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Inline Monitoring of Continuous Ultrasonic Welding Processes of Thermoplastic Composites via a Custom polyCMUT-based Ultrasound Array

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Abstract
Ultrasonic welding (UW) of thermoplastic composites (TCs) is an emerging technology in the field of composite joining techniques in the aerospace sector. Through a mechanical oscillator, ultrasound at a frequency of 20kHz is induced into the material via a welding horn, where microscopic friction and damping effects melt the thermoplastic. Under further pressure the weld area cools down, permanently joining both parts together. Like all joining processes in the aerospace industry the resulting joints need to be tested for their quality and structural integrity. The traditional testing method using water-coupled ultrasound includes extra steps. This process could be considerably improved by assessing the quality of the weld directly after or even during the welding process, allowing for immediate rework or discard of the parts in question. Ultrasound is still the best solution for this quality assessment, being inexpensive, well understood, and able to create B-Mode images, allowing a look into the cross-section of the weld. However, there are several major problems:
To increase the system complexity as little as possible it is necessary to attach the ultrasound unit next to the welding equipment, and as close to the welding horn and compactor as possible to save space and keep the end-effector manoeuvrable. This brings problems for classic piezoelectric ultrasonic arrays: The low welding frequency and its resonance modes reach into the lower resonance modes of the piezoelectric sensors leading to immense noise, hiding any potential echo from the welding zone. Classic piezoelectric crystals are also very brittle and can suffer damage from sustained exposure to this violent environment.
The authors present a novel solution: a custom-made polymer-based capacitive micromachined ultrasonic transducer array (polyCMUT). polyCMUTs are tiny drums with two electrodes. One on the bottom and the other suspended over a cavity sandwiched between two layers of polymers. By applying a DC-bias an electrical field is created and the membrane is set under tension. If then an AC voltage is applied, the strength of the electric field decreases, allowing the membrane to snap back into its original position. If done at the resonance frequency of the membrane, a strong ultrasonic signal is created. To receive this signal the polyCMUT is charged with a DC-bias, allowing it to receive the echo of the transmitted signal by measuring the changing capacitance. Not only is the polymer robust and inexpensive to fabricate, the general architecture of CMUTs also allows a design where the first mode of resonance is the actual mode the CMUT is operating in. By designing for a resonance frequency over 5 MHz all noise from the initial welding process is ignored, leading to a working pulse echo imaging system. The array is then mounted onto a PEEK block attached to the compactor unit of the welding end-effector. This publication is intended to present initial results, the design process of the custom array and the tests leading there.

Keywords: Ultrasonic welding, polyCMUT, In-line quality assurance, Thermoplastic composites, Non-destructive testing

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1. Introduction

1.1 Ultrasonic Welding

Thermoplastic composites (TCs) enable lightweight and robust construction is the aerospace sector [1]–[5] and enjoy growing popularity due to their material properties like high specific strength, stiffness [1], [4], and their resistance to fatigue [5]. This leads to a high demand of techniques for joining these materials. Joining TCs can be done by many different methods e.g. riveting or screwing but most methods need preprocessing. For screw joints for example, additional holes have to be drilled costing time and adding potential weak spots to the material. In addition, most joining techniques lead to an increased weight since more material is added to the final product. Another method to join TCs is ultrasonic welding (UW). UW is an efficient and fast [6] joining technology with the advantage that no additional material is needed to create a joint. In order to create a welded seam with UW, an electrical signal is transformed by a converter into mechanical oscillations which are lead over a sonotrode into the welding specimens [6]–[8]. At German Aerospace Center (DLR) the UW is usually conducted at ultrasonic frequencies of 20 kHz. The ultrasonic signal is damped by the material and friction generates heat [9], [10] which leads to melting of the welding material. During the continuous application of pressure, the material cools down and a joint is formed between two welding partners. For the welding process it is possible to place an energy director (ED) in the welding zone, thereby creating an area with increased heat generation and initializing the welding process [7].

When speaking about UW, two more differentiated methods can be described. Spot welding is designed to create punctual spot welds of a material where multiple spots can be added together to one welding seam. Continuous ultrasonic welding (CUW) creates a continuous welding seam while moving the sonotrode in one fluent movement over the welding material. In comparison to spot welding CUW is much faster and therefore more efficient while also producing more evenly shaped joints. At the DLR both techniques can be applied to weldable material. However, UW is a technology which is still in development and therefore the necessity arises to reliably monitor and evaluate the quality of the produced weld connections.

The quality assurance (QA) of ultrasonically welded TCs is discussed in literature. Most of the literature describes investigations about welding parameters like sonotrode displacement [11], applied amplitudes and pressures and other parameters which are responsible for creating a welding seam [6], [8], [10]–[15]. These publications mainly focus on the analysis and interpretation of the recorded welding data. Others tried to analyze welding process data with the help of an artificial intelligence (AI)-algorithm [16]–[18] but only a quality class prediction accuracy of around 70% was achieved. One flaw of observing or analyzing solely the welding parameters, which are used to start the welding process, is that errors might occur which are not connected to the defined and measured welding parameters. This is why Görick, Schuster, Larsen, et al. [19] investigated the potential of sound- and thermography data for QA. Their investigations show that these new parameters carry the potential to help with the QA of ultrasonically welded TCs but the question arises if it is possible to evaluate the quality of a produced seam even more in detail by visualizing the shape of the welding seam while the welding process is still taking place. The presented investigations deal with this question and provide new approaches for innovative and new QA methods with capacitive micromachined ultrasonic transducers (CMUTs).

