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Publication date
2022

Document Version
Final published version

Published in
Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability

Citation (APA)
Akay, E., Köhler, F., & Villegas, I. F. (2022). In-Situ Monitoring of Weld Line Thickness in Continuous Ultrasonic Welding of Thermoplastic Composites. In A. P. Vassilopoulos, & V. Michaud (Eds.), *Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability: Vol 2 – Manufacturing* (pp. 616-623). EPFL Lausanne, Composite Construction Laboratory.

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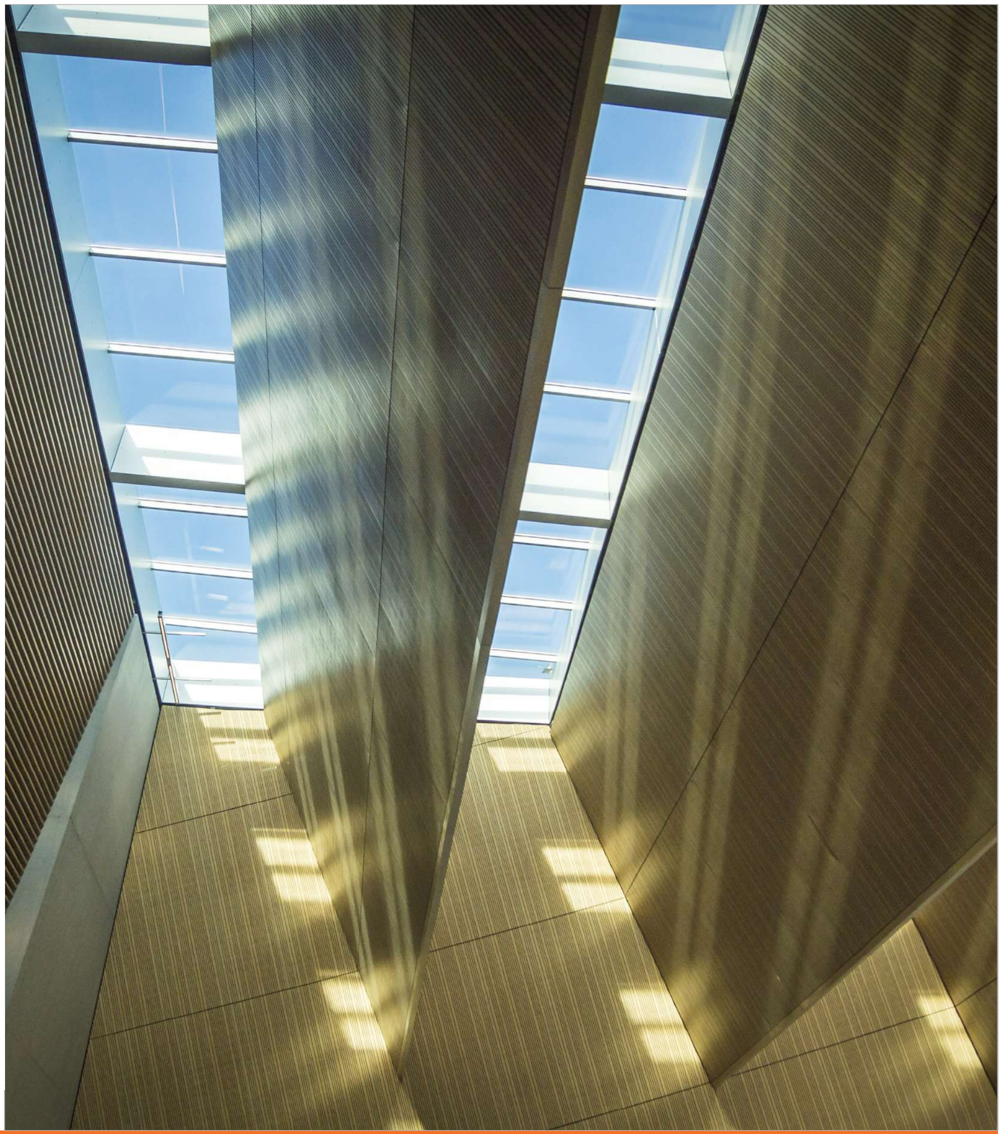

Proceedings of the 20th European Conference on Composite Materials

COMPOSITES MEET SUSTAINABILITY

Vol 2 – Manufacturing

Editors : Anastasios P. Vassilopoulos, Véronique Michaud

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Oragnized by:

