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A Roadmap for developing an Industrial Continuous Ultrasonic Welding Process for Thermoplastic Composites

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Abstract:
The increasing use of fibre-reinforced plastics in the aerospace industry leads to challenges in joining these materials. The traditionally used mechanical fasteners introduce damage when used in composites by disrupting the fibres. However, thermoplastic composites allow for fusion bonding processes to join parts. Ultrasonic welding has shown to be a very promising high-speed fusion-bonding technique for thermoplastic composites. At the moment, a thorough understanding of the process is required to upscale the process for industrial usage. This study focuses on defining a roadmap to develop continuous ultrasonic welding to an industrially applicable level by presenting the current state of the art, ongoing developments, requirements, and challenges.

Keywords: Thermoplastic Composites, Fusion Bonding, Continuous Ultrasonic Welding, Energy Director

Introduction

The use of Fibre-Reinforced Plastics (FRPs) for structural purposes in the aerospace industry increased significantly over the past decades due to their advantages over metallic materials. An important aspect is the joining of FRP components, since these are unavoidable in aircrafts. The typically used method to join metallic components relies on mechanical fasteners, such as bolts and rivets. However, these are disadvantageous when used in FRPs. The presence of holes and cut-outs causes local disruption of the fibres and introduces substantial stress concentrations. Thermoplastic Composites (TPCs) allow for fusion bonding processes to join parts. During these processes, the thermoplastic polymer melts upon heating, allowing molecular interdiffusion to take place due to the mobility of the polymer chains. Currently, industrially applied fusion bonding techniques are resistance welding and induction welding [1,2]. However, these processes are slow, generally require foreign material at the interface (e.g. a metal mesh) [3] and serious challenges arise when lighting strike protection is present in the composite structure that needs to be welded.

Ultrasonic Welding (UW), on the other hand, has shown to be a very promising high-speed joining technique for TPCs. During the UW process, a sonotrode exerts static pressure and high-frequency low-amplitude transverse mechanical vibration on the adherents. A thin film of the same resin as the composite's matrix, called an Energy Director (ED), is placed in between the adherents. Due to its lower stiffness compared to the fibre-reinforced adherents, the ED is subjected to higher cyclic strain, thus generating more heat through viscoelastic effects, resulting in a localised heat generation at the interface [4-6]. Over the past years, static ultrasonic welding has been the focus of an extensive amount of studies, leading to a good understanding of the static process [4,5,7-9]. As a result, the possibility of performing sequential spot welds has shown to be a promising method for the attachment of composite brackets and clips [10,11].

To apply the ultrasonic welding process in high performance aerospace structural components, a continuous process must be developed. Evolving UW from a static to a continuous process allows for higher loads to be transferred and minimises stress concentrations.

The current maturity level of Continuous Ultrasonic Welding (CUW) is not sufficient to upscale the process for industrial usage. For this reason, academia (Delft University of Technology), and industry (Composite Technology Center Stade) have joined forces. The goal of the cooperation is to develop this technology by sharing competences and expertise on different areas. This paper focuses on setting out a roadmap for the development of the CUW technology to an industrially applicable level by presenting the current state of the art research on CUW and analysing challenges foreseen for the future of this technology.

State of the art of continuous ultrasonic welding

The development of continuous ultrasonic welding of fibre-reinforced thermoplastic parts started in 2015 at the TU Delft. The setup used for the welding process is shown in Figure 1. The ultrasonic stack (i.e. converter, booster and sonotrode) moves with respect to the adherents. To start the welding process, the sonotrode moves down until it exerts a constant pre-defined static welding force on the adherents, then the transverse ultrasonic vibrations are initiated and the sonotrode slides over the overlap to make a continuous weld.

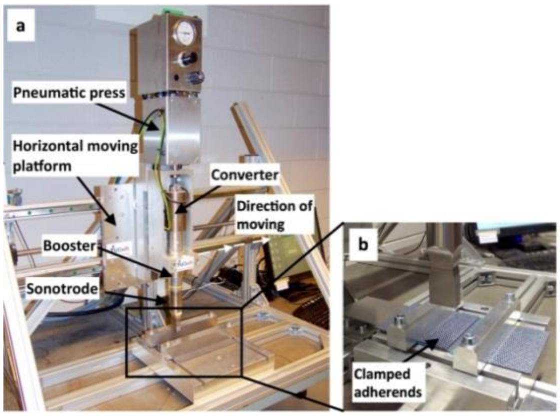

Figure 1: (a) Setup for continuous ultrasonic welding (b) close-up of clamped adherents. The displayed sonotrode is rectangular 14.9 mm by 30 mm.