1.2 Capacitive Micromachined Ultrasonic Transducers

Nondestructive testing (NDT) via ultrasound is one of the oldest and most widely used quality control methods [20]. Ultrasonic signals are sent into the specimen in question and their returning echoes are evaluated. The resulting signals contain plentiful information about the internal characteristics of the tested material. Throughout history these ultrasonic signals have mostly been created and detected through the piezoelectric effect. Piezoelectric materials are cut to a certain shape to create the desired resonant frequency and an applied electric signal will create vibrations and therefore ultrasound at that frequency. The returning signals are utilizing the reverse effect, creating measurable electric signals. This method has several drawbacks: a relatively narrow bandwidth, high acoustic impedance compared to TCs, high manufacturing cost and the main problem in this works application; lower frequency resonance modes depending on the shape of the piezoelectric element [21], [22].
A different method to create and measure ultrasonic signals was developed in recent years: Capacitive Micromachined Ultrasonic Transducers - CMUTs [23]. A silicon membrane of 50-200 µm diameter containing an electrode is suspended over a relatively thin (<200 nm) gap containing near vacuum and another electrode at the bottom. By applying a DC voltage (DC-bias) to the capacitor, an electric field is created, pulling the membrane towards the bottom electrode, thereby tensioning it. A superimposed AC voltage leads to a breakdown of the field and a resulting sudden relaxing of the created tension, leading to a vibration at the membrane's resonant frequency. To receive an ultrasonic signal, the DC-Bias needs to be applied. The incoming vibration will deflect the membrane leading to a change in capacitance and a drain in charges from the capacitor and therefore to a measurable signal. To create signals at significant strengths, hundreds to thousands of these single cells are connected in parallel to create elements which again create ultrasonic arrays. CMUTs not only exhibit a much wider bandwidth and are inexpensive to fabricate, but they also do not show any lower resonance modes, usually operating in the first mode of vibration according to plate theory. A further improvement to CMUTs for this publication's application came in the form of polymer-based capacitive micromachined transducers (polyCMUTs) published by Gerardo et al in 2018 [24]. polyCMUTs are created by the same fabrication process as silicon CMUTs, their main structural material however is SU8, a photosensitive polymer used for structural features in microfabrication. The use of SU8 leads to a reduction in acoustic impedance by an order of magnitude, leading to better sensitivity and transmission of the ultrasonic signals, offsetting one of CMUTs major drawbacks of lower output power. The adaptability and rapid design and fabrication shown by polyCMUTs in recent years [25]–[28] shows an ease in custom design and the possibility of iterative design processes. The polyCMUTs presented here are a product of these processes but will be described in further detail in a future publication.

2. Materials & Methods

In order to define, develop and built a sensor system for the continuous nondestructive evaluation of continuously ultrasonically welded TCs several subtopics are experimentally investigated: First; how does one send and receive an ultrasonic signal into the welding zone of the specimen with special attention paid to the constant movement of the welding head and ultrasonic testing array? Second; how does the strong welding signal, its many higher mode vibrations and other environmental factors impact the QA signals and therefore drive sensor design? Third; can the chosen sensor design and setup measure and distinguish between welding qualities in an initial run without welding present? Fourth; can the completed system collect ultrasonic signals during the welding process despite the numerous challenges? All described experiments are conducted with composite material consisting of carbon T700G fiber within a low-melt polyaryletherketone (LM-PAEK) matrix. Except the fourth experimental step, all experiments use a laminate with a fiber layup of $[0/90]_{3s}$ with a thickness of 1.68 mm. The plates have a length of 335 mm and a width of 60 mm (the layup in step four is $[45/90/135/0/45/135/0]_s$, for details please see section 3.4).

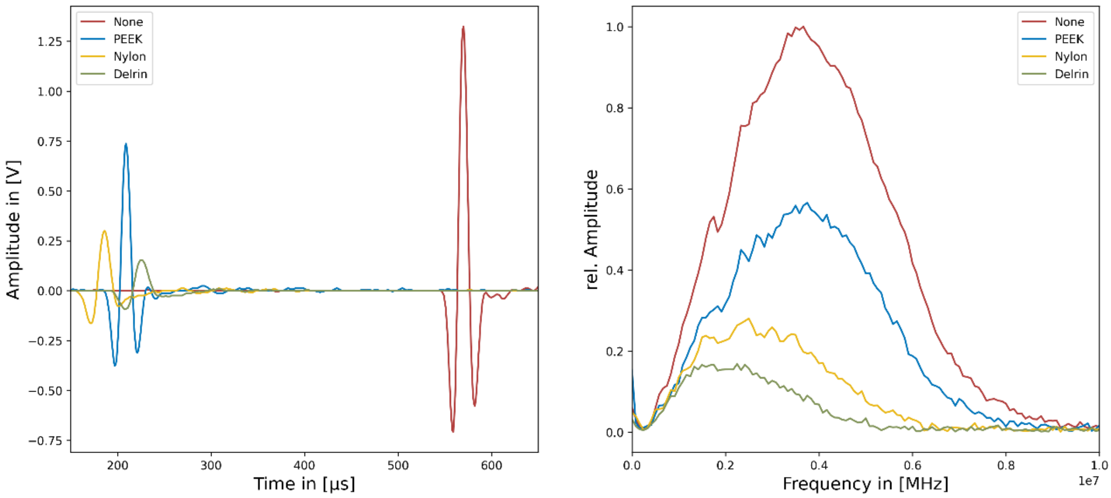

Fig. 1 Acoustic impedance measurement of different materials at 5 MHz. Left: A-scans of the different material investigations. Right: Fast Fourier transformation of the signals. Figure inspired by and data used with permission from [29].

