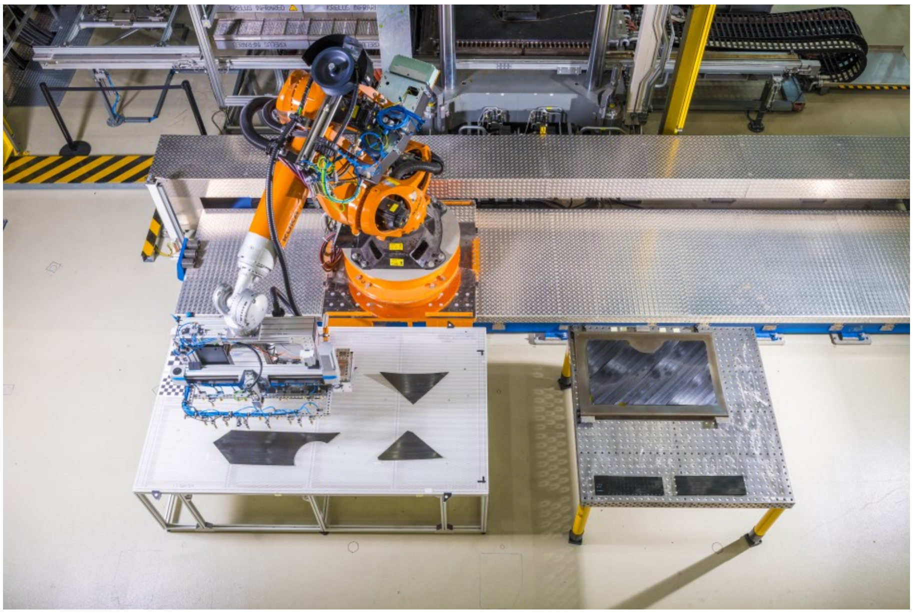

Figure 2. Automated patch-preforming of a fuselage skin demonstrator with individual cut pieces placed on a table (left) and placed within a curved mold (right) in the integrated work-cell for thermoplastic composite production at ZLP (top view)

The end-effector mounted to an industrial robot (KUKA KR210 R3100 Ultra F) is equipped with a standard vacuum generation and distribution system and the ultrasonic weld unit (BRANSON DCX S 40:0.8 H) which can be moved along a linear axis and lowered pneumatically, in order to fix each ply with at least two weld spots.

By default, the ultrasonic weld generator is controlled by the set parameter on-time. In an earlier trial it was found that the transmitted power values strongly vary over time and from layer to layer with great impact on the respective energy levels transferred. On-time as an input parameter for reproducible welding is thus insufficient.

The generator allows recording of the weld parameters in 1 ms increments and transfer of the log-file via a browser based interface. For an energy control, however, this interface is too slow and is only serves for subsequent data analysis. Instead, for energy regulation, the actual power values as analog signal were recorded by the robot control (KRC) and multiplied over 12 ms increments (sometimes prolonged up to 36 ms due to jitter) and summed in situ.

The pick-and-place routine is sustained until all plies are placed on their predefined positions. The resulting preform of spot-welded layers is then oven vacuum consolidated, i.e. processed out-of-autoclave, according to the processing recommendations of the material supplier.

Fully automated, various data including robot positioning, vacuum levels (indicating a leak tight contact between gripper and cut piece) and weld parameters are collected from all devices via OPC UA and stored in a time series management system (Kisters' Big Data – KiBiD) for further analysis and process improvement.

The near real time surveillance of the acquired data on a visualization and analytics platform enables predictive maintenance of critical system parts and a short response time on process interactions. Automated analysis tools allow an easy and quick data evaluation and post processing.

3. Results

For the automated preforming of the CF/PEKK fuselage skin demonstrator with its up to 28 layers the target energy values per ply were defined with a step wedge configuration with UD-tape cut pieces of decreasing length (see Figure **3**). In a simple trial and error approach, each new layer is welded such that it is fixed to the previous layer. The weld power as main parameter is increased starting with 6 J at a weld amplitude set to 100%. This corresponds to 40 µm peak-to-peak longitudinal displacement at the face of the sonotrode [see 11]. The weld pressure was initially set to 1.15 bar.

