Fast Ultrasonic Imaging with Total Focusing Method (TFM) for Inspection of Additively Manufactured Polymer Composite Component

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ABSTRACT

Ultrasonic adaptive imaging based on the phased-array technology and the synthetic focusing algorithm Total Focusing Method (TFM) is proposed for fast ultrasonic nondestructive evaluation of additively manufactured composite materials. Nondestructive evaluation and inspection of additively manufactured parts and components are necessary for quality assurance of the materials. Effective detection of defects and anomalies in manufactured parts prevents extra cost and production time. However, there are several limitations encountered when using conventional methods of nondestructive inspection for as built additively manufactured parts due to surface conditions and geometrical complexity. Post-processing operations, such as machining, are usually needed to detect possible defects such as layer disband, micro-cracks, and voids in the composite parts. The capability of aperture focusing in phased array ultrasonic methods provides the opportunity for the adjustment of the delay laws in ultrasonic beams and reduces the noise and beam distortion for better imaging. An additively manufactured carbon fiber reinforced Acrylonitrile Butadiene Styrene (ABS) composite sample with artificial side and bottom drilled holes of different sizes, used to represent defects, was successfully inspected using the Total Focusing Method (TFM). Unlike conventional ultrasonic techniques, results show a promising way to provide inspection of as built additively manufactured composite parts with rough surface finishes. The proposed method helps to decrease inspection time and eliminate extra machining and preparation costs.

Keywords: NDE/T, Additive Manufacturing (AM), Composite, Phased-Array Ultrasonic, Total Focusing Method (TFM), Synthetic Aperture Focusing Technique (SAFT)

INTRODUCTION

Additive manufacturing (AM) is widely used for variety of materials including metal and polymer [1], [2]. The efficient fabrication of composite materials including Polymer Matrix Composites PMC (i.e. fiber-reinforced polymers) and Metal Matrix Composites MMC (i.e. aluminum matrix composites and TiAl-based composites) is a significant challenge. AM offers an excellent opportunity to fabricate innovative and complex parts using composite materials. Polymer and composite AM techniques include Stereolithography (SLA) applied using photopolymer liquids, Selective Laser Sintering (SLS) applied using polymer powders, and Fused Deposition Modelling (FDM) applied using polymer filaments (more information about different types of AM techniques can be found in [2]). Big Area Additive Manufacturing (BAAM) [2] is an extrusion-based deposition AM system where the polymer filaments are replaced with composite pellet feedstock [3], [4]. Using pellet feedstock allows for high deposition rates (up to 45 kg/hr) and large-scale printing (up to 6 m length × 2.5 m width × 1.8 m height). However, the printed components suffer from poor surface quality (i.e. rough surface) due to the use of large nozzle sizes (ranges from 2.54 mm and up to 10.16 mm) and high-speed deposition process. These factors can also result in the formation of defects and flaws in the fabricated component, which leads to poor mechanical properties[2], [5]. In addition to the attempts for improving the material design and production techniques, material inspection and property evaluation is necessary to ensure AM parts' structural integrity [6]. The lack of standardized quality control and evaluation procedures for AM components and processes has hindered the wider adoption of additively manufactured polymer and composite components for use as final products. Currently, there are few standards specifically addressing mechanical properties of AM parts. ASTM F42.01 has a number of standards and work items focused on metal AM [7]. There is currently one ASTM standard test method applicable to powder bed fusion of plastic materials: F3091/F3019M-14 Standard Specification for Powder Bed Fusion of Plastic Materials [8].Nondestructive testing and evaluation methods are usually selected based on the type of material, geometry, and size of the part and type of defect that needs to be detected [9].

