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ACOUSTO-ULTRASONIC COMPOSITE TRANSDUCERS INTEGRATION INTO THERMOPLASTIC COMPOSITE STRUCTURES VIA ULTRASONIC WELDING

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Abstract.
Acousto-ultrasonic composite transducers (AUCT), which are made of piezoceramic materials embedded in a reinforced polymeric matrix, are promising for the health monitoring of composite structures. However, when they are integrated into highly loaded thermoplastic composite structures, ensuring proper joining properties is a challenge. The conventional approach of attaching the AUCT using adhesive may not be sufficiently reliable in aeronautic applications for low surface energy materials such as polyaryletherketone composites, where surface treatments are needed for adhesion. Welding techniques can be used to create a joint in which the interface material interfuses with the AUCT embedment and the structure matrix, resulting in a homogeneous interface with properties comparable to the host structure matrix throughout its service life. With this in mind, the main objective of the present work is to investigate the viability of attaching AUCT to low-melting polyaryletherketone carbon fiber reinforced thermoplastic composite structures using the ultrasonic welding (UW) procedure and characterize the joint performance. The ultrasonic welded joint using an external energy director in the interface is investigated by comparing the findings to those of a reference AUCT system integrated into the structure with autoclave co-consolidation. Infrared thermography is employed to monitor the process, and a parameter study of the UW process is carried out. The AUCT survivability during the UW process is determined by measuring the capacitance, and C-scan is used to assess joint quality. The results show the challenges of attaching AUCT to thermoplastic composite structures using UW and surviving the procedure.

Key words: Structural Health Monitoring, Piezoelectric Transducers, Composite materials, Ultrasonic Welding, Guided Waves.

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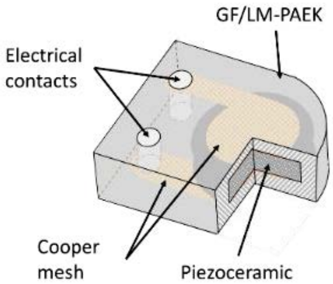
1. INTRODUCTION

Composite materials have not stopped growing in the past years for their excellent properties such as high specific strength. Recently, new applications have been rising with new materials, such as thermoplastic matrix composites [1, 2], and in new applications that require them to operate in highly loading conditions and at extreme temperatures. Despite of the fact that composite structures are designed with principles of safe life and can theoretically withstand catastrophic failure, they are susceptible to impact damage, especially hidden damage caused by low-speed impacts and fatigue that can lead to different damages such as delamination, debonding, or fracture on fibers and matrix, decreasing its properties and compromising the integrity of the structure. The detection of damages is a major problem in the maintenance of composite structures, making structural health monitoring (SHM) technology a promising tool for lighter and more cost-effective composite structures [3]. Due to their diverse advantages, piezoceramic materials are most often used for the construction of so-called "Smart Structures". Using the direct or inverse piezoelectric effect, they can be used as sensors and actuators. A very promising SHM application for detecting damages in fiber composite structures is using piezoelectric wafer active sensors (PWAS). PWAS can excite and receive acousto-ultrasonic (AU) waves through the structures. By comparing the baseline signal of a pristine structure with the actual signal, damages (e.g., impact damages) can be identified. Overall of the different PWAS available in the market, the acousto-ultrasonic composite transducers (AUCT) based on the DuraAct^{TM} design are highly reliable in terms of admissible tensile load due to their composite construction [4]. However, when they are integrated into highly loaded thermoplastic composite structures, ensuring proper joining properties is a challenge. On SHM networks, the transducers are permanently installed, and consequently, the system must ensure an acceptable performance over the lifetime of the structure in its operational conditions. The conventional approach of attaching the AUCT using adhesive may not be sufficiently reliable and difficult to evaluate. The use of co-bonding techniques is also inconvenient because the processing temperatures of the thermoplastic composite structures are higher than the curie temperature of piezoceramics, requiring repolarization of the sensors or a second co-bonding process below the curie temperature. Welding techniques, on the other hand, can be used to create a joint in which the interface material interfuses with the AUCT embedment and the structure matrix [5], resulting in a homogeneous interface with properties similar to the host structure. In order for the AUCT to be welded into thermoplastic structures, the embedment must be compatible with the structure matrix. Because current AUCTs are made with thermoset embedment, they cannot be directly welded; thereby, a new AUCT concept based on compatible thermoplastic embedment with comparable AU-SHM performance must be developed and tested. To investigate the feasibility of using the UW to attach AUCTs to thermoplastic composite structures, a set of coupons with developed AUCTs on top should be made and welded, with the process being monitored and the join performance being characterized. To determine optimal welding parameters, a parameter study of the UW process should be performed using monitoring systems such as infrared thermography. Survivability can be determined using electromechanical properties such as capacitance, and joint quality can be determined using C-scans. The results need to be compared to a co-consolidated AUCT reference system.

