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Publication date
2022

Document Version
Final published version

Citation (APA)
Choudhary, A., Mendes Florindo, A. M., van Rijswijk, K., & Villegas, I. F. (2022). *Automated Sequential Ultrasonic Welding on a full-scale Thermoplastic Composite Fuselage demonstrator*. Abstract from ITHEC 2022 – 6th International Conference and Exhibition on Thermoplastic Composites, Bremen, Germany.

Automated Sequential Ultrasonic Welding on a full-scale Thermoplastic Composite Fuselage demonstrator

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Abstract:
Multi-spot sequential ultrasonic welding is a promising joining technique for thermoplastic composites in an overlap configuration. In the framework of the EU Clean Sky 2 Multi-functional fuselage demonstrator (MFFD) and the lower shell SmarT multifUNctioNal and INteGrated TP fuselage (STUNNING) projects, a robot-based sequential ultrasonic spot welding process has been developed for joining of large thermoplastic structural components, based on process development steps reported in previous work [1]. The technology is being demonstrated on a full-scale thermoplastic composite fuselage section of 8 m length and 4 m shell radius. The fuselage skin is being joined to longitudinal stringers and circumferential frames through welded clips, in the lower shell of the fuselage demonstrator. This paper presents an overview of the robotic sequential welding technology developed at SAM|XL in collaboration with Delft University of Technology and the ongoing sub-assembly process of the fuselage demonstrator, led by GKN Aerospace.

Keywords: Thermoplastic composites, Fusion bonding, Ultrasonic welding, Automated assembly

Introduction

Ultrasonic welding (USW) is an attractive welding technique for thermoplastic composite (TPC) structures due to shorter process times and no requirement of a foreign material at the joint interface [2]. The process can be used to consistently achieve high joint strengths in very short process times (1-1.5 seconds). Multi-Spot Welded (MSW) single-lap joints have been demonstrated to exhibit a comparable load-carrying capability as well as a more localized damage upon failure, when compared to mechanically-fastened joints of similar size. This results from higher joint stiffness and lower secondary bending and hence, lower peel stresses [3]. It is also expected that MSW joints exhibit a higher damage tolerance over continuously welded seams due to a potential inherent crack arresting behaviour as a result of discontinuity in the joints and the need for a crack to re-initiate in subsequent welded spots. Hence, sequential multi-spot ultrasonic welding is a promising joining technology for industrial application, provided that the process can be automated for the assembly of large structural components with complex geometry.

Sequential ultrasonic spot welding is currently being used for joining the TPC fuselage skin and longitudinal omega stringers to circumferential frames through the use of structural clips. This construction can be found in the lower shell of the Multi-functional Fuselage Demonstrator (MFFD) i.e. the STUNNING demonstrator [4] (Figure 1). Circular spot welds are being used to join the clips to the skin/stringer and the clips to the frame as is illustrated in Figure 2. For this purpose the ultrasonic welding hardware, sequential welding strategies and automation tools have been developed at SAM|XL in collaboration with Delft University of Technology. The goal is to weld more than 1600 spots in an automated way, to join 212 thermoplastic composite clips to the skin, stringer and frames in the STUNNING demonstrator. For the automated sub-assembly operations, an overhead gantry robot with 6 degrees of freedom is being used at SAM|XL. During the sub-assembly process, the lower shell structure of the fuselage demonstrator is supported by a metallic jig developed by the TCTool consortium [5].