There are a variety of nondestructive testing (NDT) methods that have been used for inspection and characterization of composite materials [10]–[13]. Ultrasonic NDT technique is one of the widely used NDT technique for composite materials [10], [14]. Radio frequency (RF) or A-scan signals are the basis of the ultrasonic inspection data. However, the interpretation of this data form is very difficult and may lead to unreliable inspection results. The accuracy and interpretation of the results may improve by using an array of ultrasonic transducers, phased array ultrasonic (PAUT) [15]–[17], and signal processing techniques such as Synthetic Aperture Focusing Technique (SAFT) and Total Focusing Method (TFM). The SAFT method performs a full volumetric characterization of the part. SAFT has several potential advantages over physical focusing techniques. SAFT has a great deal of flexibility in data collection and image formation. The deterministic relationship between the echo location in the recorded A-scans and the location of reflectors within the test object makes it possible to reconstruct a processed image from the raw data by the coherent summation process. On the other hand, to decrease the time and cost of inspection as well as develop the capability of real-time imaging, fast imaging methods such as Total Focusing Method (TFM) are necessary. TFM uses all transmitter-receiver pair signals from an array of transducers and is equivalent to focusing on each point of the reconstruction zone. Fast and precise ultrasonic imaging of additively manufactured composites not only provides the capability for reliable inspection of the parts, but also provides an accurate tool for investigation of porosity as a major concern for fiber reinforced AM composites [18].

Surface irregularities are one of the major barriers in ultrasonic imaging of the AM parts. Several remedies have been proposed to overcome this challenge and improve the imaging results [19], [20]. The general principle in adaptive ultrasonic imaging as one of the solutions is to image the surface by applying the TFM algorithm. Then, the reconstructed surface is taken into account to make a second TFM image inside the component [21]. The other method for inspection of irregular shapes and surfaces is to use newly developed probes equipped with a flexible wedge that is filled with water [21]. This paper discusses the use of flexible water-filled wedges accompanied with the TFM technique for inspection of AM composite parts.

MATERIALS AND METHOD

Sample Preparation

Polymers and polymer matrix composites are in high interest in AM because of their unique advantages in high strength-to-weight ratio, corrosion resistivity, and efficient production rate. The sample used in this work has been manufactured by Oak Ridge National Laboratory (ORNL) using a BAAM system with a build volume of 6 m X 2.5 m X 1.8 m. The BAAM system uses a single screw polymer extruder as a printing head and has a nozzle diameter of 10.16 mm (0.4 inch). The printing material was Acrylonitrile butadiene styrene (ABS) reinforced with 20% by weight short Carbon Fiber (CF) supplied by Techmer ES. The sample dimensions are shown schematically in Figure 1a.

Artificial side drilled holes (SDH) and bottom drilled holes (BDH) with different sizes were used to represent potential defects in the AM sample. Figure 1a shows a schematic drawing for the size and location of the holes (defects). Figure 1b shows an actual image for the printed samples. The as printed, rough surface can be observed from the image. In order to perform conventional UT testing, a secondary surface coating or machining operation is needed to smooth the surface for scanning. However, in this study, the part will be scanned as printed without secondary operations.