2.1 Sending and Receiving Ultrasound Through PEEK

In order to inspect the welding area as close to the welding process as possible, the sensor array has to be attached to the compactor unit of the welding process. To protect the sensor from the rough and hot surface of the recently welded TCs, the sensor needs to be placed on top of the compactor with the ultrasonic signals travelling through the compactor into the weld and back. This leads to some significant challenges: the material of the sensor mounting point must not only be able to withstand the pressure and temperature close to the welding process, it also needs to exhibit relatively similar acoustic properties to the welded material as to not reflect most of the ultrasonic signal. Given the mentioned constraints polyetheretherketone (PEEK) was selected due to the circumstance that LM-PAEK and PEEK have similar acoustic impedance and a low acoustic absorption rate as tested at the University of British Columbia by Donja Hohendorff within the proceedings of her master thesis (see figure 1) [29]. For the acoustic impedance measurements of the specimen an ultrasonic signal is send via a custom transducer in water through different materials (Delrin, Nylon and PEEK) and the amplitude on the other side of the material is measured via an Onda HNC-1500 Hydrophone. In comparison to the other investigated materials, PEEK leads to the highest measured transmission amplitude (excluding no material between sending and receiving unit with the time difference due to differences in speed of sound). With a closer look at the fast Fourier transformation (FFT) of the measured signals, PEEK is the only material where the measured frequencies are not experiencing shifted a spectral range (see figure 1). These results indicate that PEEK is well suited to be the link between the ultrasound unit and the material to investigate. In addition, PEEK is a semicrystalline thermoplastic with a high mechanical strength, good resistance to thermal degradation and excellent sliding properties [30]. Given the high mechanical stress of the environment and the low acoustic absorption rate a PEEK block of 10 mm thickness is chosen to be the link between the ultrasonic sensor and the welding material.

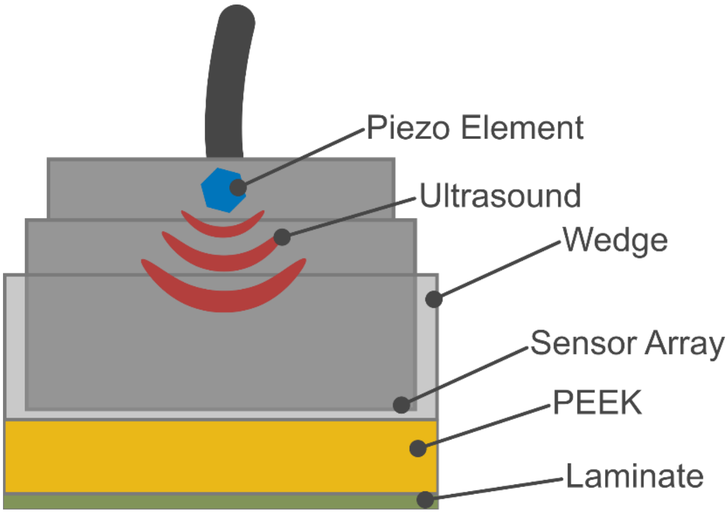

Fig. 2 Schematic measurement setup for the first experimental step. Piezo crystal generates an ultrasonic signal which is leas over a wedge to a sensor array. The array emits the signal into a PEEK block which itself stands in contact with weldable material. Sensor and wedge are coupled by glycerin.

To validate the idea of PEEK as a structurally stable acoustic matching material, measurements are conducted with an Olympus NDT array (Olympus omniscan.sx with a 5L64-NW1 transducer) where it is investigated if an ultrasound signal can be transferred and received into and from the welding material while passing the PEEK block. The commercially available imaging system was chosen to have immediate visual feedback as to the viability of the design choice. A schematic experiment setup is shown in figure 2. Between the sensor array and the wedge glycerin is used to couple both elements and the wedge with the PEEK block. No water is used for the coupling of the PEEK block to the laminate, but the sensor unit is pressed manually on the laminate. The laminate itself is placed on a metal anvil. Due to the acoustic impedance mismatch of steel and TCs, strong ultrasonic signals will be reflected by the specimen backplate. In figure 3 the result of the linking property investigations of PEEK is shown. The figure displays one of the measurement results of a center element of the sensor array. The graph in the lower part of figure 3 indicates that the emitted signal is reflected by three main features throughout the specimen thickness. Matched with the expected speed of sound and time of flight of the sensor stack, the first peak is identified as reflected sound from the PEEK block and is marked with number (1). After a delay behind the first peak two peaks with smaller distance to each other appear. The second peak is correlated to the reflection of the transition from PEEK to laminate (marked with number (2)) while the third peak is the sound reflected from the backside of the laminate (marked with a (3)). Each of the reflecting depth is also drawn in the image which is displayed in the upper half of figure 3.
The echo of the emitted ultrasonic signal of the piezo sensor is induced into a 10 mm thick PEEK block and received from different depths, including the laminate back-wall. This result leads to the hypothesis that PEEK is well suited to be the link between an ultrasound sensor unit and welded TCs. Since a polymer-based capacitive micromachined transducer (polyCMUT) due to its better acoustic matching is supposed to show comparable results to the piezo crystal [24], this setup was chosen.

