ROBUST ASSEMBLY - QUALITY ASSURED WELDING TECHNOLOGIES FOR FULL-SCALE APPLICATIONS

Manuel Endrass[1*], Manuel Engelschall[1], Monika Mayer[1], Philipp Gänswürger[1], Michael Vistein[1], Manfred Schönheits[1], Stefan Jarka[1], Simon Bauer[1], Frederic Fischer[1], Alfons Schuster[1], Lars Larsen[1], Stefan Ferstl[2] and Michael Kupke[1]

[*]corresponding author (manuel.endrass@dlr.de)

1) German Aerospace Center (DLR), Center for Lightweight Production Technology (ZLP), Am Technologiezentrum 4, 86179 Augsburg, Germany

2) Premium AEROTEC GmbH (PAG), Haunstetter Str. 225 Augsburg, Germany

ABSTRACT

Thermoplastic welding technologies offer the possibility of producing an integral assembly out of two or more separate components, with an interface that is non-distinguishable to the component structure itself. However, institutional research on thermoplastic welding technologies is mostly focusing the technology readiness levels (TRL) one to three, demonstrating the validity of the functional principle in a reduced scale. Within the European Clean Sky 2 (CS 2) initiative, the Multifunctional Fuselage Demonstrator (MFFD) an eight-meter long, cylindrical aircraft fuselage barrel will be manufactured challenging different thermoplastic part manufacturing and welding technologies in full scale. Within this paper we are focusing to present the custom-made welding jigs and end-effectors for ultrasonic and resistance welding, developed for the MFFD upper shell assembly. To assure adequate integrated quality assurance the weld tools are equipped with various sensors for component positioning and process control. The accumulated data are validated and inline stored within a storage for heterogenous product and research data (shepard) to assure the robust process execution and safeguard traceability.

1. INTRODUCTION

Fusion bonding technologies are the key enablers in thermoplastic aircraft production, especially to exploit the potential given by redesign of parts up to the entire assembly. Robust and reliable technologies have to be developed and implemented in industrial environment. Within CS 2, the MFFD, an eight-meter long, cylindrical aircraft fuselage barrel will be manufactured challenging different thermoplastic part manufacturing and welding technologies. In this context, the Center for Lightweight Production Technology (ZLP) Augsburg and its project partners AIRBUS, Premium AEROTEC (PAG) and AERNnova are developing and demonstrating technologies for the automated manufacturing and assembly of the upper shell made from the high-performance carbon fiber-reinforced thermoplastic (CFR-TP) low-melt Polyaryletherketone (LM-PAEK).

Within this paper we present welding jigs and end-effectors for ultrasonic and resistance welding developed in the framework of the MFFD upper shell project. For each of the applied welding technologies a quick introductory excurse on the respective physics background is given. Custom-made weld tools for the assembly were developed based on a predefined upper shell design with Z- stringers and integral C-frames. Stringers, frames, frame-couplings and cleats were minorly changed in its design to allow for the application of thermoplastic welding technologies. The end-effector for continuous ultrasonic welding (cUW), as well as the welding process were significantly matured within CS 2 to assure robust and reliable stringer integration. An on top of the upper shell tooling movable positioning and welding jig, the so-called weld bridge was developed, consisting of various modules for stringer guidance, clip positioning, frame and frame coupling positioning and integration. To allow for accurate cleat position and to mitigate potential stresses induced by the end-effector, a compliance-controlled cobot-on-robot integration strategy was developed.

The various welding jigs and robotic end-effectors are equipped with multiple sensors for correct component positioning and assure and follow the reliable process execution. Shepard, a storage for heterogenous product and research data which was developed in house at the DLR (available open source) [1], unites the diverse positioning and processing data as superordinate system for the integrated quality assurance and enables for traceability.