2. AUCT DEVELOPEMENT

A novel AUCT depicted in Figure 1, has been developed based on the DuraAct^{TM} design and different materials for the study of AUCT integration via UW. The DuraAct^{TM} design consists of a lead titanate zirconate (PZT) piezoceramic covered on both sides by an electrode contacted with a metallized polyester fleece, an external electrically insulating ductile polyester fleece reinforced polymer laminate that embeds the entire transducer and two contact points to solder the wires [6]. To enable the AUCT to be welded into thermoplastic composite structures, the embedment on the new proposed AUCT has been changed from polyester-fleece reinforced epoxy to glass-fiber reinforced low-melting polyaryletherketone (GF/LM-PAEK). The electrode contacts were changed from conductive fleece to cooper mesh, and the contact points were changed to a cooper lamina for the new AUCT to withstand the higher processing temperatures. In contrast, the PIC255 piezoceramic disk from PI Ceramics GmbH, with 10 mm diameter and a thickness of 0.2 mm, remains equal as in DuraAct^{TM}.



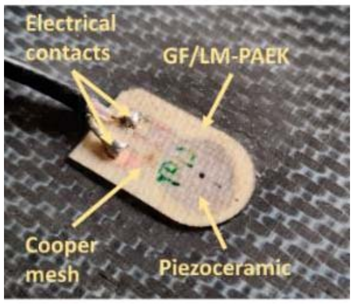


Figure 1: Novel GF/LM-PAEK AUCT

LM-PAEK was chosen because it is a high-performance, semicrystalline thermoplastic with low moisture absorption that is suitable for welding or co-bonding in aerospace PAEK thermoplastic composites [7]. As a matrix embedment, it protects the system from external environments while improving AUCT reliability under tensile loads by inducing pre-compression in the piezoceramic, which operates as a multifunctional material. Pre-compression occurs during thermal processing of the AUCT, due to the different coefficients of thermal expansion between the embedment and the piezoceramic, where embedment shrinks more than the piezoceramic when the system is cooled down. It has an endset melting temperature of 320 ºC, which is slightly lower than the PIC255 Curie temperature, allowing it to be processed without repolarization. In the study, Victrex plc. LM-PAEK film in combination with 49 g/sqm plain weave GF is used for the AUCT laminate. The addition of GF reinforcement makes the AUCT embedment more rigid and easy to process. Its capabilities to withstand high temperatures and its low conductivity makes it a suitable candidate as a reinforcement. Woven reinforcement provides certain in-plane isotropy that is desirable for wave sensing and propagation. A high fiber ratio is disadvantageous when attempting to maximize pre-compression because the coefficient of expansion of GF is smaller than that of

LM-PAEK, lowering the resultant coefficient of expansion of the embedment and resulting in lower piezoceramic pre-compression. The laminate is prepared and placed in vacuum bagging for later processing in an oven at 330 ºC to manufacture the GF/LM-PAEK AUCT. The resulting GF/LM-PAEK AUCT has a thickness of 0.5mm with proper embedment of the fibers and the piezoceramic.

3. UW AUCT INTEGRATION SET-UP

As can be seen in Figure 2, specimens configuration uses the GF/LM-PAEK AUCT on top of a 0.3 mm-thick LM-PAEK energy director (ED) mesh, welded to a Uni-Directional (UD) Carbon Fiber Reinforced Thermoplastic (CFRTP) coupon. CFRTP coupons are based on UD Toray Cetex® TC1225 carbon fiber (CF) LM-PAEK thermoplastic laminate with $[0,90]_{3S}$ stacking sequence, consolidated in a hot-platen press at 380 ºC and 10 bars for 20 min. The CF/LM-PAEK laminate had a nominal thickness of 2.18mm. Coupons were cut from the laminate so that their longer side coincided with the 0-degree orientation of the fibers in the CF/LM-PAEK laminates. The coupon design is chosen for a future 4-point bending mechanical test to determine the AUCT's and its integration's survivability.