Continuous ultrasonic welds were made by Senders et al. with the machine shown in Figure 1. CF/PPS plates (five harness satin weave fabric $[0/90]_{3s}$) were welded at a speed of 60 mm/s. In order to focus the heat generation at the weld interface a 0.08 mm-thick PPS film was used [12]. The resulting weld line and fracture surfaces after lap shear testing are shown in Figure 2. The fracture surfaces revealed a non-uniform welded area. It could be observed that intact PPS film is still present at the interface, resulting in unwelded areas and porosity. The single lap shear strength obtained was 29.5 ± 4.9 MPa, which is lower than the 37.3 ± 1.6 MPa obtained for static spot welds [9]. Even though this machine helped to prove the feasibility of continuous ultrasonic welding, it had some limitations: a low power output, a low stiffness frame holding the welder, and a limited number of parameters that can be controlled.

Figure 2: Fracture surfaces of CF/PPS laminates. Welding force of 500 N and a peak-to-peak amplitude of 49.5 µm. On the left the top surface of the laminates after welding is shown, white arrows indicate surface damage due to overheating. On the right the fracture surface of the weld is shown after mechanical testing. Adapted from [12]

To improve the uniformity of the welded area a 0.20 mm-thick PPS woven mesh energy director was introduced as an alternative to the 0.08 mm PPS film [13]. It has been shown that the mesh filaments flatten and expand almost instantly from the start of the welding process. The mesh flattening and expansion, called pre-forming, established a proper intimate contact between the mesh and the adherents early in the welding process. Most likely this intimate contact resulted in a more uniform heat generation, making it possible for molecular interdiffusion to take place all over the surface of the joint. Therefore, large areas of intact ED, present when using a 0.08 mm-thick flat film, could be avoided [13].

In 2017 a new continuous ultrasonic welding machine was developed by the TU Delft that is more powerful, has a much stiffer frame, and allows more parameters to be sampled in situ. The machine is shown in Figure 3. The ultrasonic stack is kept stationary in a high stiffness steel frame. The X-Y table is automated in X-direction and the movement can be controlled by the software developed and installed on the PC.

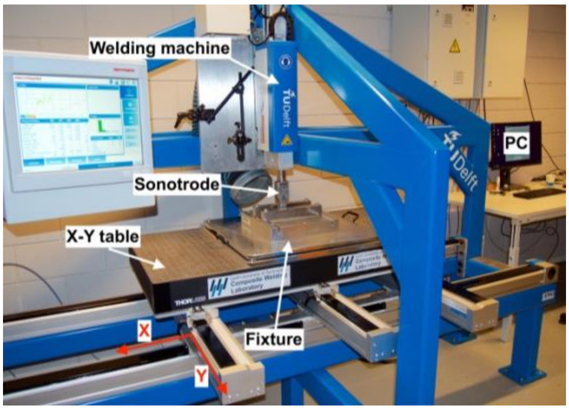

Figure 3: New continuous ultrasonic welding machine developed by the TU Delft. The welding machine is the VE20 Slimline dialog 6200 from Herrmann Ultrasonics working at 20 KHz.

The working principle of the new CUW machine is very similar to the previous setup shown in Figure 1. The movement of both, the welding stack and table is computer-controlled. During the entire welding process, the following parameters are sampled at a rate of 1000 Hz: the table location, the power, the transverse sonotrode displacement, the amplitude, and the weld force. Besides these parameters, it is possible to measure the temperature at 5 different locations with k-type thermocouples. The sampling of the temperature takes place at 1000 Hz and the data is synchronized with the data of the welding machine. Plates with 220 mm-long overlaps were welded at a speed of 35 mm/s using the new machine setup and by utilising the 0.20 mm-thick mesh. The subsequent mechanical tests showed LSS values of 30 ± 1.7 MPa, similar to the strength obtained by Senders et al. [12]. However, the fracture surfaces obtained with the new welding machine displayed uniformly welded areas, whereas the fracture surfaces from Senders et al. in Figure 2 contained intact PPS film. This higher uniformity is also indicated by the lower standard deviation in strength. It must be mentioned that the welding parameters, e.g. welding speed, have not been optimized yet and thus in the future higher LSS values are expected.