2. CONTINUOUS ULTRASONIC WELDING

The very fast possible processing speed during ultrasonic welding (4-6 m/min, [2]) is quite an enabler to achieve a high-volume aircraft structure manufacturing. However, the processing time is dominantly predetermined by the requested cycle time of the thermoplastic matrix system to assure adequate melting, intimate contact, interdiffusion and crystallization. The integration of Z-shaped stringers as longitudinal stiffeners of the MFFD`s upper shell is predestined for the use of ultrasonic welding technology, since the component geometry and the overall accessibility of the attached flange provides sufficient working space. Within the upper shell manufacturing a total number of 48 stringers will be integrated by cUW post to a pre-fixation by ultrasonic spot welding, which will be performed by the same robotic end-effector.

2.1. Ultrasonic welding principle

Two mechanisms are responsible for heat generation during ultrasonic welding, one is interfacial friction – friction between the welding partners and the layers of energy director, the second is viscoelastic heating due to intermolecular friction [3]. A generator (1) produces a high-frequent (20 kHz at DLR-ZLP, see Figure 1) alternating current that is transformed into a mechanical displacement of constant amplitude by a piezoelectric converter. The booster and horn (2) components downstream of the piezo stack increase the amplitude of the mechanical vibrations and propagate them to the welding partners. During ultrasonic welding, the horn is guided vertically over the components to be joined. The vibrations introduced under constant force result in interfacial friction at the welding interface and melt the thermoplastic matrix. During cUW, the horn is continuously moved vertically across the bondline. To ensure a sufficient joint quality, the welding pressure, which must also be maintained during the cooling phase, is applied via a trailed heatsink consolidation unit (3). The required counterpressure to remain within the static equilibrium is provided by a rigid anvil. In case of stringer integration, the metallic upper shell tooling will take over this function.

2.2. End-effector description and functionality

The booster and the horn are the above-mentioned heart of the cUW end-effector, placed in the middle of a solid construction. The end-effector (4) is attached in 45° to the axis six of a ceiling mounted KUKA QUANTEC KR270 R2700 ultra C robot (5), to assure the accessibility for stringer integration even around the longitudinal joint of the upper shell.

Part fixation under constant clamping conditions is achieved by a leading clamping device (6), as well as a trailing consolidation unit. Clamping device, horn and consolidation unit are pneumatically linked to the end-effector, which allows for tolerance compensation by avoiding a stiff mechanical coupling [4].

The pressure value of each cylinder can be controlled independently from each other. Force values can be adjusted of up to 1.8 kN for the leading clamping device, respectively the consolidation unit. The central cylinder for the infeed motion of the horn and weld force application can be controlled to a maximum level of up to 3.0 kN. All pressure levels - as well as the weld distance, measured by Panasonic HL-G112 laser triangulation sensor - are recorded with a sampling rate of 1 kHz. An additional integrated industrial camera allows to follow the stringer edges within a predefined region of interest. The cUW end-effector components are linked by a Beckhoff bus system and controlled by the software TwinCAT, allowing real time ability. A TwinCAT graphical user interface enables the parametrization of the welding and the control of the end-effector. During automatic mode, the weld parameters are set within the robot sequence control. [5]