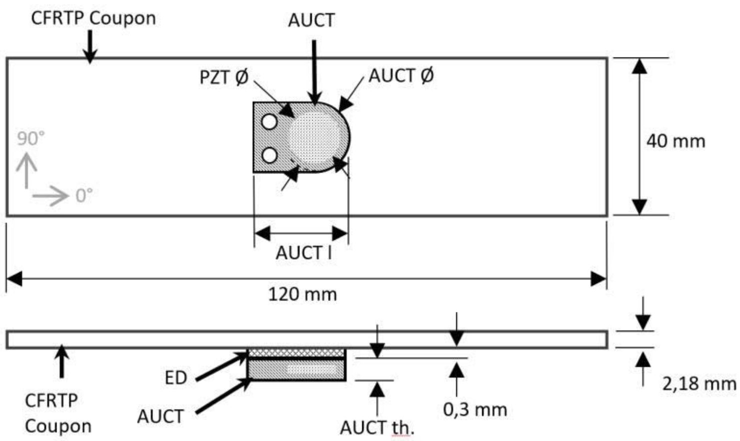
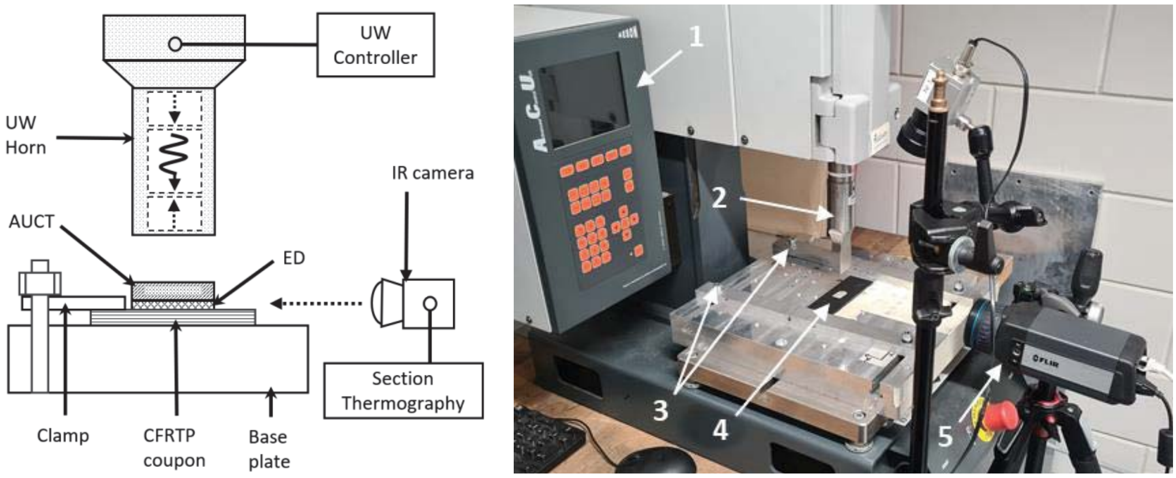


Figure 2: UW of AUCT on 4-point bending CFRTP coupon set-up

UW is done by a 20 kHz Rinco Dynamic 3000 ultrasonic welder from Rinco Ultrasonics AG from the top of the AUCT. The welding direction is defined thinking on future applications where the process can be automatized, and the AUCT will be placed when the structure will still be on the mold. Energy-controlled welding is configured in a way that the microprocessor-controlled welding unit automatically modifies the electrical power input while maintaining a constant vibration amplitude. In this study, a 1:1 booster and 1:2.75 sonotrode configuration are employed. The horn has a rectangular shape with a 10 x 30 mm edge length that meets the welding parts. There are two main sources used to monitor the welding process. The welding unit's microprocessor first records the force, power, and displacement over time. Secondly, the section side of the assembly is thermally monitored using a FLIR A655sc infrared camera. The surfaces where the coupons and AUCT join are sanded and cleaned with isopropanol. The AUCT is secured on top of the CFRTP coupon using polyamide pressure tape, and the CFRTP coupon is clamped using screwed clamps on the welding structure. Figure 3 depicts the configuration and setup for the welding.