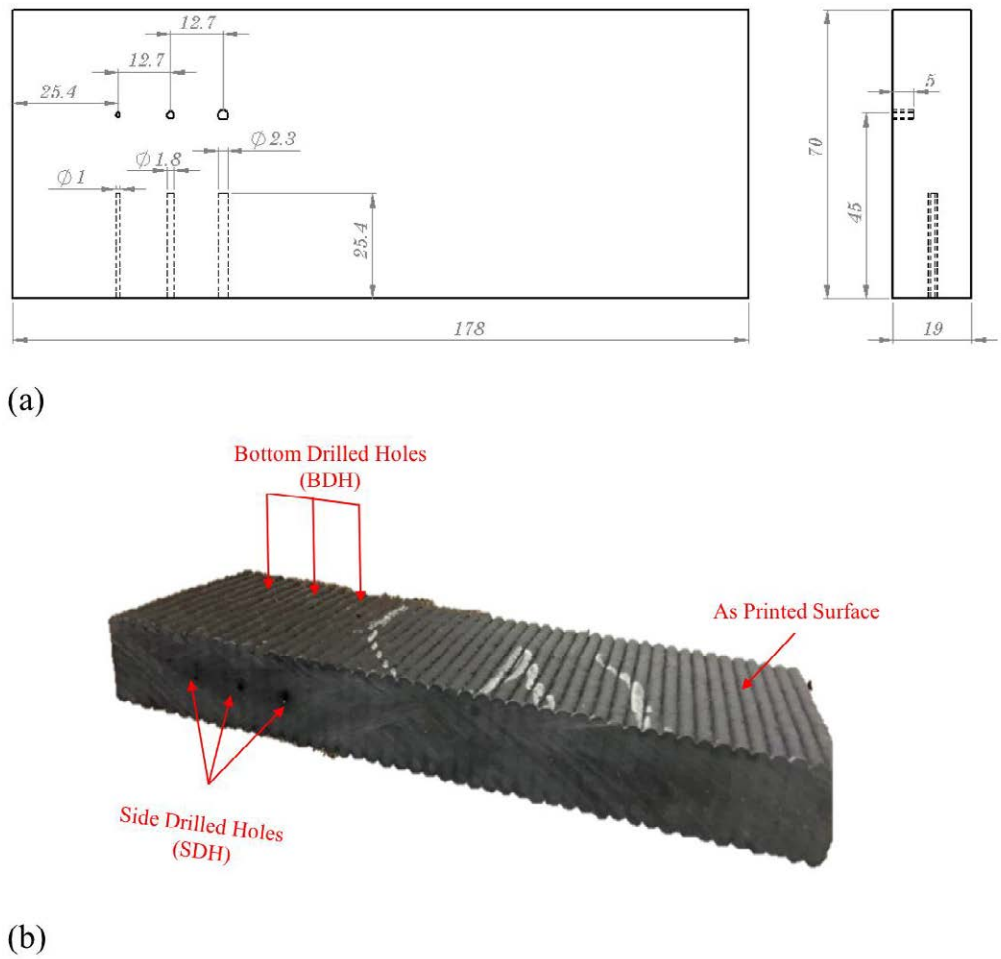

Figure 1: Additively manufactured ABS / CF 20% by weight; (a) Schematic drawing of the sample and drilled holes (artificial defects) used in the experiments (Dimensions are in mm), and (b) Actual printed sample showing side drilled holes (SDH), and bottom drilled holes (BDH)

Experimental Setup and Procedure

Contact ultrasonic transducers with central frequency of 2.5 MHz were used for wavespeed measurement in the plate. The two 2.5 MHz transducers were used in a pitch-catch configuration to measure the longitudinal and shear wave speeds. These contact transducers were similarly used to examine the possibility of defect detection in the AM composite samples. However, due to the lack of reliability and repeatability in the results, a flexible wedge phased array transducer was used for inspection of defects in the fabricated AM composite samples. In immersion ultrasonic inspections, when the structure cannot be immersed because of its size, shape, irregularities, or unavailability of the immersion tank and related equipment (like for on-site inspection), local immersion techniques can be used such as a new technology based on flexible water-filled wedges. "Local immersion" control consists of a transducer attached to a flexible water-filled wedge (Figure 2).

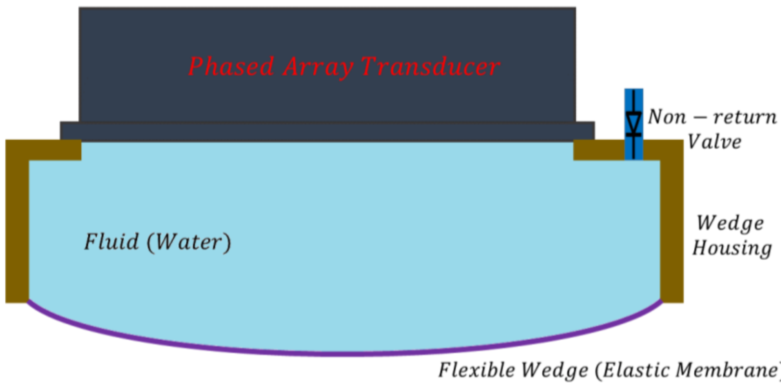

Figure 2: Schematics of "local immersion" method with a transducer equipped with a flexible wedge filled with water

Full Matrix Capture (FMC) and Total Focusing Method (TFM)

The phased-array technology allows for the adjustment of the delay laws to the geometry under the probe and for amplifying the reflector's response signal. However, the geometry of the component as well as the position of the transducer have to be precisely known, which is not always the case. Adaptive methods can improve the results by enabling measurement of the part's surface; then, the delay laws can be adapted to the real configuration of inspection.