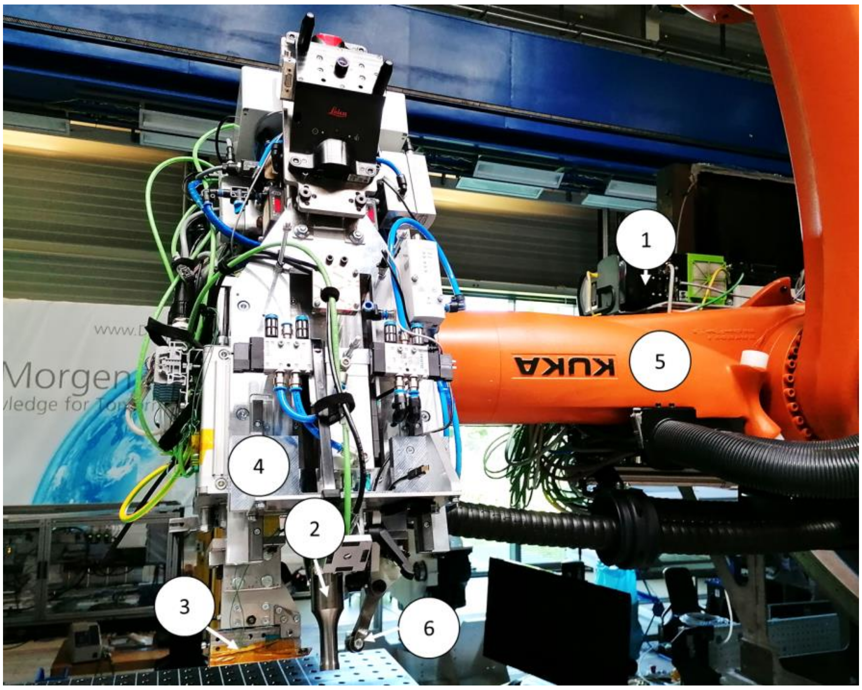

Figure 1 End-effector for continuous ultrasonic welding, attached to a ceiling mounted KUKA QUANTEC KR270 R2700 ultra C

2.3. Data management and integrated quality assurance

Data management is a part of the integrated quality assurance. The measurement and control of weld parameters during a highly transient process is quite essential to assure precise, robust and reliable welding results. Diverse sensor data, like pressure values of the pneumatic cylinders, weld distance and heatsink temperature, are collected with a sampling rate of 1 kHz. In addition, data of the power supply like power output, the ultrasonic frequency and the amplitude are merged within TwinCAT Scope. Information on the robot’s axes positions and the tool center point velocity (weld speed) are also transferred to the Scope project. All parameters are thus located in a time-triggered manner in one file and compiled within shepard.

3. RESISTANCE WELDING

Resistance welding is applied during the MFFD upper shell assembly for the integration of integral C-frames, frame-couplings and cleats. The tangible process principle, which is based on the Joule heating of an electrical conductor located in the bondline and externally applied consolidation pressure to the weldment, is particularly suitable for short welded joints compared to continuous ultrasonic welding. However, a weld length of up to 1.5 m for an all-thermoplastic rear pressure bulkhead, using a carbon fiber fabric conductor, was demonstrated in the LuFo 6.1 project HotStufF [6] in close cooperation with the industrial project partner PAG and is on track towards TRL 5. The excellent mechanical performance, process robustness and reproducibility of resistance welded joints, as well as the physical applicability due to the accessibility, were key factors in the decision to apply resistance welding in a versatile way in the context of the upper shell production. Since resistance welding has a very high flexibility in process control, heating rates, dwell and cooling rates, can be adapted to the needs of the thermoplastic matrix system. The rapid assembly capability using electrical resistance welding - (120-240) s per joint - provides a contribution to the project objective of high rate capability [7].

3.1. Resistance welding principle

As mentioned previously, resistance welding uses the Joule heating of a current-carrying conductor placed in the bondline, to generate the process heat required for welding. A direct current power supply is electrically connected via copper clamps to the welding element, which protrudes beyond the components to be connected. A weld pressure of at least 0.5 MPa, pneumatically applied, provides an adequate consolidation. Contact pressure values of the same magnitude as the weld pressure are set for proper current conduction with low contact resistance. Homogenous current introduction at low transition resistance values is quite essential to prevent from preferential heating followed by current leakage. A special aspect of the application of electric resistance welding in the context of upper-shell production is the one-sided accessibility of the joint and contacting.

3.2. Weldtool description and functionality

Due to the different application areas of resistance welding, a number of different tools have been developed for the MFFD upper shell assembly. In addition to ensue functional capability and accurate component positioning, the primary objectives in tool design were to be able to compensate production-induced component tolerances and, at the same time, to demonstrate a scalable, highly automated assembly concept. For this purpose, the weld bridge, a special tool movable in direction of flight (DOF) on top of the upper shell mold was developed, which is responsible for positioning and integrating the clips, frames and frame-couplings. For cleat integration a different positioning concept, based on a compliance-controlled cobot-on-robot principle was developed in order to overcome with the challenges of accumulating tolerances that occur due to skin thickness variations, as well as stringer and frame positioning tolerances.