Composite Construction Laboratory (CCLab)
Laboratory for Processing of Advanced Composites (LPAC)
Ecole Polytechnique Fédérale de Lausanne (EPFL)

ISBN: 978-2-9701614-0-0
DOI: http://dx.doi.org/10.5075/epfl-298799_978-2-9701614-0-0

Published by :

Composite Construction Laboratory (CCLab)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
BP 2225 (Bâtiment BP), Station 16
1015, Lausanne, Switzerland

https://cclab.epfl.ch

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IN-SITU MONITORING OF WELD LINE THICKNESS IN CONTINUOUS ULTRASONIC WELDING OF THERMOPLASTIC COMPOSITES

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Abstract: *Continuous ultrasonic welding is a very fast and efficient composite joining technique that has been developed in recent years and especially aimed for aerospace applications. Researchers have put a significant amount of effort into revealing the capabilities of continuous ultrasonic welding and the current study was aimed to complement prior work by suggesting a potential in-situ monitoring methodology for the process. Within the scope of this study, a correlation between the weld line thickness and weld quality was experimentally shown by using a robotic continuous ultrasonic welding system located at* CTC GmbH in Stade. *The aforementioned correlation then used to demonstrate a possible laser sensor based monitoring methodology for continuous ultrasonic welding process by utilizing the frame based continuous ultrasonic welding system located in the Faculty of Aerospace Engineering at Delft University of Technology.*

Keywords: Thermoplastic Composites; In-situ Monitoring; Continuous Ultrasonic Welding; Thickness Measurement; Laser Sensors

1. Introduction

Continuous ultrasonic welding (i.e. “CUW” in an abbreviated form) is one of the most efficient integration methods of thermoplastic composites. Researchers from our group have already utilized CUW method by using both frame based and robotic welding platforms to achieve sufficient amount of joint strength for aerospace applications and they have also improved CUW process in many aspects [1-6]. On the other hand, the implementation of this method into an industrial manufacturing process still requires the ability of consistent and high-quality welding in a controlled manner. It is obvious that a sophisticated monitoring system, which is developed for ensuring the highest-level of weld quality in each practice will play a key role to transform CUW process into a commonly relied on industrial tool.

Typically, experimental techniques like micrography, mechanical testing and fracture surface examinations are used to determine the quality of a welded composite joint. Information gathered from these evaluation techniques are always convenient to correlate the process parameters and other process data with the welded joint performance. On the other hand, aforementioned examinations can only be a part of the baseline research, if the ultimate goal is performing in-situ quality evaluations in an industrialized manufacturing process. To achieve this goal, several studies were conducted within the past decade. Villegas showed that monitoring welding process can be an efficient way to define a desired parameter envelope for high strength welds and also power and displacement data obtained from the microprocessor-controlled ultrasonic welding machine can be effectively used for in situ monitoring of the static ultrasonic welding process [7 - 9]. Previous research indicates that, a specialized monitoring technique for continuous ultrasonic welding process can be beneficial to take a step forward for industrialization of this joining method for thermoplastic composite structures. Therefore, within the context of this study, a possible way for in-situ monitoring of the CUW process was investigated by performing weld line thickness measurements.

2. Weld-line thickness investigation for robotic ultrasonic welding process

2.1 Experimental setup and specimen preparations

Within this part of the study, the correlation between the weld line thickness and the quality of the welds was assessed. The quality of the welds was determined by the lap shear strength of welded adherends. The study was performed on a robotic ultrasonic welding cell at the CTC GmbH in Stade as seen in Figure 1. A Kuka KR125 using a KR C2 controller is used to move the welding head along a predefined and programmed weld path. The welding head itself consists of the welding train which is supplied by Herrmann Ultraschalltechnik. The welding head is complemented by a pre-clamping and a consolidation unit to allow for sufficient consolidation. This setup was already used by our research group in a previous study [6].