(a) (b)

Figure 3: (a) UW of AUCT on the 4-point bending CFRTP coupons configuration and (b) set-up. UW controller (1), horn (2), clamps (3), CFRTP coupon & AUCT (4), and section IR camera (5).

Six specimens (*Li*) are used as a first method to establish suitable welding parameters. Following that, a parameter set is fixed and used with the other 6 coupons optimized based on the visual observations (*OLi*). Table 1 lists the welding parameter values for all specimens.

Table 1: GF/LM-PAEK AUCT welding parameters

ID	Force (N)	Cons. Force (N)	Amplitude (µm)	Power (Ws)
L1	1000	500	36.3	1200
L2	200	500	36.3	500
L3	300	500	36.3	500
L4	300	500	36.3	600
L5	400	500	36.3	500

ID	Force (N)	Cons. Force (N)	Amplitud e (µm)	Power (Ws)
OL1	300	500	36.3	500
OL2	300	500	39.3	500
OL3	300	500	39.3	500
OL4	300	500	39.3	500
OL5	300	500	39.3	500
OL6	300	500	39.3	500

A C60 measurement tool from Cypher Graph is used to perform a capacitance measurement for evaluating the AUCT's ability to survive the welding process. A C-scan is then performed to evaluate the bonding quality. An OmniScan NORTEC® 600 Data Acquisition (DAQ) system is used to scan the coupon using an automated scanning device with the source and receiver housed inside a water tank.

4. RESULTS AND DISCUSSION

The overall welding process' heat distribution of the system section is visible through the thermography monitoring. For the data analysis, a cropped portion of the section zone between the horn and the upper surface of the CFRTP coupon is considered. During the initial welding step, thermograms shows a distinct AUCT edge; however, in some specimens, squeezed material from the ED, obstructs the edge view after the welding process starts. In Figure 4 , heat distribution of croped area, when maximum temperature is spatially and temporally observed over frames, is shown. Heat distribution is not homgenuous in any of the samples, and it is mostly distributed with hot spots along the AUCT length due to the squeezed ED net. The distribution of heat shows that it is not concentrated in the ED, but relatively along the thickness of the AUCT.

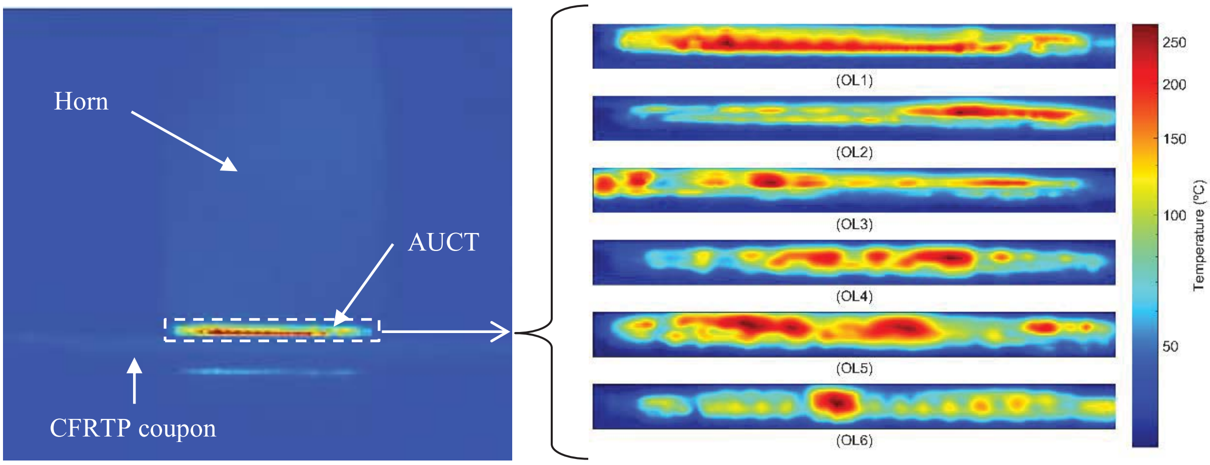
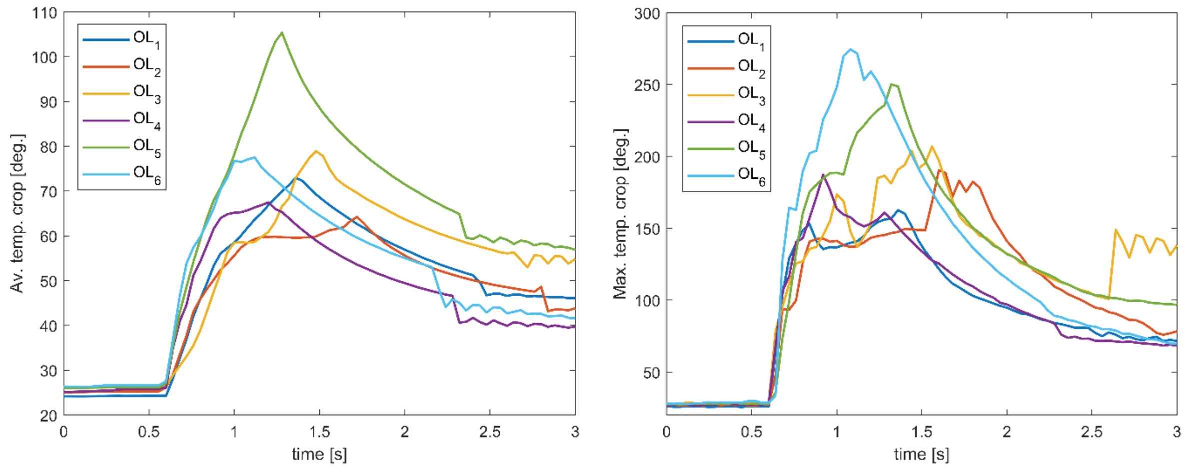