3.2.1. Weld bridge

The weld bridge (7) shown in Figure 2 is the central tooling for the positioning of clips, as well as the positioning and integration of frames and frame-couplings. Beckhoff servomotors drive the weld bridge via high-precision toothed racks guided on both sides on top of the kovar-steel tooling (8). The use of servomotors, high-precision toothed racks and the calibrated mounting of the welding bridge backbone, thus ensure a high frame positioning accuracy.

Since the C-frames are split in the center line - later top - of the upper shell structure, the weld bridge is splitted in the same position. The weld modules (9) consist of a multi-stage, pneumatically actuated kinematic system which, on the one hand, allows the entire weld modules to be moved (in DOF, related to the backbone position) to allow for the frame (10) insertion and, on the other hand, is designed to apply a coupled contact pressure and weld pressure. These modules are attached to the frame support structure (11) and can be actuated via various Festo valve terminals (12).

The welding current and pneumatic actuation is controlled by the higher-level manufacturing execution system and switched individually to the respective weld modules via a solid-state relay circuit. Within the weld bridge, the frame support structure can be moved in two stages at an angle of 45°, to assure a clash-free frame positioning. After manual frame insertion and fixation by vacuum cups, the weld modules are closed in DOF and pre-positioned on top of the welding elements. For frame positioning, the frame support structure is driven in 45° towards the upper shell tooling in the weld bridge pre-position, outside of the shell. In this state, the two-stage movability of the weld bridge at 45° still allows the frame to hover above the skin laminate without clashing during its transport to the welding position.

At the target position of the frame, the second 45° infeed movement takes place and presses the frame against the skin laminate. This movement strategy also enables the positioning of the clips, as they are clamped against the frame with an overhang to the subsequent target position, and the feed movement leads to a tracing of the actual contour of the skin and thus to a movement of the clip to the target position. The later in process conducted weld pressure application is performed by the individual weld modules, decoupled from the infeed movement.

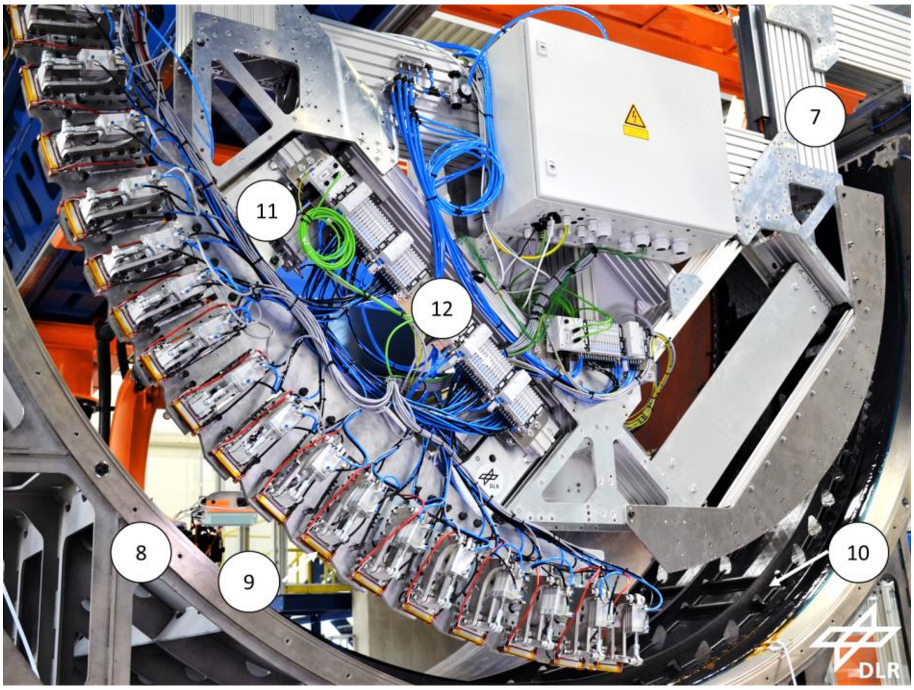

Figure 2 Weld bridge responsible for clip positioning and fixation during ultrasonic spot welding, as well as the frame integration by resistance welding