Theory

The Full Matrix Capture (FMC) consists of recording all sets of $N \times N$ signals $k_{ij}(t)$, where j $(1 < j < N)$ is a transmitter and i $(1 < i < N)$ is a receiver (Figure 3). The obtained $K(t)$ matrix is the basis of post-processing TFM, which allows focus, in emission and reception, on all points of an image area. This method is applied to the analytic time-domain signals $S_{ij}(t)$ obtained by the Hilbert's transformation of the $k_{ij}(t)$ signals [21]:

$$S_{ij}(t) = k_{ij}(t) + jh\left[k_{ij}(t)\right] \quad \textbf{(Eq. 1)}$$

Considering a point P in a TFM image, the amplitude $A(P)$ at this point is given by [21]:

$$A(P) = \left|\sum_{i=1}^{N} \sum_{j=1}^{N} W_i^{p} W_j^{p} S_{ij}\left(t_{ij}^{P} = t_i^{P} + t_j^{P}\right)\right| \quad \textbf{(Eq. 2)}$$

where t_i^P (respectively t_j^P) is the time of flight between receiver i (respectively transmitter j) and point P, and W_i^p (respectively W_j^p) is a weighting factor in reception (respectively in transmission).

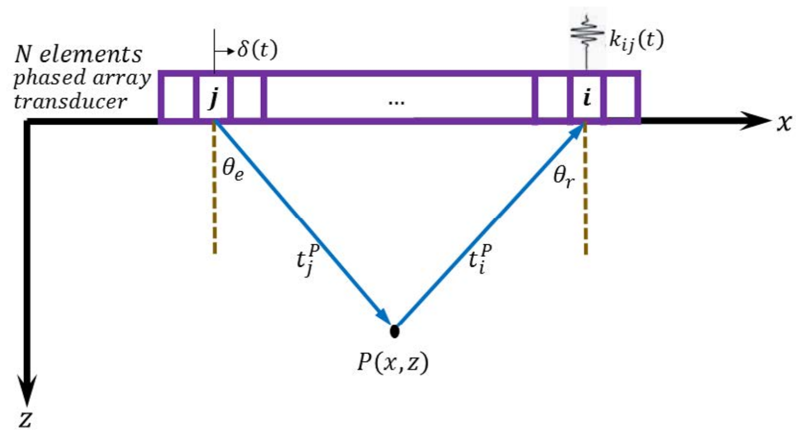

Figure 3: Inter-element impulse response $k_{ij}(t)$ for a N elements transducer in Total Focusing Method (TFM)

RESULTS AND DISCUSSION

Inspection and defect detection in AM composite samples encounters a few challenges including the attenuating behavior of the material and irregular surface condition of the part.

Wavespeed Measurement

Calculation and determination of the wavespeed is the key factor in ultrasonic inspection of materials. Determination of wavespeed is also necessary for further signal and image processing such as SAFT and TFM, which was used in this study. The longitudinal and shear wavespeed in the AM composite sample were calculated using a thru-transmission (or pitch-catch) technique. 5 MHz contact transducers with 0.5' diameter were used for the experimental determination of the time-of-flight (TOF) through the width of the sample (70 mm [2.75"]). TOF for five different trials are shown in Figure 4, which indicate that longitudinal wavespeed is $v_L = 2{,}706\ m/s$ and shear wavespeed is $v_S = 1{,}010\ m/s$. Longitudinal and shear wavespeeds are used in focal law calculations using the phased array probe and flexible wedge to improve the image quality in TFM algorithm.