Global roadmap for future development

The recent achievements in the development of CUW demonstrated its potential. In order to use the technology on an industrial level, more research is needed to further develop the process. As described in the previous paragraphs the CUW research is so far limited to CF/PPS plates. As a first step the research will be expanded to multi-axial laminates using uni-directional (UD) CF tape and PEEK or PEKK matrix systems characterised by high melting temperatures (T_m). Welding those materials is one enabler for the application of CUW on primary aerospace structures. The second step involves going from constant thickness laminates towards welding laminates with ramps and varying thickness as those are very common in aerospace structures due to load optimised designs. The welding of adherents with varying thickness requires an in situ monitoring and control system to adapt the process as the optimal process parameters will most likely change. Therefore this system will be developed simultaneously to the research on laminates with varying thickness. A very common phenomenon is local gaps between the adherents which are caused by manufacturing and positioning tolerances. To develop the process in a way to cope with those tolerances is the third step on the roadmap.

Parallel to these three steps other industrialization aspects of the CUW will be investigated. This development is also split in several steps. The first step involves the use of more industrial equipment such as an industrial robot and achieving acceptable and uniformly welded areas on flat laminates. In the second step, welding of stiffeners on flat laminates will be addressed to develop the process further. In the next step, the complexity is increased by welding parts that have double curvature with fuselage shells as a typical example. The last step involves the combination of the previous steps and also includes the aspects of already applied paint or lighting strike protection on one or both parts. Although developments can be performed in parallel, it has to be noted that all of them are interdependent. All steps are inevitable to develop CUW to a high level of maturity and finally realise the application in aerospace and other industries.

In situ monitoring of the process

One of the main advantages of ultrasonic welding is the possibility of implementing an in situ monitoring system to correlate the process output data with phenomena occurring at the weld line. This facilitates the prediction of certain characteristics and quality of the performed weld by analysing the feedback data. For static welds, Villegas [4] was able to correlate the different events in the power and vertical displacement curves with alterations at the interface polymer, which in turn could be associated with the weld quality. For continuous welds, however, an analogous in situ monitoring procedure is not straightforward. The continuous nature of the process leads to a more complex analysis of the dissipated power, given the continuous increase in joint stiffness during the welding process. For these reasons, it might become necessary to make use of additional sensors to monitor the process.

As an example, the vibrations imposed by the sonotrode on the adherents are expected to vary throughout the continuous welding process, as their propagation is affected by the state of the interface. This information about variations in the adherents' vibration could potentially be linked to the occurrences at the weld interface.

The implementation of an in situ monitoring system is beneficial, not only because it might provide real-time information regarding the joint quality, but also the location of possible weld defects. Therefore, inspection times can potentially be reduced.

The use of in situ monitoring techniques, together with process control becomes necessary when dealing with thickness variations in the adherents. Variations in thickness are quite common in aerospace structures. Examples of this are the continuous variations of a skin thickness by ending/starting of interior plies, or the placement of doublers to locally reinforce the structure. The presence of thickness variations during a continuous ultrasonic weld will most likely lead to a variation of the optimal process parameters. The in situ monitoring system can potentially be used as the basis for a closed-loop control system with the ability of adapting some of the welding parameters in real-time. Welding parameters like the welding speed or the vibrational amplitude can be used to control the process. The goal of controlling the process parameters in real-time is to maintain a uniform joint quality in continuous welds with varying thickness.

Robotic continuous ultrasonic welding

Robotic continuous ultrasonic welding is one approach for the transition from the current X-Y table setup towards more industrial machinery (Figure 4). Robotic continuous ultrasonic welding can be used to weld aerospace structures which can have a complex shape or constitute of T or L-shaped profiles welded on a base laminate as some examples.

