On the capabilities of static resistance welding of carbon fiber-reinforced thermoplastic composites

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Abstract:
Welding technologies for the assembly of carbon fiber-reinforced thermoplastics offer enormous potential for the production of fast, reliable and material-compatible joints forming an integral assembly. Static resistance welding is one of the most mature and yet often underestimated joining technologies for thermoplastic composites. Extensive research has been carried out to increase the robustness, reliability and range of applications of the static resistance welding process based on a carbonfiber heating element. The potential of the technology has been demonstrated on a full scale in the assembly of aerospace components. In this publication, we focus on the process capabilities and discuss the possibilities of preferential weld seam formation, weld continuity, mechanical performance, advanced process control capabilities and applicability for aircraft production. We take an application-related approach on maturing the technology.

Keywords: Thermoplastic Composites, Resistance Welding, Weld Seam Formation, Non-Destructive Testing, Destructive Testing, Process Control

Introduction

Costs, weight and the high-rate capability of assembly processes are besides technological maturity, decisive drivers for technological choice. Basically, the raw material costs of high-performance carbon fiber-reinforced thermoplastics (CFRTP`s) are many times higher as compared to industrial thermoset composites used within the aerospace industry. However, the major advantages using CFRTP`s are incorporated within the - in theory - unlimited shelf life, quick processing and dustless assembly opportunities, e.g. thermoforming, injection molding, ultrasonic and resistance welding. Static resistance welding (RW) is one of the most mature and yet often underestimated joining technologies for CFRTP`s.

In 2018 Soccard made a review on welding technologies for primary aircraft structures from Airbus perspective, classifying the respective Technology Readiness Level (TRL) of co-consolidation, PEI diffusion, ultrasonic-, resistance- and induction- welding, describing opportunities and current risks for the implementation within the Fuselage of Tomorrow. Here, static resistance welding was classified being from low TRL (1-3, to be continued) and addressing the weaknesses/risks of being a static process, the length limitation to (0.7 - 0.8) m and non-applicable width variation [1].

However, comprehensive research has been conducted in the meantime, focusing the increase in robustness and reliability of the static RW process, based on a carbonfiber heating element and demonstrated in full-scale aerospace component assembly, like e.g. at the world's first thermoplastic rear pressure bulkhead [2] and the Multifunctional Fuselage Demonstrator (MFFD) [3]. This paper focusses on the extended capabilities of the static resistance welding process addressing its opportunities respecting weld seam formation, weld continuity, advanced process control, mechanical performance of the welded joints and the applicability for assembling full-scale aircraft primary structures.

Weld Seam Formation

Thermoplastic welding technologies enable the manufacturing of complex assemblies consisting of components with reduced complexity, forming a unity comparable to an integral structure. In order to exploit the full lightweight and performance potential, the possibilities and limitations of the respective joining process e.g. weld seam formation and weld continuity should already be considered in the design phase.

The welding element remaining in the joint during resistance welding can be configured in the required seam width to assure the full coverage of the joint and form a preferred edge contour of the seam. Within the limits of the joining path, influenced by the semi-finished product constitution and the permissible fiber volume content in the weld seam, the matrix material emerging due to the squeeze flow can be advantageously shaped (cf. Fig. 1), using the weld toolings.

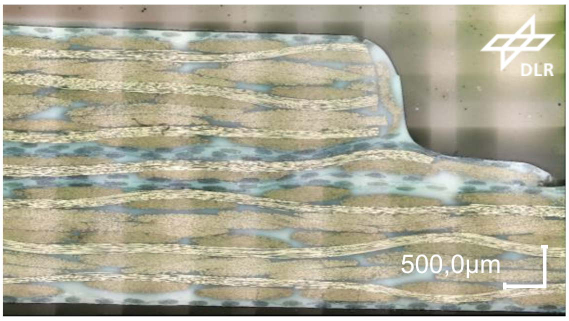

Fig. 1: *Preferential weld seam formation for decreased stress concentration and crack initiation at the edges of a representative CF/PPS SLS coupon*

In addition to the stress-reducing effect, this also seals the open cut edge of the Reinforced Thermoplastic Laminate (RTL). In order to achieve a comparable edge contour shape and sealing, continuous welding processes such as ultrasonic or induction welding require an additional processing step through additive material deposition, e.g. performed by a weld sealing process [2], or complex tool and process modification.

Weld Continuity

In addition to other requirements such as process robustness and reliability, the full coverage of a joint and its consistently uniform quality are basic prerequisites for certification. Water-coupled ultrasonic testing (WCUT) according to AITM6-4010 [4] is the most applicable non-destructive test method for validating thermoplastic composite welded joints. In the aerospace industry, the -6 dB criterion is used as the threshold value for non-conformant sound attenuation losses. These can be caused by internal disturbances and damage such as porosity, poor fusion or thermal degradation.