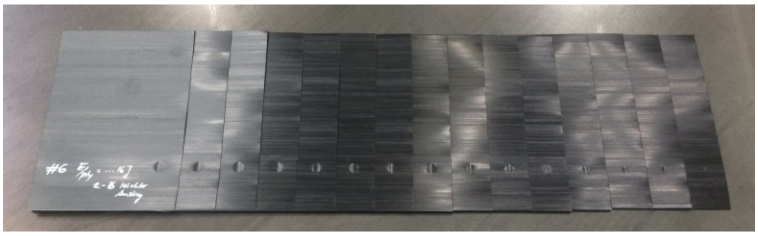

Figure 3. Step wedge configuration where ply by ply the respective weld parameters can be established

Figure 4 shows a 3D waterfall diagram of the weld power over time with predefined energy limits for the step wedge made of 28 layers. The gray area beneath the curves represents the transmitted energies. The progression of transmitted power shows no regular pattern with varying maximum power levels up to 250 W marked in dark yellow.

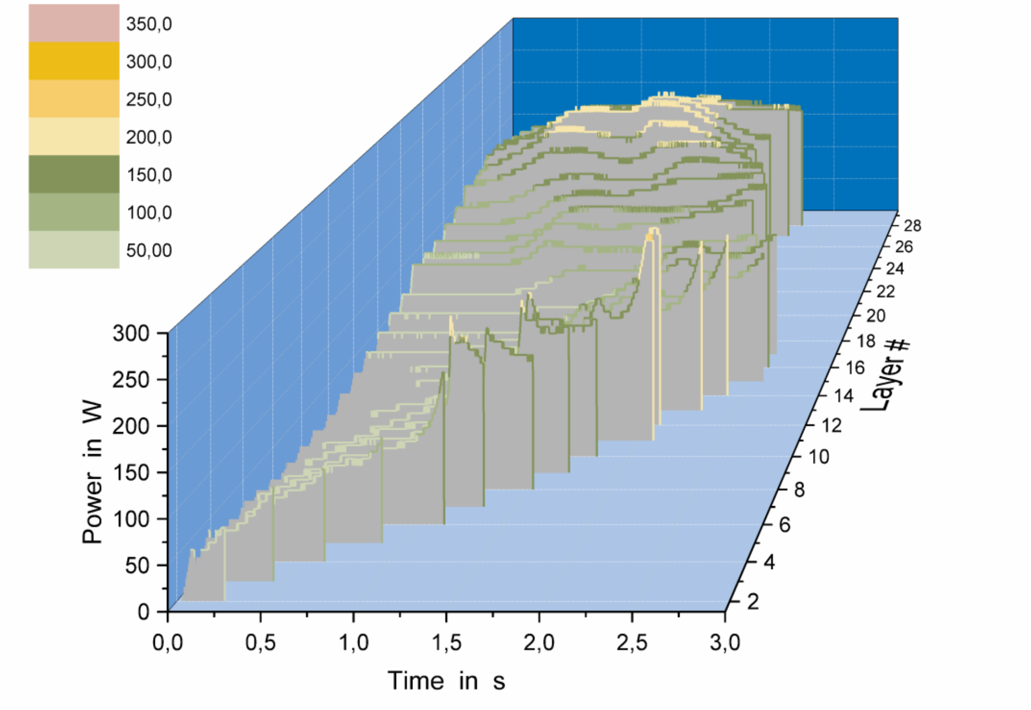

Figure 4. 3D waterfall diagram of the transmitted weld power over time depending on the respective layer of the CF/PEKK step wedge with defined energy limits

The respective energy limits were consequently employed to weld the demonstrator preform. However, it was found that the energy levels for the curved preform with quasi-isotropic and stepped lay-up needed to be increased. Beginning from layer number nine the weld energies were increased gradually, up to a final increase factor of approximately 1.75 (see Figure 5). From layer 14 onwards the weld pressure was set to 2.8 bar.

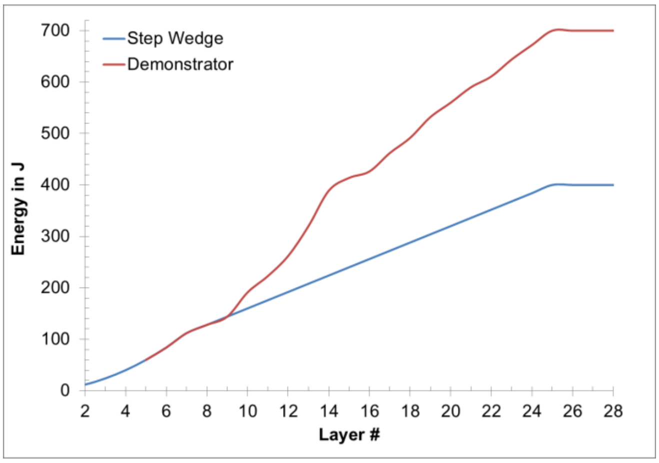

Figure 5 Defined energy limits for the automated preforming

Figure 6 shows the 3D waterfall diagram of the weld power over time for a selection of weld points of the fuselage skin demonstrator. Here, the power progression is rather irregular with peak values of up to 640 W.