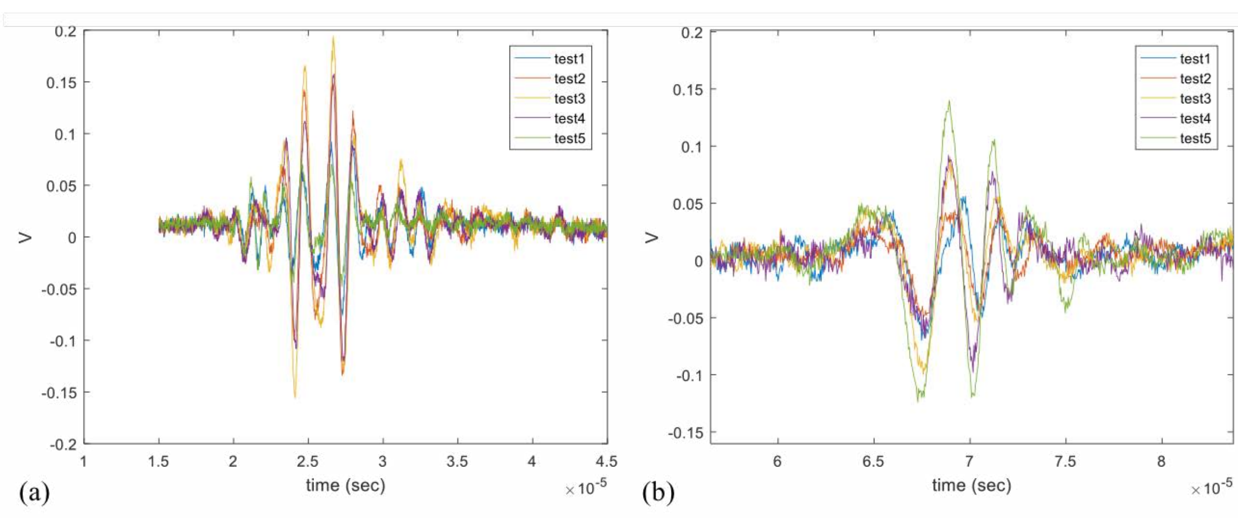

Figure 4: Experimental determination of TOF for wavespeed calculation; (a) Longitudinal wave, and (b) Shear wave

Defect Detection

As mentioned earlier, the attenuative characteristics of the polymer composite materials and their irregular surface conditions are the main barriers of inspection and defect detection. Figure 5 shows the measured signals from the BDH as the reflectors of the longitudinal ultrasound wave, and Figure 6 shows the measured signals for the shear ultrasound wave. As can be seen from the graphs in Figure 5b and Figure 6b, the amplitude of the ultrasound signal decreases as the size of the hole increases. This can be used as an indicator for defect detection and can be correlated to the size of the defects (reflectors); however, this method is less likely to be considered as a reliable method of defect detection and inspection.