Pragmatically, the welding process must ensure full-surface coverage, continuous quality right up to the edge areas of the joint, as downstream mechanical machining processes in the assembly phase lead to undesirable additional work. Fig. 2 shows an example of a WCUT image of a (200 x 40) mm² weld sample in C- scan and with applied post-evaluation. The application of the -6 dB criterion shows an acceptable weld seam quality with a conformance area percentage (OK) of 82.6 % and a flaw area percentage of 17.4 %. Flaw regions along the longitudinal axis of the specimen (X), visualize sound attenuation losses in the range of (12.0 ± 1.7) dB. These are attributed to squeeze flow-induced porosity, caused by a local weld pressure reduction.

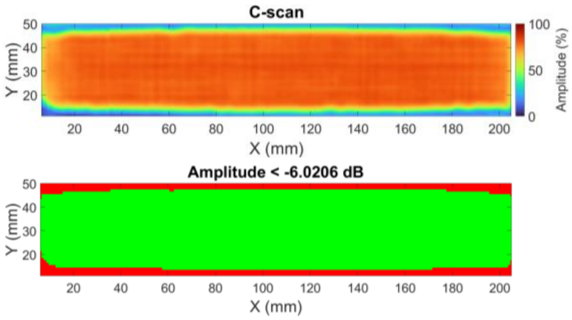

Fig. 2: *WCUT of a resistance welded coupon in the dimensions of (200.0 x 40.0) mm² with non-optimized tooling configuration*

The occurrence of increased sound attenuation losses towards the coupon longitudinal edges has already been discussed in [3] and can be prevented by optimizing the configuration of toolings and squeeze flow capabilities of the semi-finished weld product. In comparison Fig. 3 shows the C-Scan of a (200.0 x 12.7) mm² weld, manufactured under an optimized setting. Here, the application of the -6 dB criterion shows a very high weld seam quality with a conformance area percentage (OK) of 99.6 % and a flaw area percentage of 0.4 %. However, flaw attenuation losses were found being very close to be conformant at (6.4 ± 0.2) dB.

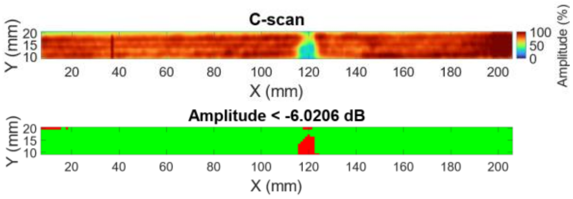

Fig. 3: *WCUT of a resistance welded coupon in the dimensions of (200.0 x 12.7) mm² with optimized tooling configuration*[1]

Mechanical Performance

Within an aerospace TRL 1-3, the three most applicable tests are validating the Single Lap Shear Strength (SLS, according to AITM1-0019) [5], Mode I fracture toughness by Double Cantilever Beam testing (DCB, according to AITM 1-0053) [6] and the Interlaminar Shear Strength (ILSS, according to ASTM D2344) [7]. Since RW is an applicable process for e.g. the frame integration within an aircraft fuselage, the described coupon tests can be extended by specific element tests like L-Pull static testing.

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[1] Please note that the non-conformance indication at (115 ≤ X ≤ 125) mm is caused by an invasive thermocouple measurement and was neglected within the evaluation.

The strength values published as follows were generated using a use case-oriented manufacturing approach. Consequently, focus was not set on maximizing the respective characteristic mechanical values by optimizing the semi-finished welding products, but on the premise of utilizing qualified or qualifiable off-the-shelf semi-finished products. Thus, the objective was driven by a given RTL configuration and a minimization of the welding auxiliary materials, which have a direct impact on the complexity of creating the welded joint, the component costs and its weight.

The coupons were welded using Toray Cetex TC1225 (CF/LM-PAEK) RTL`s, pre-consolidated 5HS, T300JB carbon woven prepreg weld conductors (281 gsm) and 4HS, EC5 glass woven prepreg (105 gsm) insulation sheets [8]. Mechanical testing showed SLS values of (28.3 ± 2.0) MPa [9] for adapted[2] SLS coupon dimensions. However, these values are in high agreement with achievable strength values for Cetex TC1100 CF/PPS joints (28.2 ± 0.8) MPa which showed the same fracture pattern at the glass matrix interface (c.f. [10]). Within the SLS and DCB testing dominant failure occurred at the GF/LM-PAEK interface which was described within [10] to be an effect of insufficient fiber-matrix adhesion respectively weak through thickness impregnation of the already pre-impregnated semi-finished GF product.