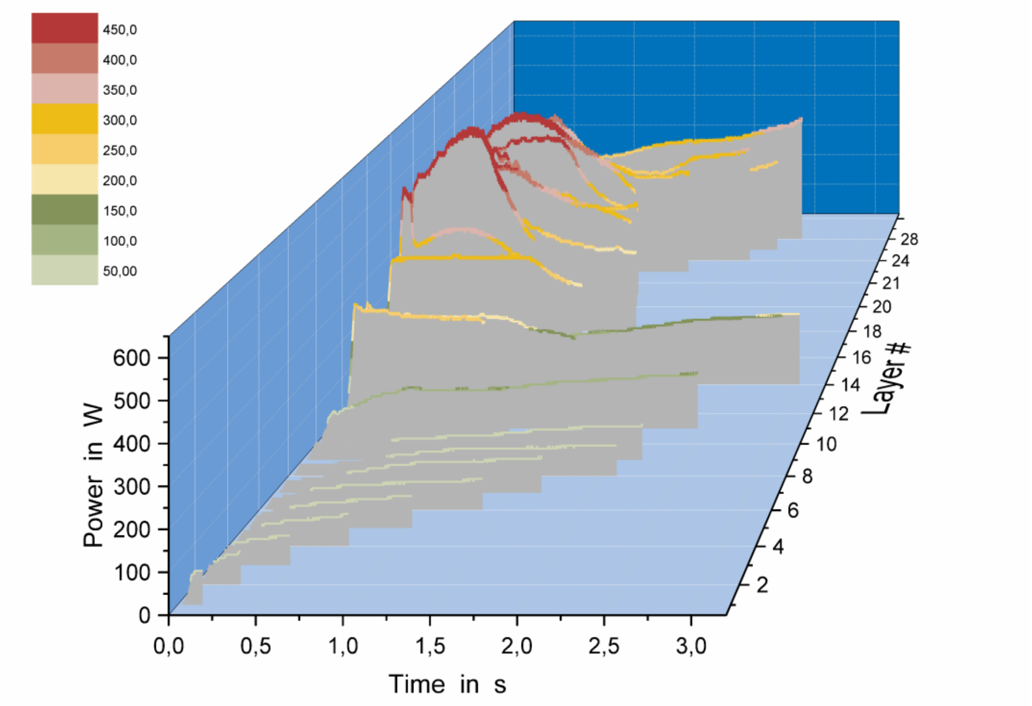

Figure 6. 3D waterfall diagram of the transmitted weld power over time depending on the respective layer of the CF/PEKK fuselage skin demonstrator with optimized energy limits

4. Discussion and Outlook

From the waterfall diagram (see Figure 6) one may constitute that the intromission of sound and transmission of weld power is enhanced by increasing the acting pressure on the sonotrode. From layer 14 onward the power levels transmitted by the generator are significantly increased and thus the vibration on-times reduced. The weld time then subsequently rises as higher energies need to be reached to fix the respective uppermost ply to the subjacent stack.

From Figure 5 we clearly find that compared to the step wedge trial increased energies are needed starting from layer 9 onward. With increased weld pressure after layer 14 the slope of the red curve then slightly reduces.

A number of factors may account for this deviation whose relative impact could not be separated in this experiment:

1) Orthotropic lay-up instead of UD may lead to differences in heat dissipation
2) Steps and splices within the lay-up may also lead to dissipation of frictional energy
3) Curvature of the mold may hinder vertical setup of the horn and thus energy transfer
4) Vibration of the comparably thin mold may cause additional energy dissipation
5) Metal pins as marker for later part trimming may lead to macroscopic vibration of loosely placed plies and thus energy dissipation
6) Too little fixation of the plies by the end-effector vacuum cups may also cause displacement of plies and thus energy dissipation

Certain measures have already or will be introduced to eliminate potential sources of production-induced defects. In the future, we will reconsider the part marking and eliminate the metal pins to guarantee a flat lay-up of the stack without bridging. Additional vacuum suckers will be added to the end-effector closer to the horn in order to assure ply fixation and eliminate ply movement during welding.