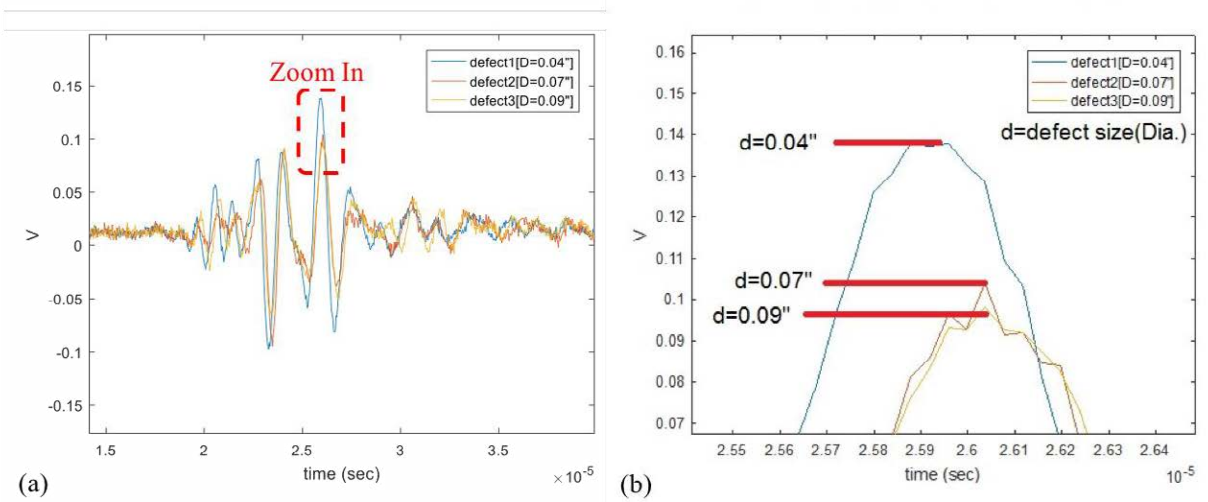

Figure 5: Experimental defect detection using 5MHz longitudinal contact transducer; (a) Result signals from different size of holes, and (b) Zoom in plot for determination of amplitude drop at different size of holes

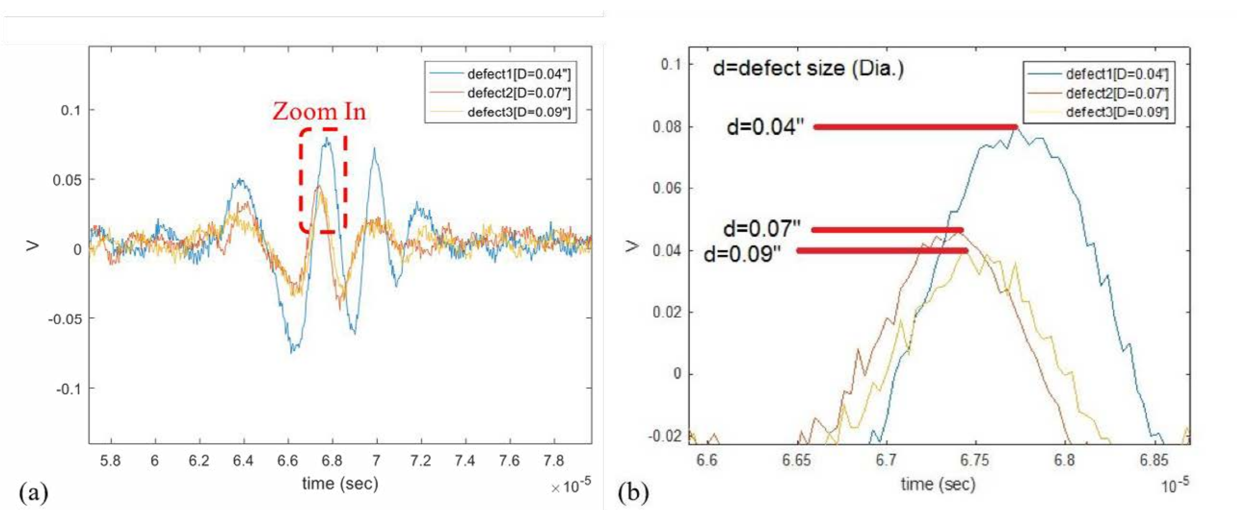

Figure 6: Experimental defect detection using 5MHz shear contact transducer; (a) Result signals from different size of holes, and (b) Zoom in plot for determination of amplitude drop at different size of holes

Figure 5 and Figure 6 show that single element transducer inspection is not feasible as ultrasonic beams are deflected and distorted by the complex rough surface. Unreliability and challenges in results shown in Figures 5 and Figure 6 indicate that different inspection methods and signal processing techniques are necessary for reliable and accurate inspection of additively manufactured composite materials. Using the Total Focusing Method and flexible water-filled wedge for inspection of additively manufactured polymer composite component provides the capability to adjust for the surface irregularities and post-processing of the inspection data to achieve accurate and reliable results. The use of phased array probes for nondestructive evaluation permits a significant improvement in terms of defect detection and image quality. Figure 7 shows the schematics for using phased array probe setup for defect detection in the composite sample. Figure 8 shows the TFM image results for detection of different sizes of SDH and BDH features in the sample. As seen in Figure 8, using TFM not only provides the capability and reliability in defect detection in attenuative and irregular surfaced AM composite materials, but also improves the imaging and result quality of the inspection. Using coherent summation of signals acquired with a transducer array in TFM, the image of the inspected object can be reconstructed with a higher resolution. The constructive summation of the array of signals helps to reconstruct an image where the features in the signals are constructively added, while the noises are suppressed due to the summation procedure. This gives a higher chance of defect detection in attenuative material and in near filed imaging.

