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Future Plans for the Development of an Industrialized Continuous Ultrasonic Welding Process

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Abstract:
The need for robust joining methods for thermoplastic composites increases since the usage of these materials expands steadily in the aerospace industry. Continuous ultrasonic welding has been demonstrated in the recent years as one of the most promising joining techniques for thermoplastic composites to fulfill this need. This paper presents our state-of-the-art research conducted on continuous ultrasonic welding and aims to provide insight into the future steps needed to obtain an industrialized robotic welding process.

Keywords: Fusion Bonding, Continuous ultrasonic welding, Continuous seam, In-situ monitoring, Industrialization, Automation

Introduction

To increase the fuel efficiency of aircraft there is a constant need for weight reduction. The introduction of fibre reinforced polymers, hereafter referred to as composites, into aircraft plays an important role in weight reduction because of their high specific strength and stiffness, and the possibility to tailor the material properties. However, it has been challenging to be cost effective. This is where thermoplastic composites come in since they make it possible to use cost-effective forming and welding processes. Thermoplastic composites soften and eventually melt under the application of heat which can be utilized by these forming and welding processes.

The three welding techniques that are considered most promising are resistance, induction, and ultrasonic welding. Resistance welding and induction welding are both currently utilized welding processes in aviation. The rudder and elevator of the Gulfstream G650 were welded using induction welding [1], and the fixed leading edge of the A380 and A340 have been assembled using resistance welding [2]. Ultrasonic welding has not yet been applied in to assemble aircraft, but because it emerges as the fastest and most-energy efficient welding technique [3] and because the continuous process makes it possible to make long continuous seams for overlapping configurations [4, 5, 6, 7], it is considered a technology with a very high potential.

During the continuous ultrasonic welding process, a horn called sonotrode is pressed against the to-be-welded adherends while exerting high-frequency low-amplitude mechanical vibrations [8]. To focus heat generation at the welding interface an energy director (ED) is placed there. This ED is a resin-rich layer typically consisting of the same matrix material used for the adherends. Heat at the welding interface is composed of: frictional heating between the ED and the adherend surfaces and viscoelastic heating, which is expected to be significanlty higher at the ED because of its lower compressive stiffness [8, 9, 10].

In the past 5 years a lot of progress has been made by TUDelft on the development of continuous ultrasonic welding. This paper aims to show the progress made so far and to present our future plans within SAM|XL and TUDelft for the industrialization of the process. Firstly, we will discuss our progress made on laboratory scale. Secondly, a novel and promising quality monitoring system will be introduced based on laser line measurements. Finally, we will describe our plans for future process development to work towards a automated robotic continuous ultrasonic welding process that is suitable for aerospace applications.

Process development on laboratory scale

The usage of a sufficiently compliant ED was found to be of utmost importance to achieve a uniformly welded seam [6]. For CF/PPS adherends consisting of six 5HS fabric plies we compared the weld uniformity when using a 0.08 mm-thick film ED and a 0.20 mm-thick woven mesh ED. A significant increase in weld uniformity was observed in the case of the mesh as seen in Fig. 1. This was related to more uniform heating resulting from more uniform contact between the more compliant energy directing mesh and the adherends compared to the thin film [6].

In a follow-up study [5] on different welding parameter combinations, it was seen that changes in welding force and vibrational amplitude have a similar effect on the continuous process as compared to the static process. It was observed that significantly higher welding speeds can be achieved for high-force high-amplitude combinations as also seen for the static process. Welding speeds up to 55 mm/s were reached. However, the singe lap shear strength of continuous welds in this study was significantly lower than that of static welds, which was caused by the continuous process lacking a consolidation step, i.e., after the passing of the sonotrode the joint cooled down under no pressure.

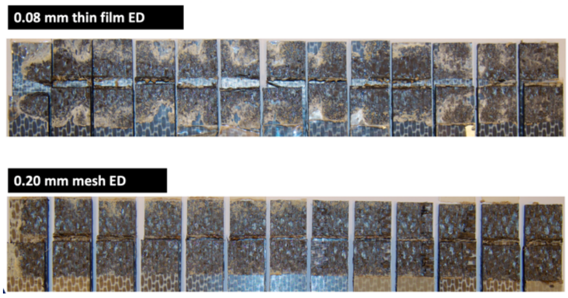

Fig. 1: *Fracture surface obtained after mechanical testing of adherends welded with the thin film and mesh energy director. Taken from [6].*

Consequently, we improved our continuous ultrasonic welding setup. We redesigned the entire setup, shown in Fig. 2, and added a consolidator. The main components of our improved setup are a stiff frame, an off-the-shelf welder from Herrmann Ultrasonics with a sonotrode having a rectangular contacting surface, an XY table that can translate in X-direction in an automated fashion and the consolidation unit. The setup allows us to make welds up with a length of approximately 80 cm. Additionally, the sonotrode can easily be exchanged to perform research on the effect of the sonotrode type.