3.2.2. Cleat end-effectors

The absolute positioning accuracy of the ceiling-mounted KUKA QUANTEC KR270 R2700 ultra C (13) robot (see Figure 3) in the DLR ZLP Multifunctional Cell proved to be insufficient for cleat positioning to meet the challenges of accumulating tolerances. To ensure exact, gap-free and teachless fine positioning of the cleats in the welding position, an LBR iiwa cobot (14) is used. Due to the low payload capacity of the iiwa (14 kg) compared to conventional industrial robots, the cleat end-effectors were designed to be as slim as possible. In order to accommodate all functionalities, such as weld pressure application and contacting, in a limited installation space, two separate end-effectors, split by its joining task cleat-frame (1st step) and cleat-stringer (2nd step), were designed for this purpose. To allow for the automated installation of the cleats at the farfield and door surround structure side, it was necessary to design a number of four end-effectors.

The rough positioning of cobot and cleat end-effector (15) is performed by a ceiling-mounted KUKA QUANTEC KR270 R2700 ultra C. The three-dimensional positioning of the cobot is carried out using a fixed offset with respect to each cleat position in the mold. Note, the iiwa base is kept in the same orientation all the time due to the gravity vector which has to be configured in the iiwa sunrise controller and cannot be changed during runtime. Fine positioning of the cleats is conducted by the cobot using its compliance-controlled steering capability.

As a basic principle for the cleat end-effectors, a closed pincer design was used to apply the process forces. The process forces applied by contacting and welding pressure thus lead to a closed force flow within the weldtool and do not apply external forces into the structural assembly of the upper shell. However, smaller gaps occurring due to fine positioning inaccuracies are closed by the end-effector itself and lead to a readjustment of the compliance-controlled cobot and avoid internal stresses within the assembled structure.

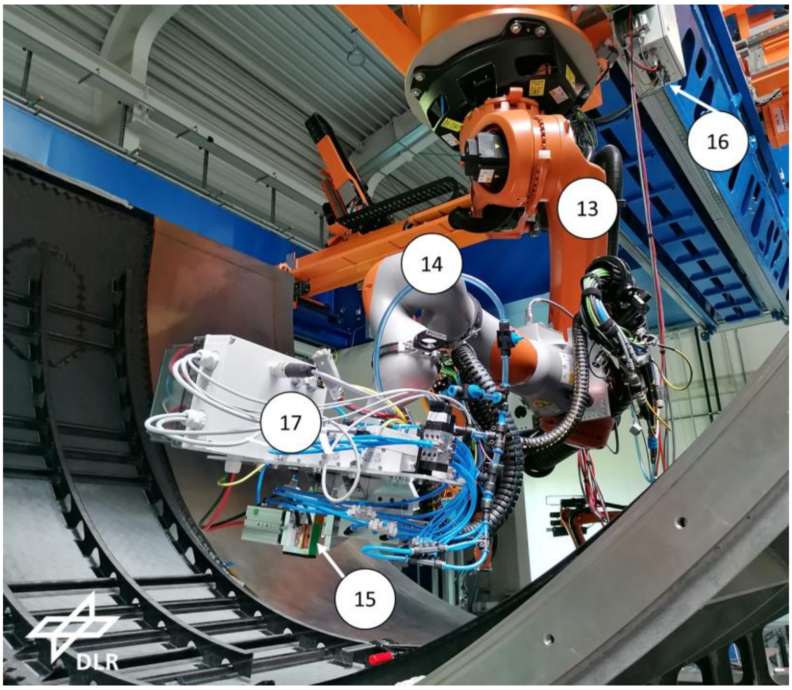

Figure 3 Cleat-frame end-effector for the cobot-on-robot-based cleat integration

In order to reduce the end-effector size and prevent from self-collision with the cobot, the iiwa control system and the welding power supply (16) unit were mounted on the linear axis at the base of the ceiling-mounted KR270. The peripherals (17), like current and voltage measurement devices required for welding process control on the other hand, were placed directly on the end-effector in order to keep cable lengths short and reduce interference on the analog measurement signals.