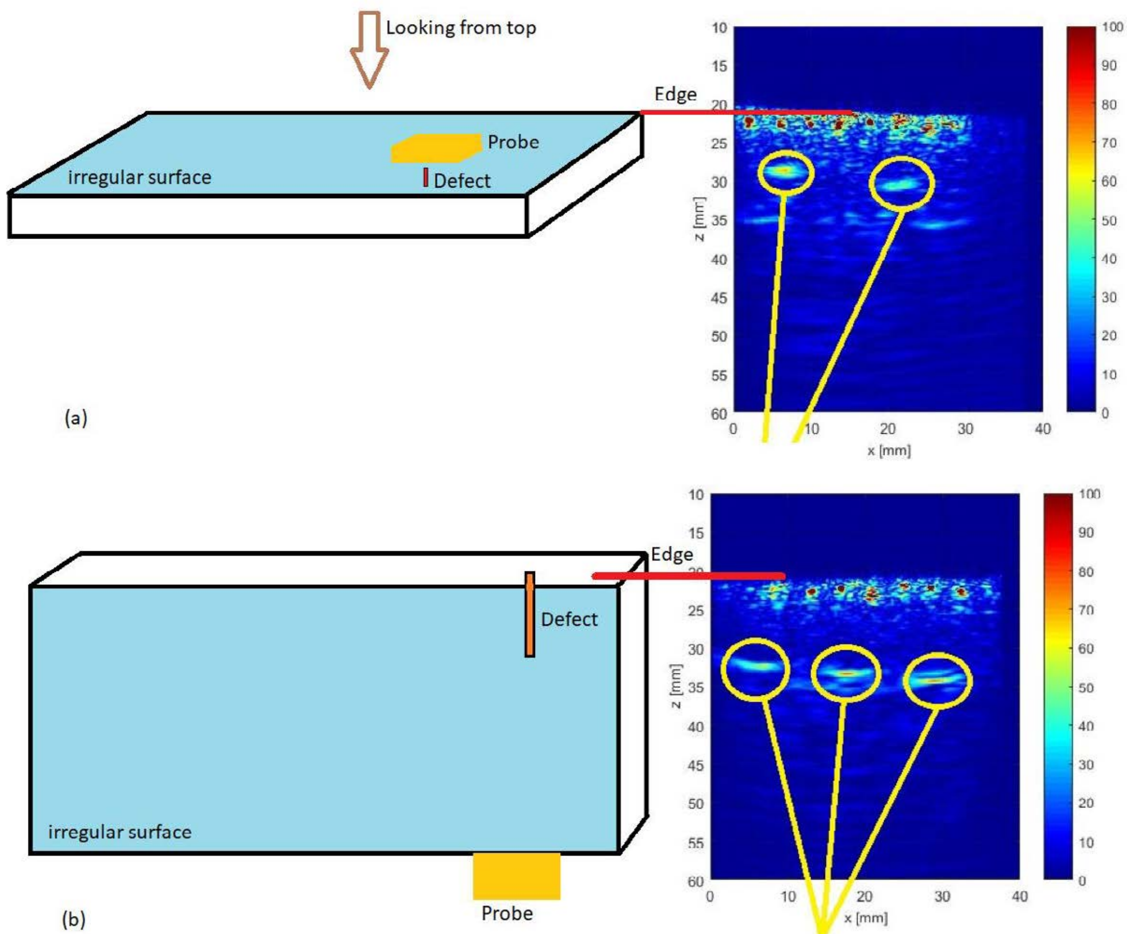

Figure 7: Schematics for using phased array probe setup for defect detection in the composite sample; (a) bottom drilled holes (BDH), and (b) side drilled holes (SDH)