Figure 4: Maximum temperature thermography image frame of the cropped areas of each *OLi* specimen.

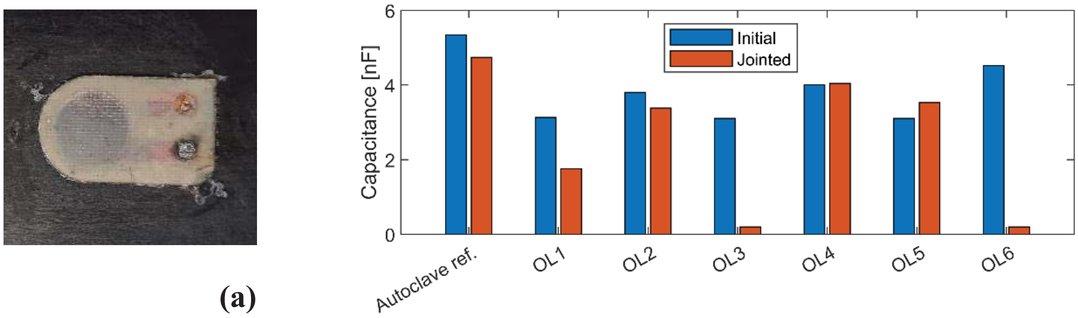
Average and maximum temperatures of the cropped area during the welding process are plotted in Figure 5. The heating process was carried out approximately in 0.5 second, followed by a consolidation phase of 1 second, after which the horn is removed. When the horn is removed, a drop in temperature can be seen. Maximum temperatures are observed varying between 180 ºC and 280 ºC, but in any case, higher temperatures above the melting temperature of the AUCT. Most of the specimens have matching average and maximum temperature peaks. Due to a hot ED spot that moves and appears from behind on specimen OL_3, the maximum temperature rises rather than decreases after removing the horn.



(a) **(b)**

Figure 5: Average (a) and maximum (b) temperature over the welding time of the infrared crop area.

Capacitance of the AUCT (Figure 6 (a)) are measured before and after the welding. Results shown in Figure 6 (b) demonstrates a significant drop in some cases and a slight increase in others. In cases of OL3 and OL6, a complete drop can be observed denoting a loss of connection with the piezoeramic or loss of piezoceramic properties. In the survived AUCTs, capacitance do not have significant change compared to the the ones experimeted from the reference autoclave consolidated AUCT.



(a) **(b)**

Figure 6: UW GF/LM-PAEK AUCT (a), and AUCT capacitance (b).