Considering the interlaminar shear strength (ILSS) values, resistance welded joints were from the same value of (73.1 ± 1.1) MPa as compared to the press-consolidated reference. Within DCB testing values for Mode I fracture toughness of (1279.3 ± 224.6) J/m² were reached within a preliminary screening. Again, fracture surfaces showed the same failure location at the GF-matrix interface, as compared to the SLS testing results.

Bauer et al. [11] published the results derived from L-pull testing of resistance welded joints. Here, strength values of (4.1 ± 0.3) kN are reported showing predominant failure offside from the weldline within the first ply of the base laminate, underlining the dedicated applicability of resistance welded joints for e.g. frame integration.

Advanced Process Control

Within thermoplastic welding the weldline characteristics, such as crystallite size and absolute crystallinity, are influenced by the cooling cycle. Though, advanced control of time, pressure and temperature have a decisive influence on the achievable matrix properties. Monitoring of welding parameters, like current, voltage and weld pressure allows for in-situ observation on the reliability and a dedicated comparison of the weld conduction with respect to a defined target envelope. Fig. 4 visualizes as follows an exemplary process cycle for resistance welding of CF/LM-PAEK with an as-designed first phase for quick heating, second phase for advanced crystallization at a dwell for 120 s at the temperature of maximized crystallization rate of 220 °C, followed by 120 s of cool-down towards the tooling temperature level of 90 °C.

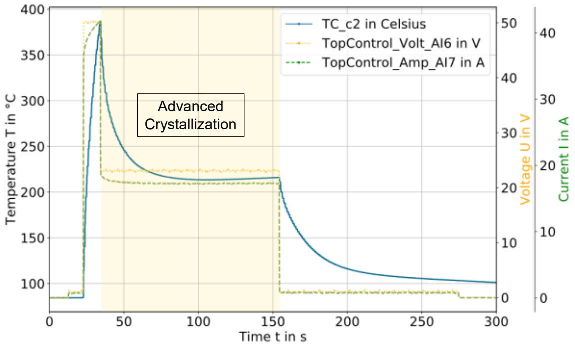

Fig. 4: *Multi-stage weld process control for targeted formation of the desired matrix properties in the weld seam*

However, when the scope is set on quick processing, neglecting a focussed generation of matrix properties, the second phase of dwell can be skipped. It becomes obvious that one of the essential benefits of resistance welding is the possibility of designing the process comparable to hot-forming with respect to the thermal management in the weldline. This enables for as-designed modification of through thickness heating, generating preferential weld seam thicknesses to allow for e.g. defined squeeze flow, stress relaxation or reduced-order tolerance compensation purposes.

Applicability

The transfer from coupon level towards full-scale of a dedicated component is a decisive step for visualizing scaling effects and confirming the technical applicability of a process in manufacturing. Within the MFFD upper shell manufacturing, resistance welding was chosen for the automated frame, frame-coupling and cleat integration demonstrating the process maturity and technical applicability on an eight-meter long aircraft fuselage shell. Additionally, questions like limited and one-sided component accessibility, accumulating tolerances or robot payload restrictions were covered by intelligent process and weldtool design. Thus, in total about 650 joints were generated using the

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[2] Referring to a 45° cover ply orientation in the weldline and a shear area of (25.4 x 22.0) mm².

resistance welding technology. However, comparable short welds with a maximum length of 102 mm were produced within the MFFD.

The ability to perform even longer welds of 1.5 m in aerospace quality was shown within the project HoTStufF. Here, the maturity of static resistance welding using a carbonfiber-based implant was essentially increased and demonstrated on base of the world's first all-thermoplastic aircraft rear pressure bulkhead [12]. The technical maturity, considering application-related, mechanical and qualitative requirements, was confirmed by an achieved aerospace TRL5 level.

Concluding Remarks

Resistance welding for the assembly of high-performance CFR TPs shows enormous potential for the production of an integral, high-quality welded assembly. This article is intended to demonstrate the possibilities of static resistance welding, focusing on an application-oriented technology development, considering incorporated requirements such as the use of qualified or qualifiable off-the-shelf semi-finished products and the reduction of welding consumables. Possibilities of preferential weld seam formation, weld seam continuity, mechanical performance, advanced process control and the applicability of static resistance welding for the assembly of full-scale aerospace components are discussed.

Acknowledgement

This study was made possible by the support of the projects "Hochkadenzfähige Thermoplast-Strukturen für Flächenanwendungen" (HoTStufF), funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), funded under grant agreement number 20W1915E as well as by the project MFFD funded by the Clean Aviation Joint Undertaking (CAJU), under grant agreement CS2-LPAGAM-2020-2023-01. The JU receives support from the European Union's Horizon 2020 research and innovation program.

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