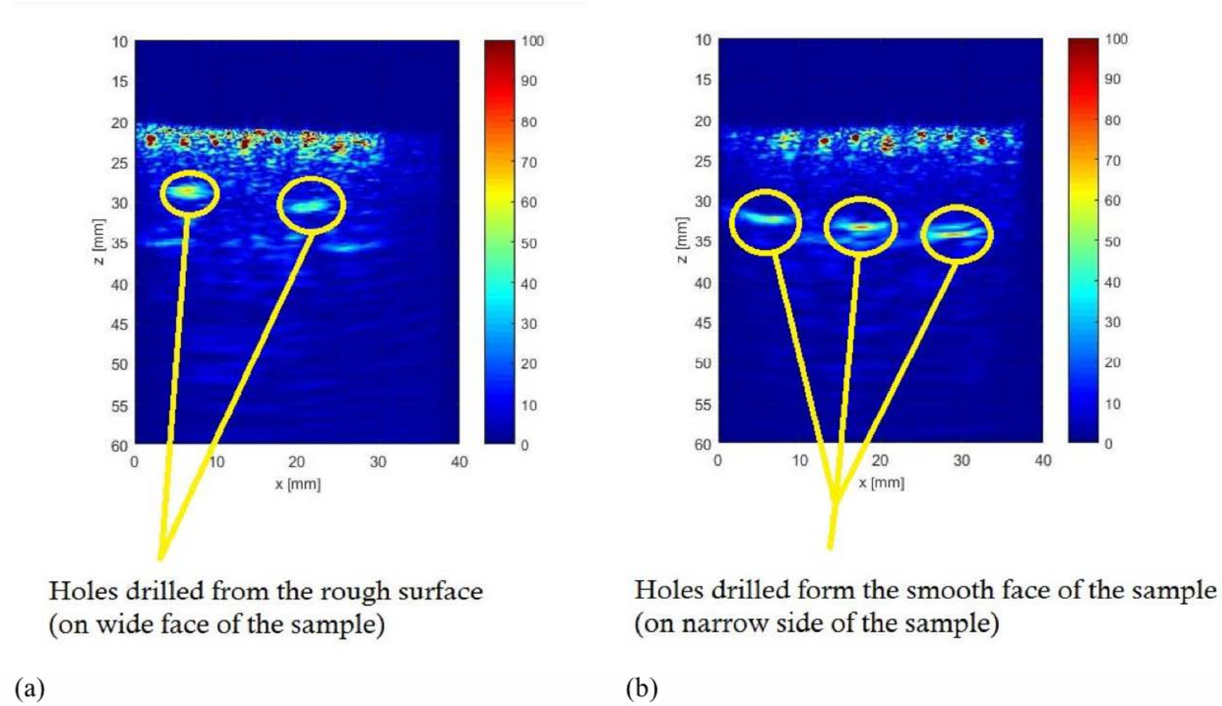

Figure 8: Total Focusing Method (TFM) experimental results using phased array ultrasonic probe with flexible wedge filled with water; (a) bottom drilled holes (BDH), and (b) side drilled holes (SDH)

SUMMARY

Inspection and material characterization of AM polymers and composite materials is necessary for their quality assurance and control. The attenuative characteristic and irregular shapes and surface finishes of AM parts are the main barriers in the application of nondestructive testing and evaluation methods in these components. Ultrasonic nondestructive evaluation techniques are efficient tools for inspection and characterization of materials. Ultrasound data processing techniques such as SAFT and TFM have evolved over the years to the point where they are now the tools that can provide considerable improvements in ultrasonic testing through high resolution imaging. The TFM imaging provides high image resolution where the spatial resolution can be optimized at any depth, and a single FMC acquisition can be used to measure the surface of a part and build an image inside the component. Its main drawback is the computation time it requires if the number of elements or focusing points are high.

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