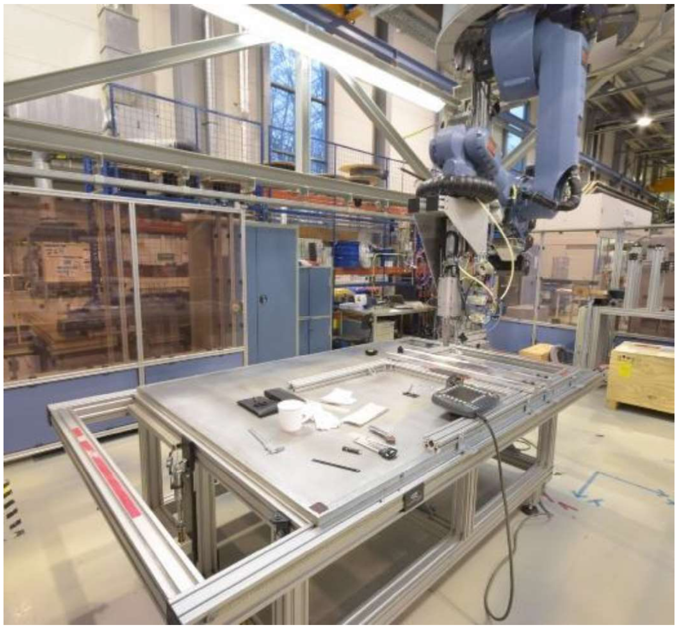

Figure 1. Robotic ultrasonic welding cell at CTC GmbH in Stade

Welding was performed on coupons in a single lap configuration. The total weld length was 250 mm. The adherends were made out of high performance unidirectional material from the PAEK family. A multiaxial layup was used which resulted in a adherend thickness of 2.2 mm. After welding the adherends were cut into single lap shear specimen and were tested according to ASTM D1002 with a crosshead speed of 1.3 mm/min. In total 8 samples were extracted while areas at the beginning and at the end of the weld line were discarded. The sample dimensions and the cutting plan are shown in Figure 2. A discontinuous energy director with an areal weight of 160 g/m² made out of the same polymer material as the adherends' matrix was used throughout the study.

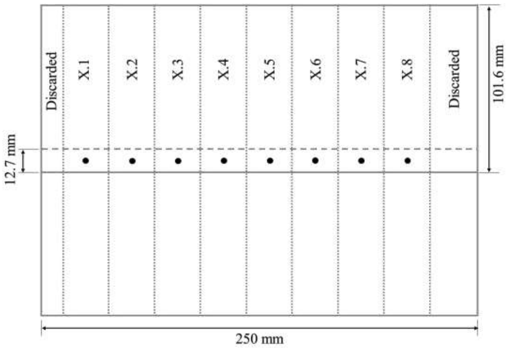

Figure 2. Sample dimension and cutting plan of the coupons used for welding. The black dots mark the point of measurement for the weld line thickness

2.1 Measurements and results

To determine the weld line thickness (i.e. t_{weld_line}), the thickness of the coupons (i.e. $t_{upper\_adherend}$ and $t_{lower\_adherend}$) in the intended weld area was measured before welding. After welding the total thickness of the welded area was measured. To obtain the resulting weld line thickness the thicknesses of the upper and lower adherends are subtracted from the thickness in the weld area according to the equation below:

$$t_{weld\_line} = t_{welded\_area} - (t_{upper\_adherend} + t_{lower\_adherend}) \tag{1}$$

All measurements were done using a caliper. To correlate the weld line thickness to the achieved lap shear strength, measurements were taken in the center of each specimen prior to welding and prior to final testing. The locations of the measurement points are shown in Figure 2. Within the study, a constant vibration amplitude and only one type of energy director was used while the welding speed was varied between 18-32 mm/s.

Figure 3 shows the lap shear strength as a function of the calculated weld line thickness. The lap shear strength is given as percentage of the highest lap shear strength achieved within this study. The weld line thickness is given in relation to the energy director thickness before welding, while 100% (vertical line) marks the original energy director thickness. Each color represents a coupon welded with a specific welding speed. The graph indicates a correlation between the weld line thickness and the lap shear strength which can be achieved. Weld line thicknesses which are higher than the original energy director thickness tend to result in lower final lap shear strength. Those samples also showed porosity within the weld line which is a sign of poor welding quality and, in those cases, insufficient consolidation. In contrast, specimens with a weld line thickness of 10-30 % of the original energy director thickness show lap shear strength values around 80% or higher compared to the maximum achieved value. Those specimens also show no signs of porosity or un-welded areas. For those specimens showing a negative weld line thickness it has to be noted that the chosen method of determining the weld line thickness cannot distinguish between thickness decrease happening in the weld line and a decrease in thickness of the adherends itself. Negative thickness therefore can be caused by significant through-the-thickness heating and fiber squeeze out. Although the resulting lap shear strength values are not affected by this, through-the-thickness heating and fiber squeeze out should be prevented as much as possible as it can lead to porosity within the weld line especially at the edges of the weld area. It is assumed that even lower weld line thicknesses would also have an effect on the lap shear strength as the integrity of the adherends is reduced.