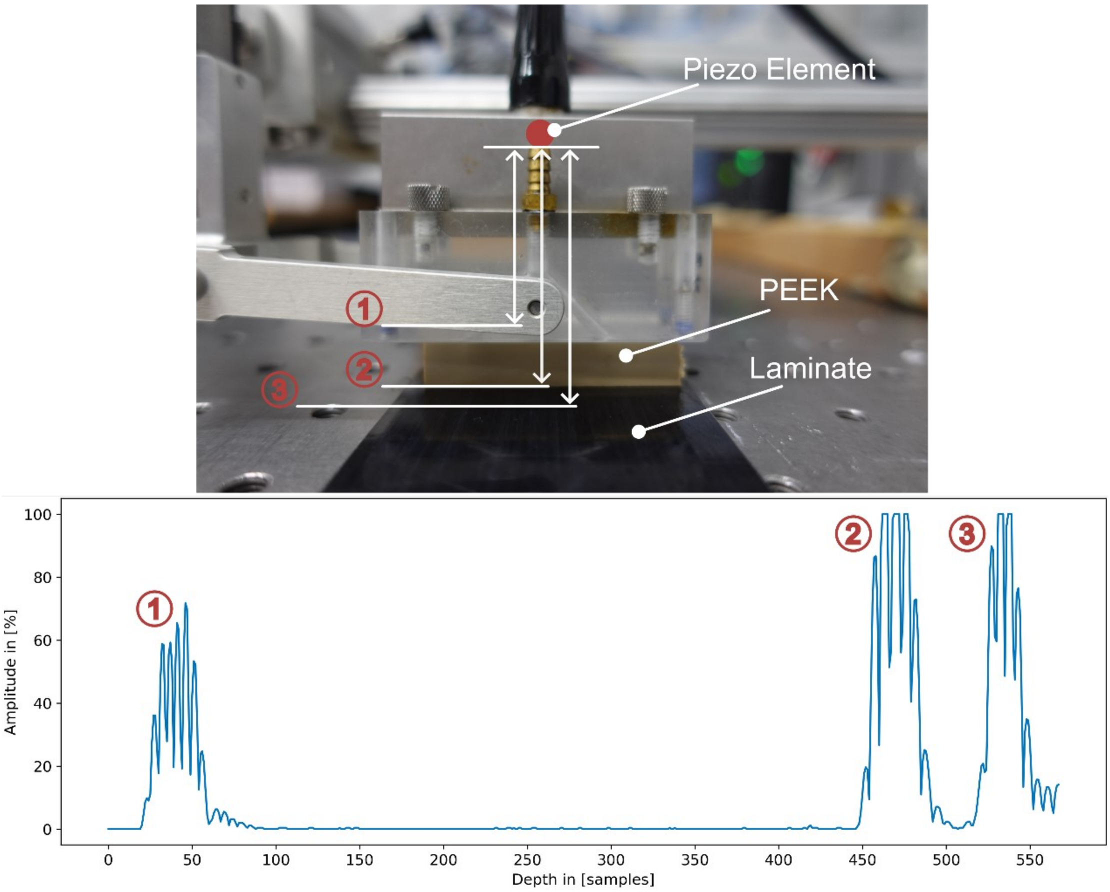

Fig. 3 Results of the experiment of the first investigation step. On top: Olympus transducer on top of a PEEK sample, pressed to a laminate. White arrows indicating the traveling paths of sound. Bottom: A-scan of one of the center elements of the sensor array. Numbers indicate correlating depth of reflection.

2.2 Sensor Frequency Response Evaluation

To characterize the acoustic environmental conditions of the welding process, a custom 1 MHz single element piezo transducer with a 70 % bandwidth is mounted onto the compactor unit, at the approximate future array position (see figure 4). The comparatively low frequency is chosen to visualize all higher vibration modes and characterize their relative strength. The sensor is positioned onto the brass sled since at the time of experiment no attachment option for the PEEK block was available. To improve the sensitivity of the measurement a coupling paste (Korasilon Silikonpaste - mittelviskos, Kurt Obermeier GmbH & Co. KG) is used to connect the sensor to the sled. The sensor signals are passively monitored with an oscilloscope during a welding process in order to evaluate if the ultrasonic welding signal has the potential to interfere with the measuring signals of a polyCMUT. Figure 5 shows the result of the passively measured ultrasound during a welding process. The measured voltage signal is shown in yellow while the FFT is displayed in red. At a frequency of approximately 20 kHz the FFT has a peak value originating from the ultrasonic welding signal. At increasing frequencies, the higher mode vibrations decrease in strength until a frequency of approximately 500 kHz where they disappear into significant background noise with no further peaks. The results indicate that most higher mode vibrations of the welding process appear below a frequency of 1 MHz. This led to the design choice of a custom polyCMUT sensor unit with a resonance frequency of 7 MHz and a bandwidth of 100 %, being well suited to send and receive ultrasonic signals into the welding zone while having enough resonance distance and energy to not be disturbed by the welding signal. The design choices were still validated by further experimental trials since the sensor of the here described experiments was a piezo sensor and mounted on a brass sled instead of a PEEK block. In addition to the results described here, it has to be investigated if different welding zone conditions lead to different ultrasonic signals if the ultrasound passes through a sample of 10 mm PEEK.