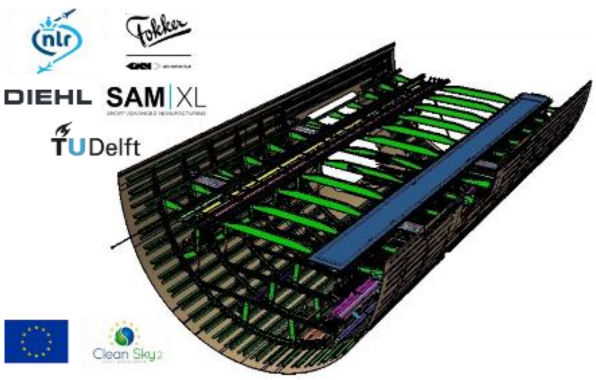

Fig. 1: *Overview of lower shell of the thermoplastic composite fuselage demonstrator.*

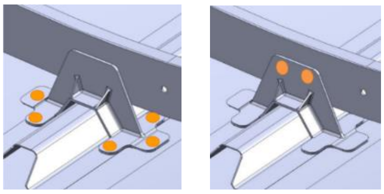

Fig. 2: *Joint configurations for spot welding the clips to skin/stringer (left) and for spot welding the clips to the frames (right).*

Materials and Geometry

The welded joints between clips, skin, stringers and frames consist of parts of varying fibre architecture and thicknesses. The clips were manufactured by the ECOCLIP consortium [6] and are injection moulded from recycled short-carbon fibre reinforced low-melt Polyaryletherketone (LMPAEK) composite with an average thickness of 3 mm. The skin, stringers and frames are manufactured from continuous fibre reinforced LMPAEK composite. The skin has a varying thickness ranging from 1.5 mm to 10 mm**.** The stringers and the frames have a thickness ranging from 2 mm to 3 mm. At the weld interface, the clips are manufactured with 0.2 mm high triangular riblets (Figure 3), which act as energy directors. The riblets were produced during the manufacturing of the clips using special features in the mould.

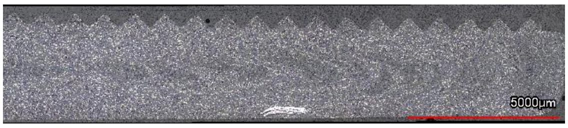

Fig. 3: *Cross-sectional micrograph of a spot weld location on the clip with the molded energy director riblets at the weld surface (top).*

Welding hardware

For the two joint configurations shown in Figure 2, a welding end-effector (EEF) was developed which consists of two different tools. These can be mounted individually on the EEF for each of the welding configurations i.e. clip-to-skin (CTS) and clip-to-frame (CTF) as can be seen in Figure 4. In the CTS tool, the welding stack is actuated vertically, normal to the parts to be welded which is the clip to the skin/stringer. It also includes a pneumatically actuated clamp that is used to grip and clamp the clip during the welding operation. In the CTF tool, the welding stack is actuated horizontally. The tool includes an integrated anvil to provide back pressure on the frame during the welding process. Feedback from the ultrasonic generator as well as displacement and pressure sensors integrated in the welding EEF are used to control the welding process. The welding EEF is mounted on the wrist of an overhead gantry robot with 6 degrees of freedom. This allows for reachability of the EEF at all locations in the demonstrator and for positioning of the sonotrode perpendicular to the clip welding locations.

Fig. 4: *Ultrasonic welding EEF in the CTS configuration (left) and CTF configuration (right) on a static test bench.*

Process development and weld quality determination

The demonstrator presents a large variation in material configurations and geometry of parts to be joined by ultrasonic spot welding. Therefore, extensive trials were conducted to characterize the welding behaviour of the materials and to verify the welding parameters that were determined in previous studies [1]. Welding trials were conducted in each joint configurations with the welding EEF on a static test bench with the material configuration as in the demonstrator. This entailed short-fibre composite coupons/clips welded to continuous-fibre composite panels to mimic the skin, stringers and frames. The static test setup can be seen in Figure 4. Each spot weld was produced with a circular sonotrode of 20-mm diameter. The resulting welds were approximately circular in shape with an average diameter of 18 mm. The obtained weld quality was assessed based on single lap shear strength of the joints, cross-sectional images of the interface as well as ultrasonic scans of the weld. An average single-lap shear strength of 30 MPa (coefficient of variance: 1.8 %) was achieved for each welded spot. During single lap shear testing as well as pull-tests, material failure was observed in the short-fibre reinforced clip material rather than at the weld interface. This indicated that the weld strength is higher than the strength of the clip material itself.