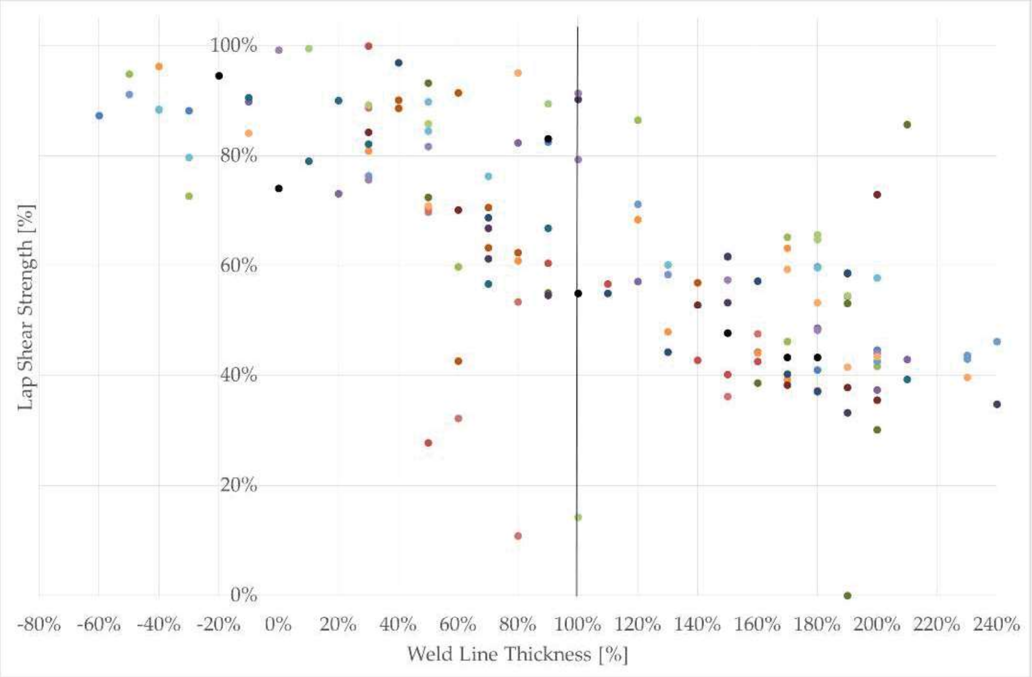

Figure 3. Graph shows the lap shear strength in relation to the weld line thickness. Lap shear strength is given as percentage to highest achieved lap shear strength. Weld line thickness is given in relation to energy director thickness prior to welding (marked as vertical line). Each color stands for one specific welding speed.

3. Monitoring system development for weld-line thickness measurements

3.1 Continuous ultrasonic welding machine and welding experiment details

The correlation between weld-line thickness and weld quality observed from the experiments performed with the robotic continuous ultrasonic welding system indicated the possible benefits of a well established in-situ monitoring methodology for continuous ultrasonic welding process based on thickness measurements. Consequently, it was decided to develop a weld-line thickness monitoring system for performing in-situ measurements and quality evaluations with dedicated sensors. For this purpose, the continuous ultrasonic welding frame-based machine located in the Faculty of Aerospace Engineering at Delft University of Technology was chosen. This particular CUW machine utilizes a very stiff frame structure and consists of four main subsystems, namely ultrasonic welding machine, consolidation system, movable X-Y table and the welding fixture, as seen in Figure 4a. The sketch in Figure 4b shows the lay-out of the adherends and energy director within the welding clamping fixture for welding process.

Composite adherends for the welding experiments were manufactured out of 5 harness-satin CF/PPS thermoplastic powder-impregnated material . The dimensions of the adherends cut from the manufactured laminate were 220 mm x 101.6 mm. The nominal thickness for each adherend was measured as 1.8mm and the overlap length was 12.7mm. A 0.2mm-thick discontinuous PPS energy director (i.e. the woven mesh introduced in [2]) was used for the experiments. A specific set of welding parameters (i.e., welding force, amplitude, consolidation force and distance between consolidator and sonotrode) were applied along the entire study. During the welding experiments, only the welding speed was changed between 7mm/s to 30mm/s, to differentiate the weld line properties in a controlled manner.