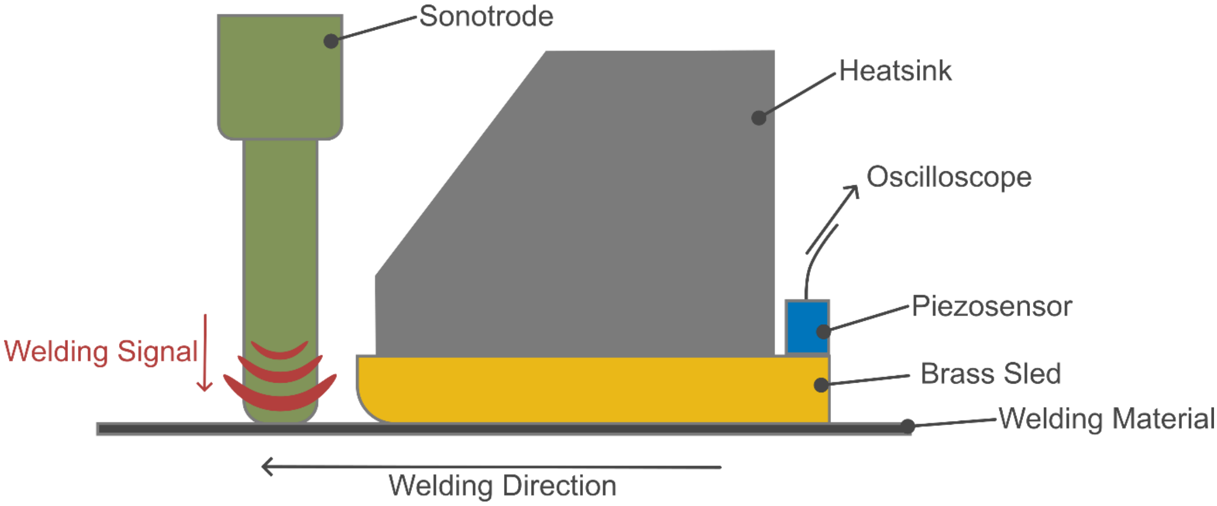

Fig. 4 Schematic measurement setup of the sensor frequency response evaluation. Piezo sensor (blue) is fixed on the brass sled (yellow) which is part of the heatsink unit (grey). In front of the heatsink a sonotrode (green) leads ultrasonic vibrations (red) into the welding samples. Piezo sensor is connected to an oscilloscope.

2.3 Error Investigations with a Common Ultrasound Setup

To investigate the ability of the polyCMUT technology to visualize different qualities of welded joints, a welding sample with defects is prepared. In order to create a defective welding seam, 25 mm wide Kapton tape is placed orthogonal to the welding direction over the whole welding sample. The tape is placed with a rising frequency in the welding zone in a pattern of 100 mm ED, 25 mm Kapton, 71 mm ED, 25 mm Kapton, 51 mm ED and 25 mm Kapton. Areas with Kapton tape also have a layer of ED to prevent different thicknesses. The ED had a width of 40 mm, was 100 µm thick and was placed in two layers in the welding zone. To fix the ED in position, it is fixated with smaller spot welds (manually operated sonotrode with low pressure so only the matrix is melted locally). After one plate is prepared that way, another plate without additional modification is placed on top of the modified plate. Both plates are welded together with a welding speed of 18 mms^{-1}, a welding force of 600 N, a consolidation pressure of 5 bar, a compaction roll force of 300 N and a welding amplitude of 100 %. The commercial piezoelectric medical transducer is a linear array (Ultrasonix L 14-5, 7 MHz) with 128 elements with comparable performance to a custom polyCMUT array [27]. The transducer is attached to a Verasonics Vantage 256 System. As mentioned previously, the PEEK spacer and small amounts of glycerin were used. A plain wave signal is sent with the center 64 Elements of the transducer into the welded sample. The sensor is connected with glycerin to the 10 mm thick PEEK block. Due to the fact that the welding process roughened the specimens' surface, glycerin is also put under the PEEK block to improve the contact conditions and to ensure that the ultrasonic signal is lead into the welding seam without major reflection at the PEEK backwall. The sensor unit is then shifted over the welded sample and measurements are taken at intervals of one mm. The middle 32 elements are used for data analysis because the array was too wide and extended over the PEEK block/ the welding seam.

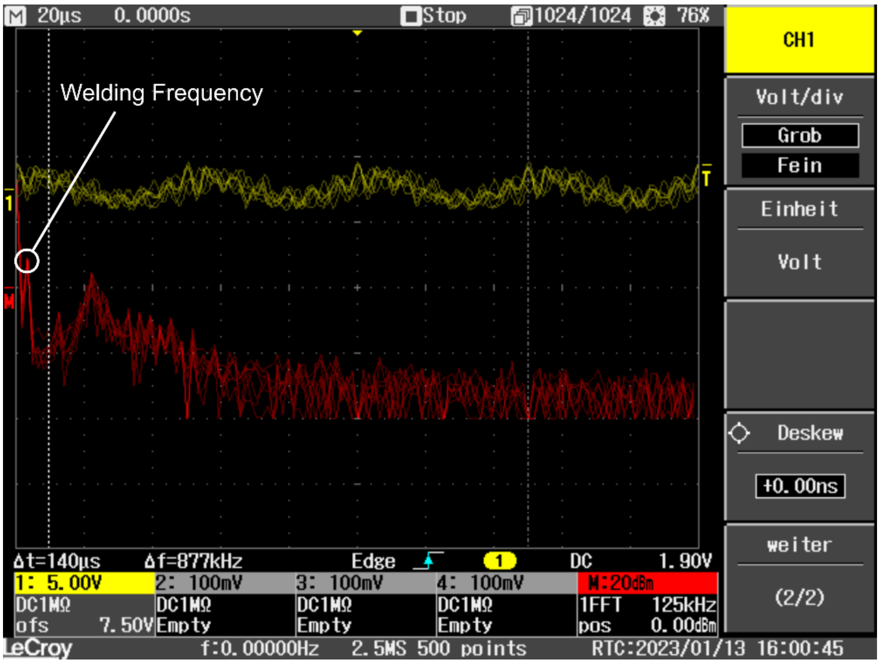

Fig. 5 Ultrasonic signal recorded by the piezo sensor unit during a continuous welding process. In yellow: measured voltage. In red: Fast Fourier transformation of the measured signal. Each division on the x-axis is equal to 20 µs or 125 kHz.

In figure 6 an exemplary measurement is displayed. On the left side the original measurement with all 4096 data points can be seen. Since the depth of interest is close to the surface of the measured geometry, the length of the measurement is cut off and only data from index 0 to 800 are taken for further data processing (middle graph in figure 6). The Hilbert function (SciPy library [31]) is than applied to the values before extracting the absolute values (Numpy library [32]) (right side of figure 6). This way only the general shape of the data is visible and smaller peaks are smoothed out. It has to be mentioned that figure 6 only displays one recorded signal of an element to visualize the data processing steps. At each measuring position 32 of these signals are recorded and processed as follows. Four measuring positions are taken to investigate the shape of the measurements of different shaped welding zone areas. Namely the area at 47 mm and at 175 mm are characterized as good welding seams (based on a water ultrasound investigation with focus on the echo from the welding zone depth) and areas at 117 mm and 208 mm are taken because they are evaluated as bad quality welds (positions where the Kapton tape was positioned).