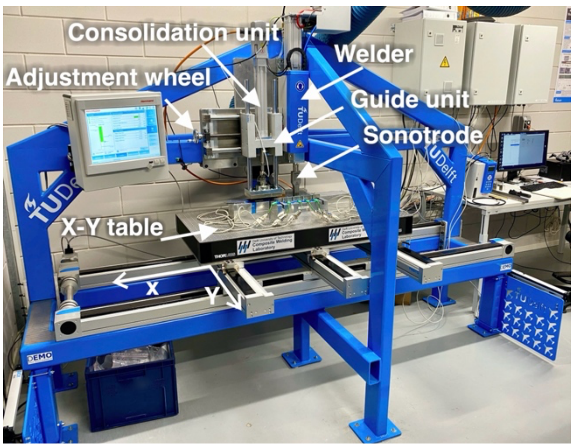

Fig. 2: *Continuous ultrasonic welding equipment at the Delft University of Technology. Taken from [4].*

The introduction of the consolidator behind the sonotrode significantly increased the singe lap shear strength of the joints [7]. Strength values up to 40 MPa were observed for the CF/PPS six plies fabric-based laminates. The thermal history of the joint however was found to play a crucial role on determining the placement of the consolidator. Placing the consolidator close to the sonotrode resulted in excessive matrix and fibre squeeze out and subsequent deconsolidation. Consolidation distances further away from the sonotrode resulted in high-strength joints with almost no porosity as shown in Fig. 3.

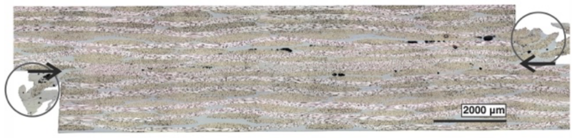

Fig. 3: *Cross-sectional micrograph of continuous weld consolidated using a far consolidation distance from the sonotrode. Taken from [7].*

Despite placing the consolidator further away from the sonotrode to minimize fibre and matrix squeeze out, still some squeeze-out was observed from mainly the top adherend, which indicated unintended through-the-thickness heating [7]. Most likely the top adherend consumed a larger portion of the vibration energy compared to the bottom [4]. The excessive squeeze out could be avoided by reducing the energy introduced in the material during welding. This could be achieved by either decreasing the vibration amplitude or by using a rounded sonotrode (Fig. 4) instead of a rectangular sonotrode. For both routes high quality welds could be obtained. An important added benefit of the rounded sonotrode, besides reducing the through-the-thickness heating [11], is the fact that it would allow welding of single-curved panels. This would open the door towards welding more complex structures.

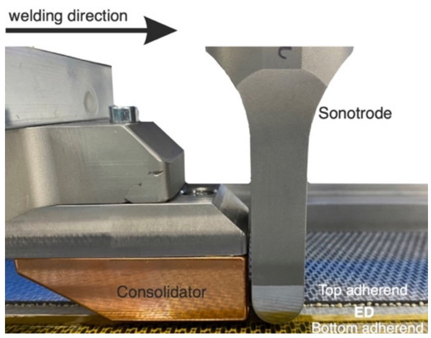

Fig. 4: *Rounded sonotrode and corresponding consolidator placement on a welded flat specimen.*

Demonstration panel

To demonstrate the potential of the continuous ultrasonic welding process a demonstrator consisting of a 400 mm by 500 mm flat stiffened panel was made, as seen in Fig. 5. Two CF/PPS omega stiffeners were welded to a skin using the round sonotrode shown in Fig. 4 by means of 4 long continuous welds.

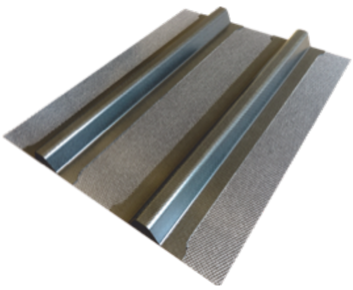

Fig. 5: *Omega stiffened demonstration panel assembled by means of continuous ultrasonic welding within the EcoTECH project.*