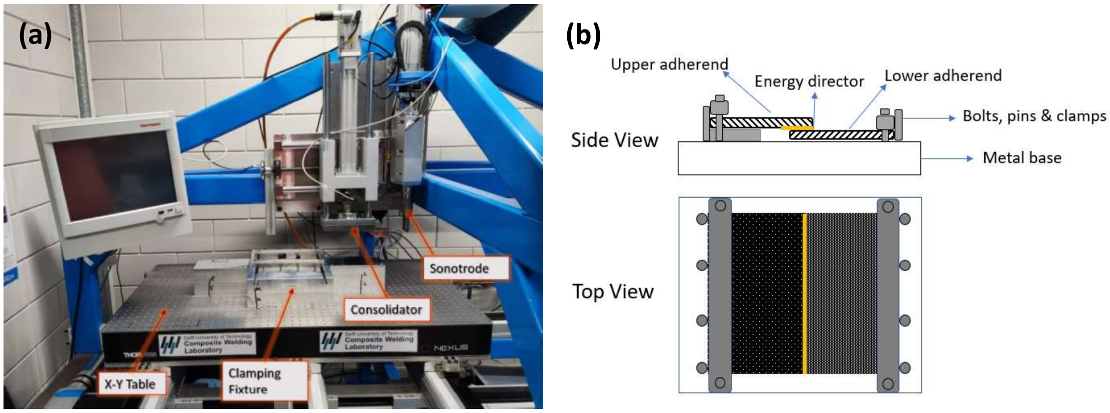

Figure 4. (a) Continuous ultrasonic welding system, (b) the welding clamping fixture that is used for adherend and ED placement for CUW experiments

3.2 Monitoring setup and measurement methodology

The stiff structural frame of CUW machine was able to accommodate any size of sensors while keeping them attached rigidly in place, which was important for creating a system without any complexities or calibration problems. Initially, two different types of laser sensors (i.e. spot laser sensor and 2D line laser sensor) for weld-line thickness measurement and a thermal camera for temperature measurement were utilized along with the designed sensor frame. All of these components were integrated into the CUW system for performing in-situ monitoring experiments as seen in Figure 5. After conducting some preliminary experiments with this initial design of the in-situ monitoring system, it was soon understood that subsequent sensor frame iterations had to be performed to achieve an optimal measurement experience, which resulted five different iterations of monitoring setups in total. In each setup, different equipment configurations and consequently different variations of the data processing and analysis algorithm were generated due to the modifications on the sensor locations and measurement methodologies.

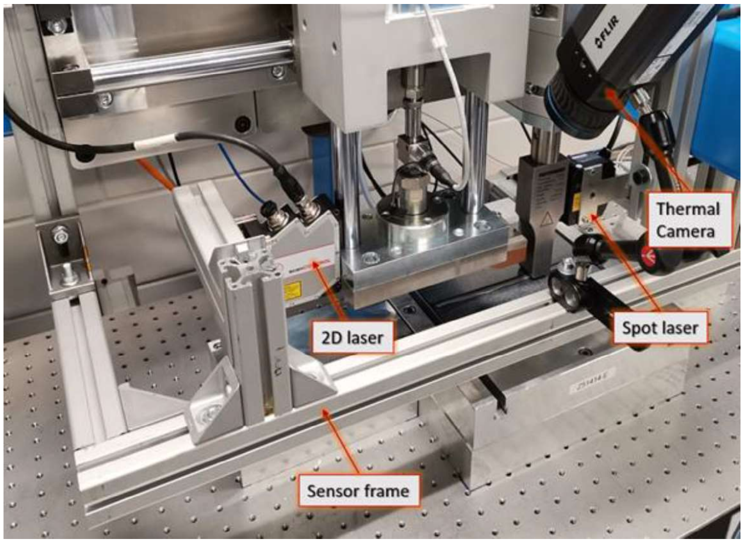

Figure 5. The initial design of in-situ monitoring setup for CUW process

Using the least possible number of sensors is desirable for achieving an efficient and easy to apply in-situ monitoring system for CUW process, since there is a direct proportion between the number of sensors, data size, computation time and system complexity. Therefore, the configuration that utilizes a single 2D laser sensor was chosen for the demonstration purposes in this study. For this purpose, a single 2D laser sensor (i.e. Micro-Epsilon scanCONTROL 2950-25) was used to scan the upper and lower adherends before the weld process, and it is used to scan the welded area after the weld process as seen in Figure 6. By performing these 2D scans, three set of data files were obtained. Following that, recorded data files were processed within the Python algorithm to calculate the thickness of the upper adherend, lower adherend and welded area at thousands of equally spaced stations along the weld direction, respectively. Finally, the thickness information obtained from each scan were used to calculate the actual weld-line thickness values at the same stations along the weld direction by utilizing Equation 1.