2.4 Inline Investigations

In the investigations described here, the laminate with a fiber layup of $[45/90/135/0/45/135/0]_s$ is used (fiber type and matrix are the same as described for the other experiments). Welding plates had dimensions of 378.2 mm (in welding direction) and 104.6 mm. Similar to the other welding experiments, two layers of ED with a thickness of 100 µm and a width of 11.7 mm are placed in the welding zone. The ED is fixed in place with a hand sonotrode in a way that one fixation point is set for each lap shear strength (LSS)-sample which is cut later from the welded plates. For the welding process one welding plate with EDs and one plate without EDs are placed with an overlapping zone of 12.7 mm on an aluminum anvil and fixated with clamps. The welding process took place at a welding force of 600 N, a consolidation pressure of 5 bar and a compaction roll force of 300 N. The heatsink is pulled behind the sonotrode and is actively

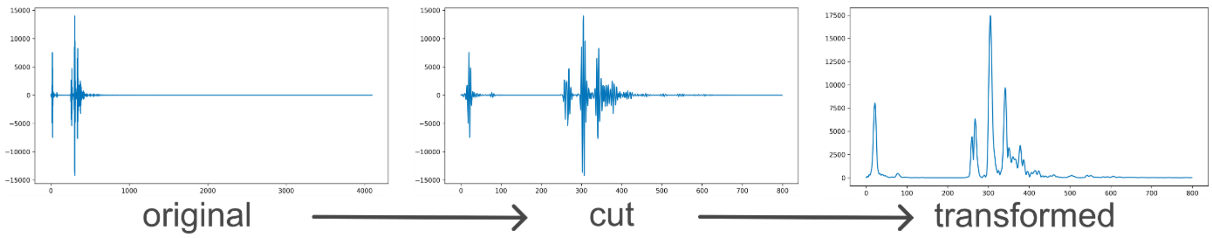

Fig. 6 Processing of an ultrasonic signal. From left to right: Original signal is cut in time before Hilbert function is applied and the absolute values are extracted.

cooled to 23 °C, slightly above room temperature to avoid condensation on the brass metal. At the end of the heatsink the PEEK spacer with the mounted custom polyCMUTs array is attached. The array is connected to the PEEK block with silicon paste and a 3D printed holder is used to apply slight pressure to the sensor (see figure 7 right side) in order to fix it in position and ensure the contact between capacitive micromachined ultrasonic transducer (CMUT) and the PEEK material. Due to issues with an uneven welding surface it was decided to use small amounts of glycerin as a contact fluid between PEEK and the welding specimen. The glycerin is pressed through a hose into a cavity below the PEEK block to ensure good coupling conditions between the PEEK and the laminate and to compensate smaller irregularities on the welding surface which might occur due to the welding process itself. To circumvent the need for an expensive and potentially vulnerable ultrasound system close to this rough environment the decision was made to use Texas Instruments Evaluation Boards as a custom small system that could be mounted onto to the end effector (see figure 7 on the left). As a pulser the TX 7332 EVM is used, creating a square, 1 ms pulse of 60 V DC that is sent to 32 elements of the polyCMUT transducer. The signals are then recorded by the neighboring 32 elements, connected to an AFE 5832 EVM Analog Digital Converter (ADC) and a TSW 1400 EVM Field programmable gate array (FPGA) with 1 GB Ram. The recorded signals are 4096 datapoints long at a sampling rate of 40 MS/s and a programmed high gain. The recording is triggered by a connection from the pulser to the FPGA and the data is sent via USB to a computer running TIs High Speed Data Converter Pro v. 4.3. (Texas Instruments). The step of using different elements for sending and receiving is taken to limit crosstalk and protect the ADC from eventual voltage spikes. With an element width of only 300 μm the resulting transverse resolution is still sufficient at 600 μm due to a failure detection requirement of 1 mm. Due to the experimental nature of the setup recordings were initiated manually, with a measurement happening roughly every 300 ms, limited by the bandwidth for data transfer of the system and leading to a measurement roughly every 5.6 mm since the welding velocity is set to 17 mms^{-1}.

3. Results & Discussion

3.1 Error Investigation with Ultrasound

The error investigation was conducted via water-ultrasound, Ultrasonix transducer and polyCMUTs. The water ultrasound imaging is supposed to function as a base evaluation and is seen as an orientation in the work. In figure 8 at the bottom the water-ultrasound image is displayed. Since the gate is set to the approximate depth of the welding zone blue areas (equivalent to low measured amplitudes) indicate a good welding quality because the ultrasound is lead over the welding zone into the lower sample. Inverse to this, red areas mark regions in which no or bad bonding occurred. Notice that the welding seam should be centered on the plate which is why blue sections appear only in the middle, the edges are not supposed