Novel quality monitoring methodology based on laser line scanner

The real-life industrial application of continuous ultrasonic welding cannot be viable without ensuring the high-quality of welds for the entire welding process. Therefore, an in-situ monitoring methodology was developed in collaboration with the CTC in Stade for the continuous welding process to accelerate its industrialization as a first step towards closed-loop quality control. The study indicates that the thickness of the weld-line is one of the most important parameters to evaluate weld quality of continuous ultrasonic welds. The weld line thickness can be monitored by utilizing 2D laser sensors measuring from the top and backside. Subsequently, an advanced in-situ monitoring methodology has been developed that utilizes 2D laser sensors. The Python-based monitoring system has been intended to operate in a wide welding speed spectrum (i.e., between 10 mm/s – 30 mm/s) to accommodate various CUW applications by performing analysis using the laser sensor data to evaluate the weld quality. The initial results revealed that the 2D laser sensor-based monitoring system can effectively track the thickness variations along the weld-line, which seems promising for the evaluation of the local and global weld quality.

Technology development roadmap

A schematic overview of the technology roadmap we are working on can be seen in Fig. 6. The process developments on laboratory scale form a strong foundation for further industrialization developments. However, for the technology to be useful for the aviation industry it is important to keep the actual applications in mind. The applications we aim at are welding of stiffeners to skin and welding of longitudinal/circumferential lap joints for example to join fuselage shells. For these applications we need to investigate the following topics:

- Welding of composites made from unidirectional plies.
- Welding of large overlaps (13-30 mm).
- Welding of long overlaps (1+ m).
- Welding of complex structures (e.g. thickness differences, realistic structures, curved components, step joints.)

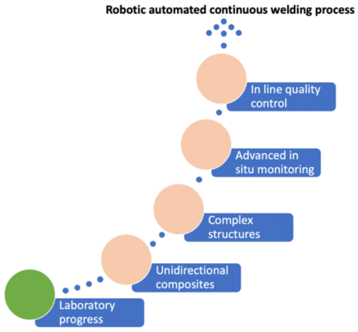

Fig. 6: *Schematic of roadmap for development of continuous ultrasonic welding.*

Being able to weld unidirectional composite materials is important for the applicability in aviation. We are currently studying the welding of laminates built up from 12 unidirectional plies CF/LMPAEK. The preliminary results look promising and high strength values were obtained. This study however needs to be expanded towards larger overlaps and longer welds. As soon as longer overlaps come into play, tolerances between parts and between the tooling might become more critical for the weldability. Another important aspect that needs to be investigated is the welding of realistic structural components that might have ramps or thickness differences and that might have small defects. Take for instance the automated fibre placement (AFP) technology for in situ consolidation. When this technology is used to manufacture components, it is highly likely that local defects are present. It should however still be possible to properly welds these components. Finally, being able to weld curved panels would be very important for the applicability of the technology. We applied for a patent [11] on a rounded sonotrode that would allow these types of welds. We are planning of investigating how to use consolidation rollers as an alternative to the consolidation shoe to allow the welds to cool down under pressure.

To further industrialize the continuous ultrasonic welding process and to guarantee a high weld quality it is important to have a solid weld quality monitoring system and potentially even be able to directly control it using close-loop control of processing parameters. The weld quality monitoring system would be a best step towards such a closed-loop controlled welding process. Currently we are working on a monitoring capability based on the combination of welding parameters and on the laser line measurements as presented before. However, for the presented laser line measurements in the previous section two laser line scanners were used: scanning from the top and the other scanning from the back of the overlap. This approach would not be feasible in an actual production environment, as most likely there is no clear line of sight for the laser scanner to the backside. Therefore, we are studying the possibility of only using one laser line scanner from the top. A potentially very useful tool that we will explore for quality monitoring and prediction is a model based on artificial intelligence.

Currently within SAM|XL we are working on the development of a robotic end effector. We are setting up a robotic continuous ultrasonic welding lab. We are ultimately planning to incorporate the in-situ monitoring and control system into this end effector to reach to an automated robotic welding technology.

Conclusions

This paper highlighted the progress made so far at SAM|XL and the TUDelft and set out the next steps to be taken to further develop and promote the industrialization of the continuous ultrasonic welding process. The main progress on the process is summed up below:

- Improving the weld uniformity by using a more compliant energy director.
- Studying the effect of the welding parameters on the process.
- Improving the weld quality by introducing a consolidator.
- Reducing through-the-thickness heating in the top adherend.
- Successfully welding of a demonstrator panel.
- Measuring the weld line thickness and identifying this as a promising parameter to monitor the weld quality.

To further industrialize the continuous ultrasonic welding process, it is needed to have a solid weld quality monitoring system in place that could be utilized as a first step towards closed-loop controlled welding. Additionally, for the industrialization of the process it is important to keep actual applications in mind. A roapmap for future planned developments has been presented to tackle the challenges imposed by these actual industrial applications.

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