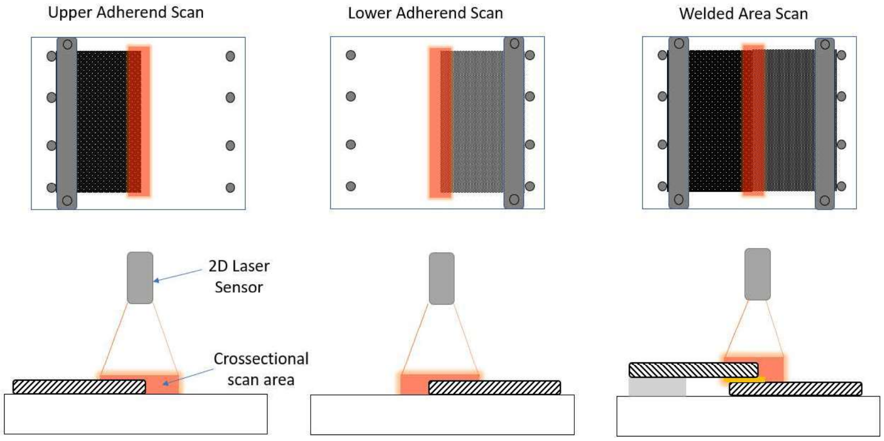

Figure 6. Adherend and welded stack thickness measurement

3.3 Weld-line thickness monitoring

The output of a weld-line thickness measurement analysis for the experiment performed at 15mm/s weld speed is provided in Figure 7 as an example. For this experiment, the welding process was started at approximately 15mm away from the starting edge of the adherends and continued up to the point of 205mm from the same edge resulting with a 190mm long weld. Y axis of the given curve in this plot indicates the weld line thickness of the welded stack calculated by moving-average of the data and x-axis shows the weld direction starting from the edge. It can be seen that a significant weld line thickness decrease occurs in the first 15mm, then a relatively flat weld line thickness behavior is visible and lastly the calculated weld line thickness increases significantly after around 205mm. From the experiment, it is known that the initial and final areas with steep thickness variation in this plot falls out the actual welded area, therefore it can be stated that the gap between the unwelded adherends is misleading the thickness measurement in these locations and the actual weld line thickness (i.e. the flat area in the plot) of this welding experiment deviates around approximately 60µm. Within the monitoring algorithm, the first derivative of the moving-average data was analyzed to designate these unwelded areas. By using the result of this analysis, the start and end locations of the actual welded area were calculated, and initial & final unwelded areas were automatically indicated as seen in Figure 7.

The variations in weld line thickness were also used for identifying local quality issues. In Figure 8a, the blue plot indicates the weld-line thickness measurement output of the monitoring system for the experiment that previously discussed (i.e. performed at 15mm/s weld speed).

Here, the single lap shear strength percentage values (i.e. with respect to the maximum achieved strength value) of individual specimens cut from the same welded plate are also shown as green bars. Additionally, in Figure 8b, actual fracture surface images of each specimen are shown in the picture. From the figure, it can be observed that the general correlation of the calculated thickness variation with the lap shear strength values seems promising. Especially the reflection of one of the larger unwelded areas (i.e. area indicated with the red rectangle) onto the thickness measurement output and lap shear strength values indicates the potential advantage of the developed system for precise quality monitoring along the weld line.