5. Conclusion

Fully-automate patch-preforming was applied to produce a fuselage skin demonstrator for future thermoplastic composites aircrafts. A camera-based ply detection hereby tracks and places the single cut pieces according to the pre-defined ply book. The entire set of process data, including robot positioning, vacuum levels of the grippers and weld parameters were recorded via OPC UA and stored in a time series management system (Kisters' Big Data – KiBiD).

Weld data of the 104 cut pieces with at least two welds spots each was analyzed. An implemented energy control proved to be a vital measure as transmitted power levels during welding are genuinely non-reproducible. Thus vibration on-times vary from weld point to weld point and layer to layer. As an input parameter for a robust process on-time is not suitable.

Also, the knowledge transfer from trial testing to actual part production was found to be limited as tooling, ply lay-up and end-effector placement differ. With the implemented test function of the manufacturing execution system (MES) the respective parameters for welding could be swiftly adapted.

6. Outlook

With the gathered expertise from spot welding during preforming, a test bench with an integrated end-effector for continuous ultrasonic welding was designed and set up (see Figure 7). The described data acquisition routine was transferred to the test stand and enhanced with an automated analytics tool.

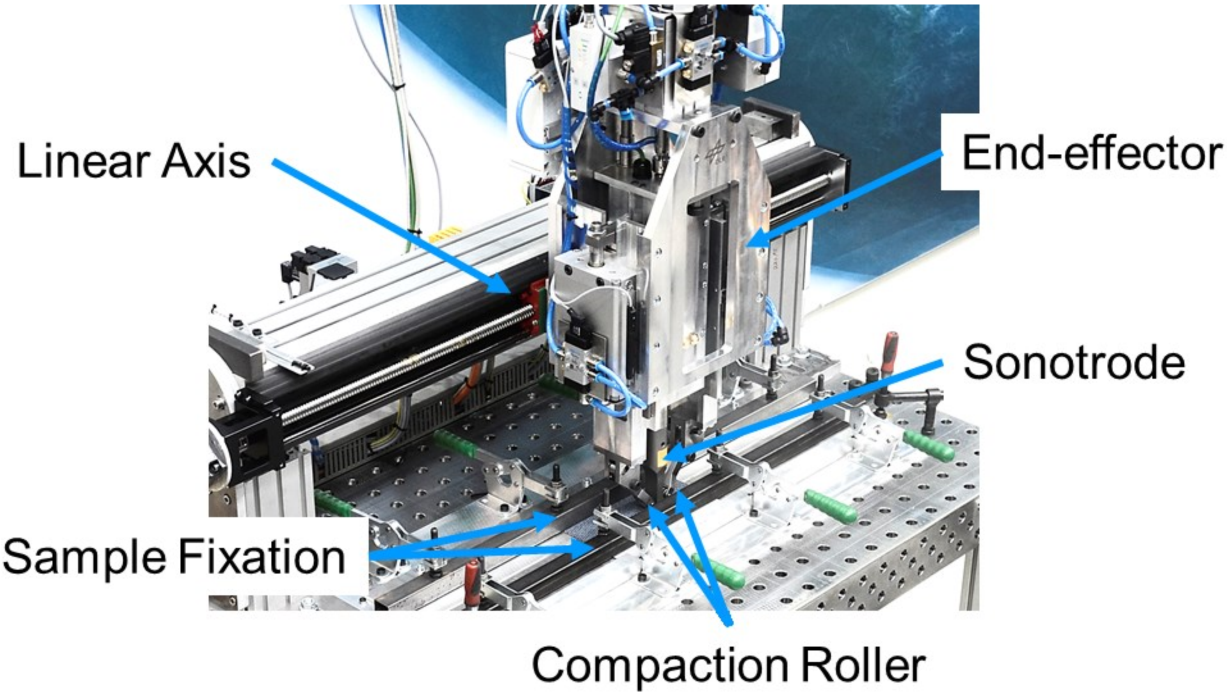

Figure 7. Test bench for continuous ultrasonic welding

Thus, continuous ultrasonic welding shall be employed to join the stringers to the cured skin. A focus is currently laid on establishing an appropriate processing window, defining weld energy, movement speed, amplitude and pressure for CF/PEKK. The end-effector was designed such that it can be simply mounted to a standard industrial robot in the integrated work-cell (see Figure 2) to then weld larger aerospace structures.

In a nutshell, each process step is evaluated concerning its quality relying on sensor-based in-line quality assurance and additional NDT where required. Thus an alternative production route for advanced thermoplastic structural parts is demonstrated.

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