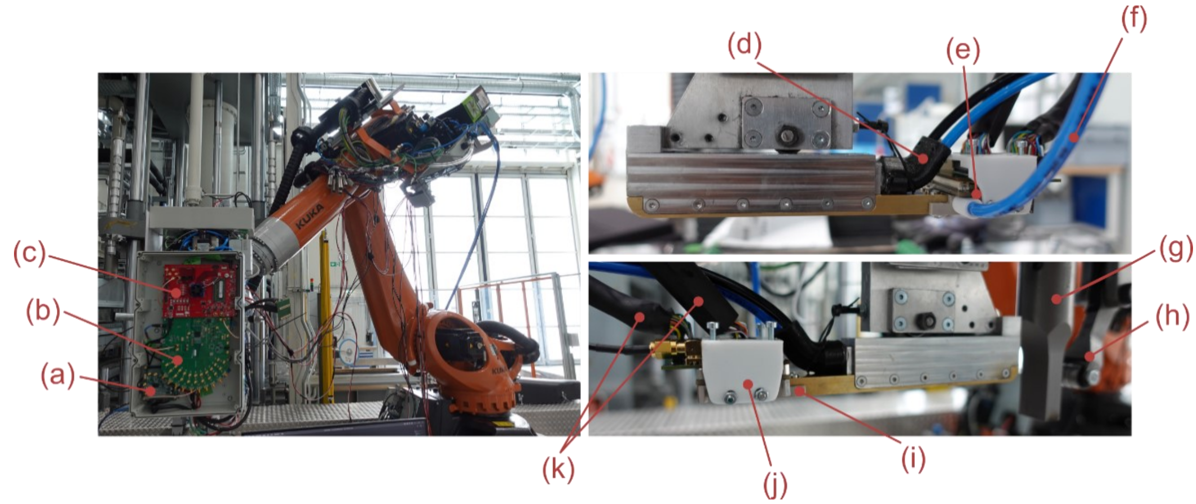

Fig. 7 **Sensor setup during the welding experiments. Transmit and receive electronics are attached to the welding robot and CMUT is dragged behind the heatsink on a PEEK block. A tube is connected to the PEEK block to be able to press glycerin into a cavity on the underside of the block. (a) TX7332EVM, (b) AFE5832EVM, (c) TSW 1400EVM, (d) Cooling System, (e) polyCMUT, (f) Glycerin Tube, (g) Sonotrode, (h) Compaction Roller, (i) PEEK Block, (j) Fixation, (k) Connection Wires.**

to be bonded. For a qualitative investigation only four measuring positions are taken from the Ultrasonix array and the polyCMUT measurement. The results of the Ultrasonix array are positioned in figure 8 above the water ultrasound images. In all measurements two areas show distinctive signal peaks. The first peak is relatively similar for all measurements but in the second area three or more peaks appear in different shapes and amplitudes. For welding areas predicted to be of good quality three prominent peaks appear where the middle peak has the highest amplitude. In comparison, bad welding areas seem to have one or two larger peaks which are followed by multiple peaks with an exponentially falling amplitude. In general, there seems to be a difference in the general shape of the measured signals of the medical array as well as of the polyCMUT, depending of the geometry and quality of the welding zone. This observation further strengthens the idea that the welding zone of ultrasonically welded TCs can be visualized in detail by a polyCMUT while the welding is still taking place.

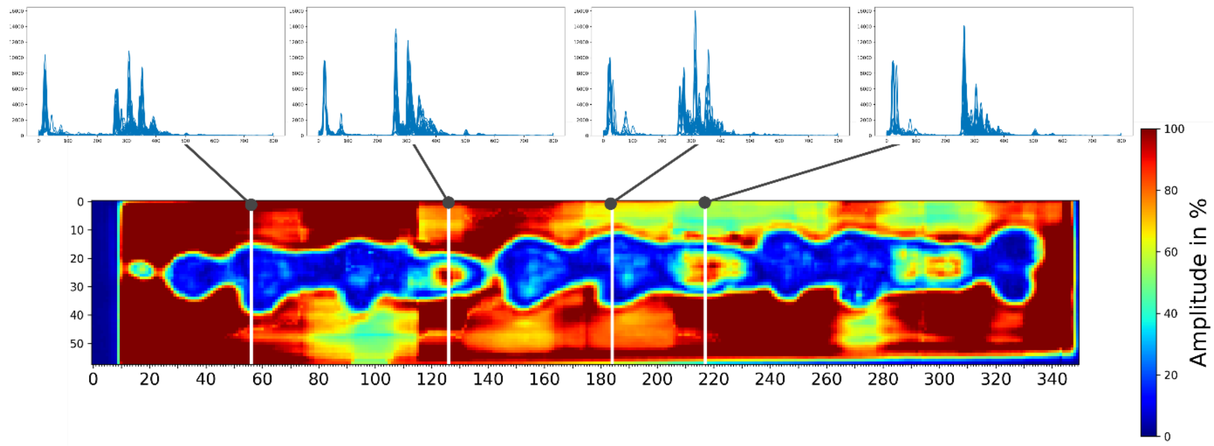

Fig. 8 **Investigation of defective welding sample with the Ultrasonix transducer (top) and water ultrasound (bottom). White lines indicate the position of measurement.**

3.2 Inline Investigations

Figure 9 shows one measured ultrasonic signal recorded during welding number eleven. The signal is extracted from element 16 in the polyCMUT sensor array of the 8th measurement. The whole measurement of this sensor element is shown in figure 9 (a) while figures 9 (b) and (c) are zoomed in the x-axis direction in order to magnify the measured sound echoes. The signal is composed of one big peak which is followed by several smaller peaks. Matched with the expected speed of sound and time of flight, these smaller peaks are suspected to be the signals reflected from the depth of the welding zone. From visual investigation of this signal, it seems that the measurement with polyCMUT sensors is well suited for inline measurement during the process of CUW because in the signal no significant noises from the welding process are visible.