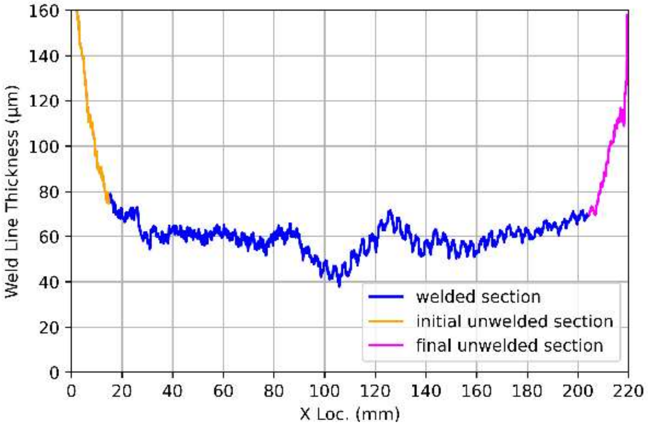

Figure 7. Weld line thickness measurement and unwelded area detection

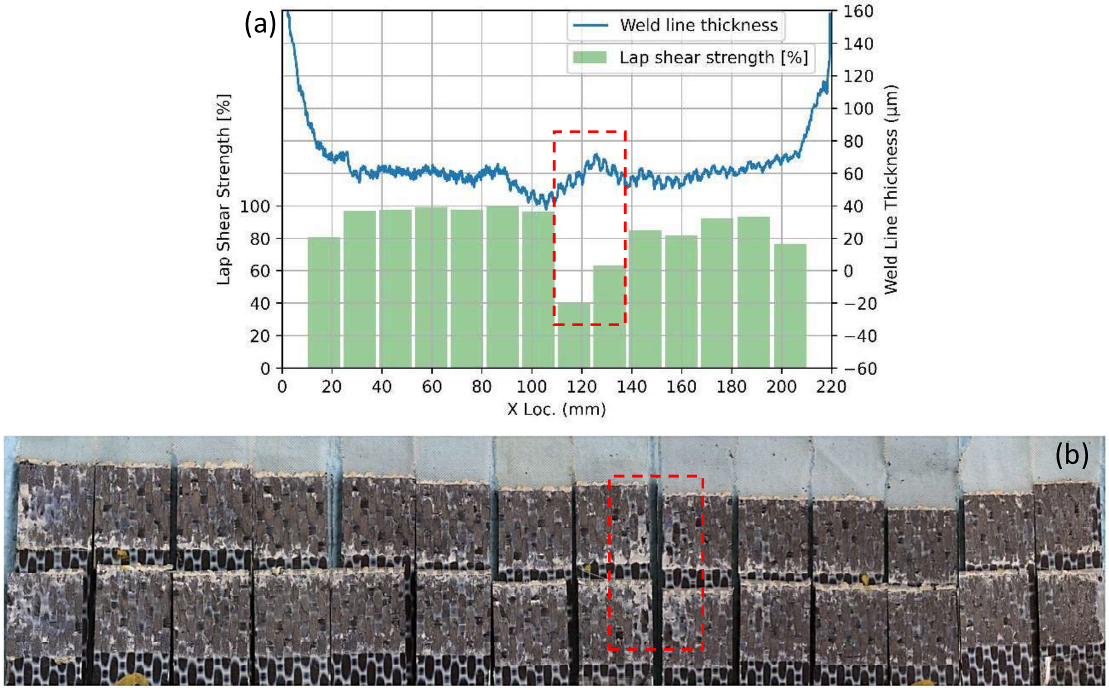

Figure 8. (a) Weld-line thickness (in blue) and SLS strengths (in green) comparison, (b) fracture surface image of single lap shear test specimens

4. Conclusion

Even though continuous ultrasonic welding promises a very fast and efficient joining capabilities for aerospace grade thermoplastic composites, the requirement of consistency in high quality results is one of the main challenges for industrialization of this technology. Investigations performed within the first part of this study (i.e. with the robotic CUW system) revealed that there is a significant correlation between the weld line thickness and lap shear strength values. Since lap shear strength is one of the most reliable indicators of the weld quality, it is obvious that the correlation between these parameters can play a key role as a monitoring tool to maintain high quality welds during each CUW process. The conducted experimental work during the second part of this study (i.e. with the CUW frame based system) indicated that a 2D laser sensor monitoring system can be potentially utilized to track this correlation, which is believed to be an important step forward to industrialize continuous ultrasonic welding technology for aerospace applications. The tested monitoring configuration that consists of a single 2D laser sensor provides the opportunity to analyze the weld-line thickness in a relatively fast and efficient way. On the other hand, the analysis methodology is heavily dependent on the data of the utilized single laser sensor. Consequently, different sensor configurations should be tested to develop the most sensitive and accurate measurement methodology and to acquire reliable results. Moreover, the demonstrated monitoring setup can only be used as an off-line system (i.e. after the actual welding process) in its current state. Therefore, the proposed laser sensor setup should be integrated in the CUW machine to perform its tasks simultaneously with the continuous welding process as an effective in-situ monitoring system.

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