Representative cross-sectional micrographs as well as ultrasonic C-scans of the welded section are presented in Figure 5 and Figure 6, respectively. It can be seen in Figure 5 that a uniform weld seam is obtained and based on a qualitative analysis, no large voids are observed at the weld interface. Note that the spot welds are produced with the sonotrode introducing the mechanical vibrations on the upper adherend, which is the short-fibre reinforced composite material. In Figure 6, the approximately circular welded spot can be seen in the joint overlap with an average diameter of 18 mm.

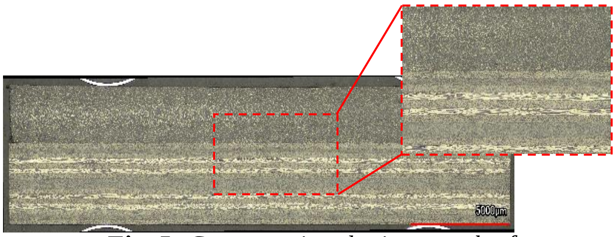

Fig. 5: *Cross-sectional micrograph of a representative weld between a short-fibre reinforced clip (upper adherend) and continuous-fibre reinforced skin panel (lower adherend).*

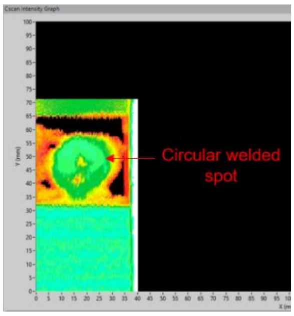

Fig. 6: *Ultrasonic C-scan of a single spot welded joint with an approximately circular welded spot of 18-mm diameter.*

Automated clip welding strategy

The welding EEF was designed considering the specific requirement of spot welding each clip at 8 different locations to the skin, stringer and the frames. Due to the large number of welds and the tight tolerances required between the parts themselves as well as between the sonotrode and the part, it was critical to carefully integrate the EEF with the gantry robot and calibrate the tool with respect to the stiffened skin. This task proved to be time consuming due to various deformations in the skin and stringers during the assembly steps prior to clip integrations (skin manufacturing, stringer integrations etc.) as well variations in stringer positions (relative to product definition in CAD) within assembly tolerances.

For the clip to skin and clip to stringer welding operation, a decision was made to first weld the outer feet of the clip that make contact with the skin directly. Subsequently, the remain four spots on the clip-stringer interface are welded. The welding sequence can be seen in Figure 7.

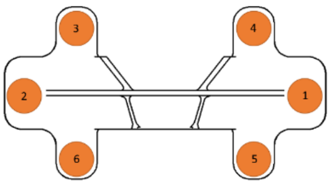

Fig. 7: *Sequential spot welding sequence for the clip, skin and stringer joint.*

This sequence was chosen due to multiple contributing factors. Firstly, it helps mitigate the risk of in-plane misalignment of the clip with respect the frames due to gaps ranging from 0.5 mm – 8 mm, identified between the stringers and the clip feet. Secondly, this welding sequence also helps ensure good quality welds at a minimum of two spots, i.e., at the clip-skin weld interface. A result of the welding sequence is the relatively complex motion of the gantry robot, in order to position the sonotrode and the clamp above the weld locations.

For the clip to frame welding configuration, since the vertical flange of the clip needs to be welded to the vertical flange of the frame, extra tooling is needed to apply back pressure. Hence, the CTF welding tool contains an integrated anvil that can reach around the joint location and apply back pressure from the rear of the frame, while the sonotrode is positioned on the clip. A simulation image in Figure 8 depicts the CTF tool for welding a clip to the circumferential frame. The sequence of welding the two spots on the clip to frame interface does not matter from the welding process point of view. Hence, a sequence is chosen based on the ease of robot motion.