3.3. Data management and integrated quality assurance

The measurement of processing parameters, its storage and the process data localization are part of the overall inline quality assurance strategy within the upper shell manufacturing and assembly. During frame integration the process parameters weld pressure, current and voltage values as well as the weld bridge position are tracked and stored within shepard. Compared to the frame integration by the weld bridge, the contact pressure, as well as the cobot and robot axis positions are tracked for cleat integration. This allows not just for documentation purposes but also for the application of deep learning algorithms for positioning and weld processing improvements. However, the application of artificial intelligence is not part of the upper shell manufacturing, but is being matured with respect to the application of welding technologies at the ZLP.

4. PERFORMANCE VALIDATION – TEST SHELL PRODUCTION

Prior to the eight-meter demonstrator production, the different weld jigs and end-effectors were validated on test bench level for process parameter identification, in a first evaluation phase. Upscaling effects and full-scale capability were validated in the second evaluation phase during the so-called test shell production. The test shell itself was built based on a - comparable to the Airbus A320 – full-scale upper shell loft tooling, in reduced length. This allowed the demonstration, validation and maturation of the developed processes and toolings and was part of the risk mitigation strategy towards the manufacturing of an eight-meter full-scale upper shell structure demonstrator made from CFR-TP`s. For the production of the test shell, a shell design adapted to the constraints of the end-effectors and tools with regard to tape placement and welding technologies was developed in cooperation with the project partner PAG and coordinated with the project leader Airbus under consideration of maximum transferability. Lessons learned derived during manufacturing, were tracked within a root cause and failure analysis. Stepwise improvements on design, welding infrastructure and processing were thus already implemented within the test shell manufacturing. Thus, the different technology bricks were validated and matured within a full-scale production scenario and prepared for the eight-meter demonstrator production.

5. CONCLUSIONS

In this paper, we present the jigs and end-effectors, responsible for the structural assembly of the Multifunctional Fuselage Demonstrators upper shell. The robotic end-effector for continuous ultrasonic welding, was significantly matured within the project in order to overcome with the challenges of continuously producing high quality welds in the demonstrator length of eight-meters during stringer integration. For clip positioning, as well as for frame positioning and welding, a further custom-made jig - the weld bridge - was developed, enabling the accurate frame integration by resistance welding. The integration of cleats, by resistance welding, follows a new cobot-on-robot integration principle to allow for compliance-controlled cleat integration, without stress introduction into the upper shell assembly by external forces.

This process was split into two stages due to part size and complexity reasons. Each developed jig and end-effector is equipped with various sensors for process control and inline quality assurance and allows part and process traceability. The process data generated is stored in an in house developed higher-level data management system, called shepard.

Acknowledgements

This project has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 945583. The JU receives support from the European Union's Horizon 2020 research and innovation program and the Clean Sky 2 JU members other than the Union.

Disclaimer

6. REFERENCES

[1] T. Haase, R. Glück, P. Kaufmann, M. Willmeroth, F. Krebs, and H. Voggenreiter, "shepard - storage for heterogeneous product and research data." German Aerospace Center (DLR), Jul-2021.

[2] G. Gardiner, "Welding thermoplalstic composites," *CompositesWorld*, pp. 50–63, Sep. 2018.

[3] 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.

[4] M. Engelschall, L. Larsen, F. J. C. Fischer, and M. Kupke, "Robot-based Continuous Ultrasonic Welding for Automated Production of Aerospace Structures," in *SAMPE Europe*, 2019.

[5] M. Endrass, M. Engelschall, M. Vistein, M. Mayer, P. Gänswürger, S. Jarka, S. Bauer, and F. Fischer, "Deliverable D2.1.8-56 (DEK) - Developement and production of welding end-effectors," Dec-2020.

[6] S. Jarka, "Fast Lane and HoTStufF: Thermoplastic Rear Pressure Bulkhead (Cooperation with Premium Aerotec GmbH)." Deutsches Zentrum für Luft- und Raumfahrt (DLR), https://www.dlr.de/zlp/en/desktopdefault.aspx/tabid-14336/24880_read-61148/#/gallery/37304, Jun-2022.

[7] CAJU, "Multi Functional Fuselage Demonstrator." Clean Aviation Joint Undertaking (CAJU), Jun-2022.