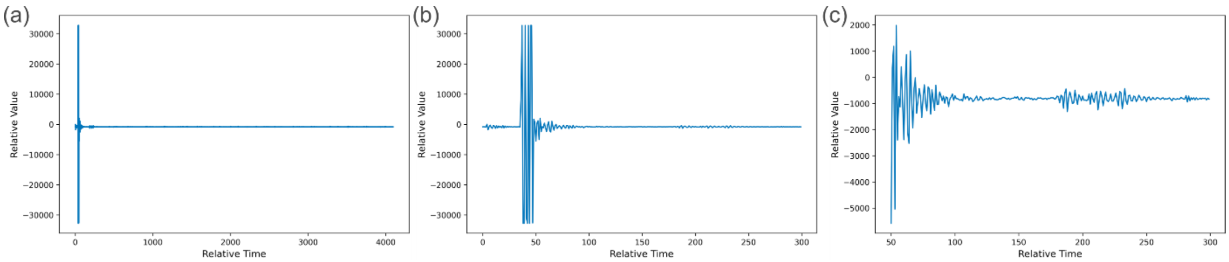

Fig. 9 Example measured CMUT signal recorded during the CUW process. (a) Signal in original length. (b) Signal from index 0 to 300. (c) Signal from index 50 to 300.

Building on the investigation described above the question remains if the measured signals change depending on the measuring position and weld quality. To answer this question the measurements of weld number 11 from measuring positions eight to twelve from array element 16 are visualized (see figure 10). It was decided to visualize element 16 because this element is located in the center of the CMUT sensor unit. Since the signals after the bigger peak are of interest, the signal is displayed from signal index 78 to 520. In addition, the mean signal value is shifted to zero because of slight variating offsets in their y-value. Around index 200 the recorded signal seems to undergo some changes depending on the measuring position. Behind index 200 the signal shows smaller differences, but the differences at index 200 are the most prominent. This observation shows that it is not only possible to measure an ultrasonic signal from the CMUTs during the welding process without interference but also indicates that the measured signals do change depending on the measuring position. Figure 10 shows the real measurement and not a Hilbert approximation as in figure 8. Nevertheless, the signals in figure 10 at index 200 seem to have similar shapes. As for an example at position 8 the graph has two peaks like the areas which are supposed to be of good joining quality in figure 8 and at position 10 the shape of the graph drops exponentially like the bad welding joints in figure 8. Since the here presented data is strongly reduced for simpler understanding it may be advisable to use AI in order to further deduce connections between the weld quality and the polyCMUT measurements. Nevertheless, changes in the signal are recognizable with the human eye and the welding signal seems not to interfere with the measurement which is why this new measuring approach for inline QA of the welding process is seen as a technology with much potential for a future establishment in the welding process.

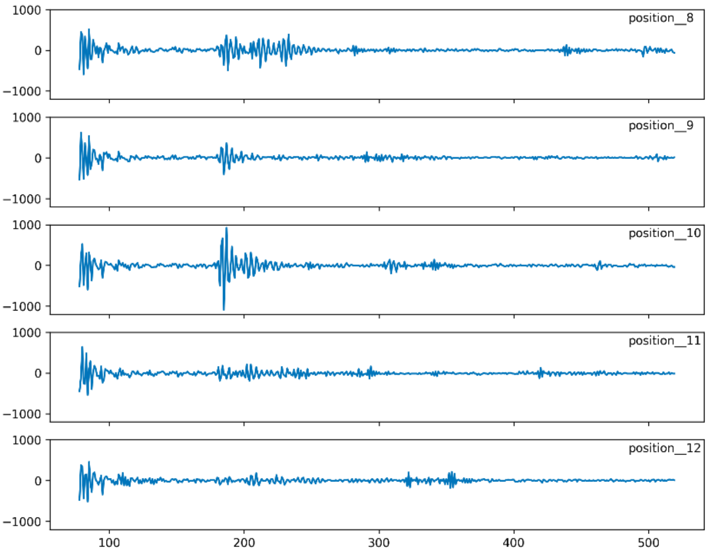

Fig. 10 Example measured polyCMUT signal recorded during the CUW process at positions 8 to 12. Signals are shown within the timeframe corresponding to the echoes of the welding zone according to time of flight calculations.

4. Conclusion & Discussion

In this work an application and implementation of a new technology for inline investigation of the welding quality of ultrasonically welded TCs is developed and evaluated. As part of the measurement, it is investigated how a measurement signal is transferred into the welding specimen, if the welding process has the potential to interfere with the measurement signal and in which way the sensor measurements change depending on the weld quality. PEEK is found to be a good link between the polyCMUT and the welding samples. In addition, it was decided to develop a polyCMUT sensor with a resonance frequency at 7 MHz in order to avoid interference by the welding signals below 1 MHz. Investigations with artificially created errors in the welding zone led to the conclusion that ultrasonic signals transferred into the welding zone over a 10 mm thick PEEK block show recognizable changes in their shape, depended on the welding zone quality. After these three successfully proceeded trials, the developed sensory system is applied for inline measurements during the CUW process. During this welding process no signals of the welding itself interferes with the CMUT measurement while the recordings show changing patterns depending on the measurement location. The different shapes in signal could not be connected to the welding zone shape due to poor x-location identification, but future experiments where a measurement trigger is set automatically and can be reliable be connected to the x-position.

In this work a first step in the development of a new technology for inline investigations of the continuous ultrasonic welding of TCs is presented. Future experiments will help to make this system more reliable, understand the measured signals more in detail and establish it as a key component for QA in the ultrasonic welding process of TCs. After successful implementation of the technology in the welding process it might be possible to extend the use of this technology to other industrial processes.

Author Contributions
Conceptualization, D.G. and J.W; data curation, D.G. and J.W.; formal analysis, D.G. and J.W.; investigation, D.G. and J.W.; methodology, D.G. and J.W.; resources, C.D.G; software, D.G. and J.W.; visualization, D.G.; supervision, M.K., E.C. and R.R.; writing—original draft, D.G. and J.W.; writing—review and editing, C.D.G., M.K., E.C. and R.R.; All authors have read and agreed to the published version of the manuscript.

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