A 6-axis industrial robot offers a more flexible work space and allows welding more complex parts. However, it is expected that an industrial robot interacts differently with the ultrasonic welding process compared to the currently used equipment consisting of an X-Y table and a static sonotrode. As described in the state of the art section of this paper the first generation of continuous ultrasonic welder at the TU Delft (Figure 1) already indicated that the stiffness and displacements of the welding machine might influence the welding process. In contrast to the very stiff current machinery, an industrial robot presents a less stiff system leading to possible displacements within the robot joints. Additionally, it continuously changes its stiffness while moving its axes to create the weld line. The reason for this is the structure of the robot consisting of links and joints. Different postures of the robot to reach the weld points or the weld line leads to different stiffness and therefore to different displacements [14].

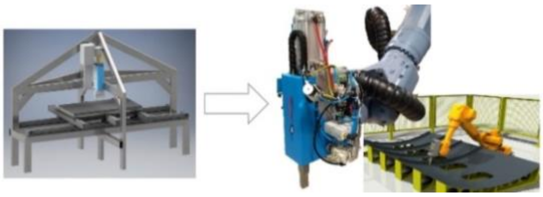

Figure 4: Transition from current setup using X-Y table and static sonotrode towards an industrial robot moving the sonotrode along weld line as an example for industrial machinery

The second step is the application of robotic continuous ultrasonic welding on realistic aerospace structures, which requires overcoming several challenges. This includes the maximum length of a weld line that can be welded with constant parameters, welding of stiffener edges, the sonotrode design and insufficiently welded stiffener feet.

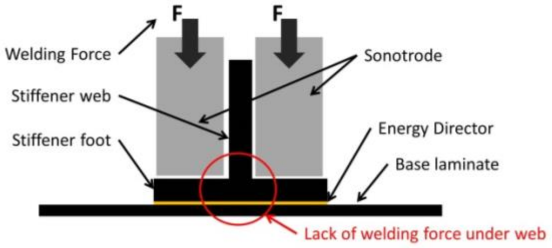

Figure 5: Application of welding force under stringer web which is critical for a T-stiffener on a base laminate because the sonotrode is only applied on stiffener feet

A very common example for an aerospace structure which faces some of the challenges listed before is the welding of a T-stiffener on a base laminate as it is shown in Figure 5. In current research activities the sonotrodes were either circular (for spot welding) or rectangular (for static and continuous welding). Assuming that both feet of the T-stiffener in Figure 5 will be welded simultaneously to save process time and use the full potential of the technology, the geometry of the sonotrode needs to be adapted to the shape of the stiffener. Most certainly this will have an impact on the welding process. The sonotrode needs to be design in order to avoid non-uniform vibration, but no research has been performed on this field in the frame of continuously welding FRPs. The specific of the T-stiffener with a vertical web currently makes it impossible to apply weld force and cyclic strain on the area of the foot underneath the web (Figure 5). Although no welding force and cyclic strain will be applied directly under the web, the effect that the energy director is still melted partially or fully needs to be studied. In case a fully welded stiffener foot cannot be achieved, the impact of a non-welded area onto the overall performance of the stiffener needs to be investigated. Solving those challenges related to stiffeners brings CUW closer to be applied in industry and the results can be transferred to applications such as welding spars and ribs of wing or flaps as examples for typical aerospace structures.

Conclusions

This paper outlined a roadmap for the development of industrialised continuous ultrasonic welding by describing the state of the art and by setting out a roadmap for future development steps. Currently, high strength joints were obtained on a lab scale at welding speeds of approximately 35 mm/s by continuously welding CF/PPS plates. In order to use this promising technology in the aerospace industry certain development steps need to be taken. The paper identified a number of those steps and the following ones will be addressed in the near future:

- Understand the effect of different thermoplastic composites on the welding process (e.g. stiff plates made from UD tapes and thermoplastics with a high T_m) and develop a strategy to weld them.
- Develop a system to continuously monitor and control the welding process. The feedback data of the process can potentially be related with phenomena occurring at the interface.
- Be able to weld parts with thickness differences and ramps.
- Develop a robotic continuous ultrasonic welding process.
- Further develop the robotic continuous ultrasonic welding process for the welding of stiffeners onto base laminates.

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