C-scans of the autoclave-consolidated AUCT, shown in Figure 10, illustrate low dispersion of signal attenuation with approximately -4 dB in the GF/LM-PAEK versus the coupon's -3 dB. The piezoceramic has slightly higher attenuation with a value of around -8 dB and the electric copper lamina has a value of around -6 dB. Furthermore, the AUCT's edges have a -10 dB effect on signal attenuation.

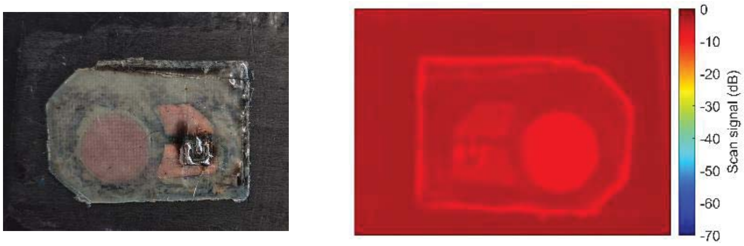


Figure 7: Autoclave consolidated GFRTP C-scan.

A variety of effects can be seen in the C-scans of the UW specimens shown in Figure 11. In the case of L1, the power and force completely destroyed the ceramic and joined the AUCT in the majority of its area. The behavior of L2, L3, L4, and L5 is similar, with values ranging from -8 dB to -13 dB in the ceramic, -4 to -8 dB in the GF/LM-PAEK, and high values in the cooper contacts. L3 and L4 show the closest values to the reference value in the piezoceramic and surrounding GF/LM-PAEK areas.

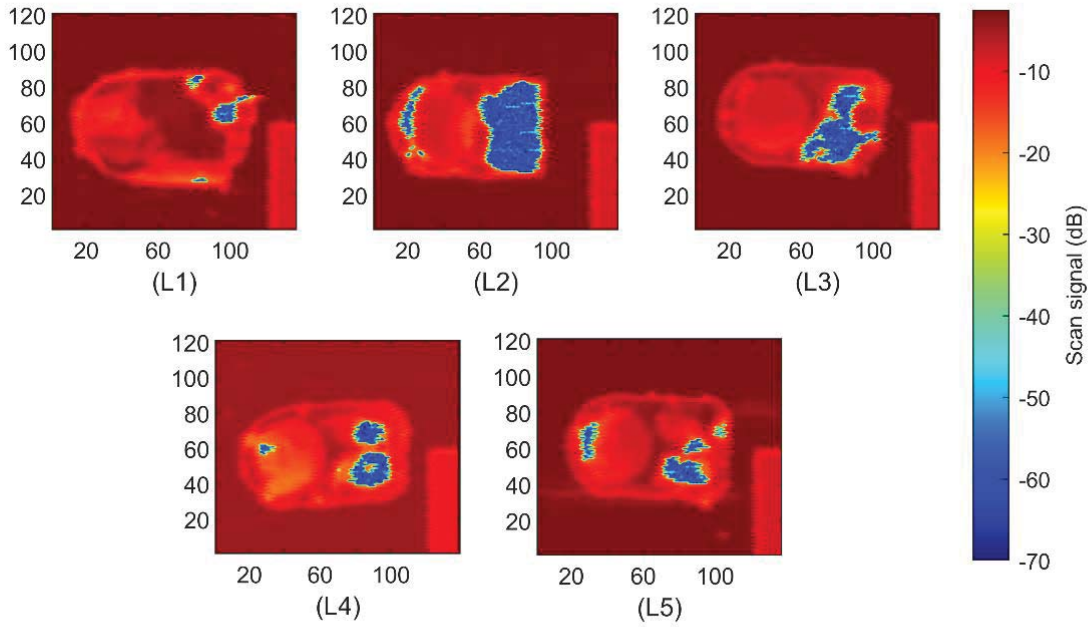


Figure 8: C-scan of *Li* GFRTP AUCT

Through analyzing the OL specimens, observations show that some of the AUCTs have been rotated due to the improper clamping. The issue of non-uniform bonding distribuation in the contact region can be seen across all specimens. Taking a closer look at OL4, values denote acceptable welding in the left bottom region, while values jump following the net fabric of the ED, indicating that the welding has not completely melted it. This effect is repeated in other specimens and indicates that the welding pressure or energy is not uniformly distributed.