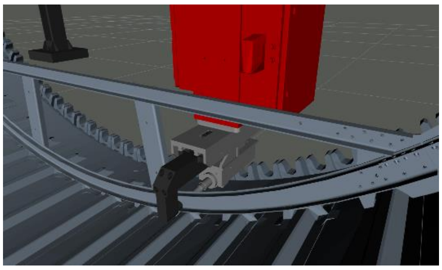

Fig. 8: *Ultrasonic welding EEF in the CTF configuration with integrated anvil (in black).*

Positioning and orientation of the welding EEF with respect to the clip required high accuracy. Due to the shape deformation of the skin/stringer profile from the initial design as well as the variation in part location (within manufacturing tolerances), each clip position and orientation ended up being manually measured using a Leica laser tracker which has a measurement accuracy of approximately 0.1 mm. Subsequently, the simulation model was updated with the real positions of each clip and a motion program was generated for the gantry to accurately position the welding EEF for each spot weld.

Demonstrator manufacturing

Currently, ultrasonic spot welding of the clips to the skin and stringers on the demonstrator is ongoing. In Figure 9, the CTS welding EEF can be seen being positioned over a clip by the gantry robot before welding. After the clip to skin welding is complete, the frames will be positioned in the shell and the CTF welding will commence.

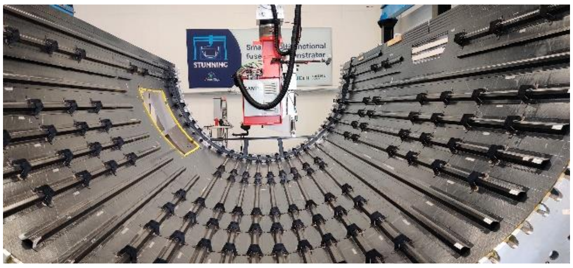

Fig. 9: Welding EEF in the CTS configuration being positioned over a clip to skin weld location on the lower shell of the fuselage demonstrator.

Conclusions

This paper highlights the process development steps that have been taken at SAM|XL and Delft University of Technology to realize an automated sequential ultrasonic spot welding process which is being demonstrated on the lower shell of the Multi-Functional Fuselage Demonstrator. The results obtained through experimental trials with the robot-based welding tools developed are promising and indicate that the ultrasonic spot welding process can be used with a high level of confidence for the joining of large-scale thermoplastic composite structures. Spot welded joints in composites with different fibre architecture and thicknesses have been demonstrated and the process has proven to be robust with respect to minor part misalignments and tolerance issues. However, it must be emphasized that weldabilty of structures through the ultrasonic spot welding process is highly dependent on gaps, tolerances and surface quality in the parts. Industrialization of the ultrasonic welding process for joining of structures should take into account the reachability of weld surfaces, deformation of parts and process tolerances. Furthermore, due to high process forces involved, the stiffness of the chosen industrial robot system as well as the stiffness of the back support structure play an important role in the success of the upscaling of the welding process.

The main outcomes of this project can be summarized as following:

• The concept and the functionality of robot-based welding tools in both clip-to-skin and clip-to-frame welding configurations was experimentally tested and demonstrated at coupon- and part-scale.

• High spot weld quality was achieved during welding trials in various thickness configurations of the short-fibre to continuous-fibre reinforced joints.

• Currently the clips are being welded to the skin and stinger, following which the welding of the clips to the frames will commence.

Acknowledgement

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 programme and the Clean Sky 2 JU members other than the Union.

The gantry robot at SAM|XL was established with support from the European Fund for Regional Development under grant agreement KVW-00176.

Disclaimer

The results, opinions, conclusions, etc. presented in this work are those of the author(s) only and do not necessarily represent the position of the JU; the JU is not responsible for any use made of the information contained herein.

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