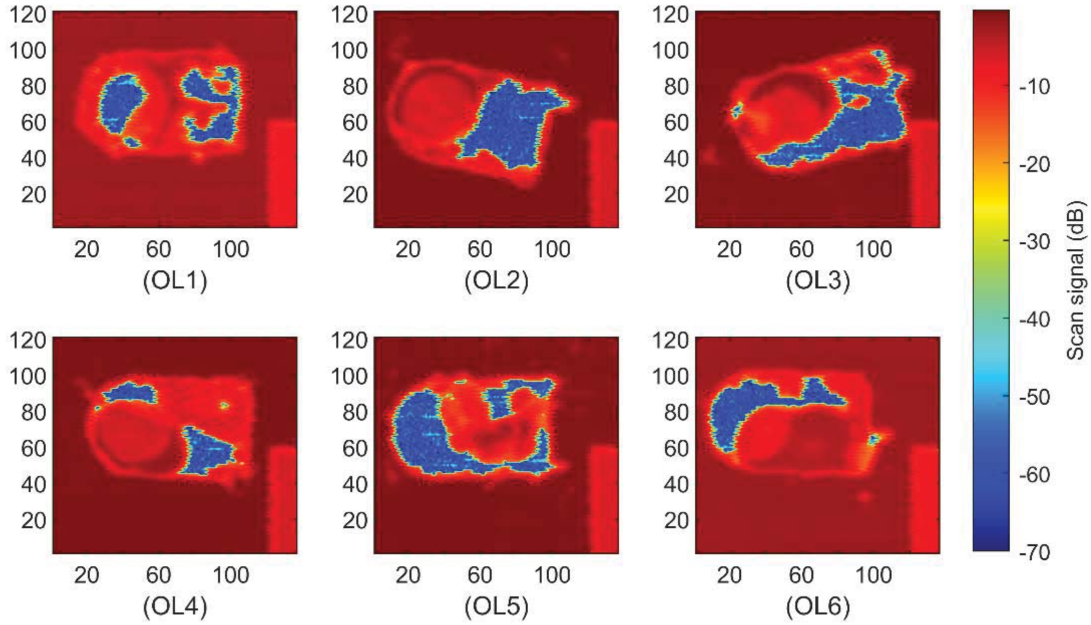


Figure 9: C-scan of *OLi* GFRTP AUCT.

5. CONCLUSIONS AND OUTLOOK

The study's findings show that it is challenging to integrate AUCTs into CFRTP structures via UW and survive the process. After these preliminary tests, it has been seen that they can varely survive with many unknowns about their reliability and performance in AU-SHM. The tests revealed that changing the materials to adhere to the same design principles as DuraAct^{TM} is not a viable option for integrating AUCTs via UW. The first assumption of using very low fiber content and thus achieving higher pre-compressions does not appear to be appropriate for the UW process because, in order to be successful and focus on energy in the ED, the stiffness difference between the AUCT and the ED must be greater, which requires higher percentages of fiber content in the AUCT. Furthermore, due to the complexity of holding the AUCT properly during the UW process, as well as the interference of the horn with the copper sheets, the geometry of the AUCT and the arrangement of the contacts appear unsuitable for the UW and should be optimized. In terms of the UW process, changing the design and using different shaped horns, following piezoceramics shape, may contribute to better heat homogenization and pressure distribution during UW, which cannot be achieved with the used horn configuration and AUCT placement using polyamide pressure tape. In regard to process monitoring, C-scans revealed that some of the AUCT edges and central regions were properly welded, but during thermography monitoring, none of the section regions, reaching the melting temperature, could be directly obsereved , which indicates that it needs more endeavor to achieve a good overview of the heat distribution and additional devices are required to understand the heat distribution during the welding process for parameter optimization.

For future developments, different design and monitoring assumptions should be considered.

- The stiffness of the AUCT must be much greater than that of the ED in order to better concentrate heat on the interface.
- During the welding process, the AUCT design should allow for proper clamping.
- To avoid interfering with the welding process, electrical contacts must be located outside of the welding part.
- The horn shape should follow the piezoceramic shape for better heat and pressure distribution.
- Additional thermography system on top and different thermocouples can be used to achieve a better understanding of heat distribution.

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