Ultrasonics 108 (2020) 106227

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

A review of ultrasonic testing applications in additive manufacturing: Defect evaluation, material characterization, and process control

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ARTICLE INFO

Keywords:
Additive manufacturing
3D printing
Ultrasonic testing
Laser ultrasonics
Defect evaluation

ABSTRACT

Ultrasonic testing (UT) techniques are highly capable of detecting defects in engineering components. The present manuscript intends to review the ultrasonic testing techniques applied to additive manufacturing products; either in-situ or offline. While the in-situ applications of ultrasonic testing to additive manufacturing are more favorable, literature holds a few research works on this topic. On the other hand, most of the works reported on ultrasonic testing of additive manufacturing products deal with offline applications. In many of these works, samples with artificial defects are prepared and tested through ultrasonic testing techniques including laser ultrasonics, phased arrays, guided waves and immersion ultrasonic testing. These UT methods and their applications in damage detection of additive manufacturing products are discussed in detail. Moreover, the codes and standards which are currently being developed for ultrasonic testing of additive manufacturing products are introduced. The choice of UT methods in detecting defects and material characterization in additive manufacturing is found to be highly dependent on the manufacturing process and capabilities of UT techniques.

1. Introduction

Additive manufacturing (AM), also known as 3D printing, solid freeform fabrication, or rapid prototyping, is a revolutionary manufacturing technique that is expected to reshape the future of manufacturing industries [1]. In 2018, the AM industry exceeded US$7.3 billion reflecting nearly 21% increase as compared to that of 2017 and it is expected to elevate to US$26.2 billion by 2022 [2,3]. Unlike conventional manufacturing at which the product is formed by inserting pressure or by cutting away from a solid block, in additive manufacturing, material is deposited precisely at desired spots by using computer-aided-design (CAD) and 3D scanners [4–6]. Material is added layer by layer to produce near net-shape components with complex geometries easily and at low cost. Various build materials, including plastics, metals and ceramics are used in AM processes. A major obstacle in widespread adoption of AM by industries is attributed to the complexity involved with detection and evaluation of defects in AM products [7,8]. Advanced nondestructive testing (NDT) techniques are utilized to effectively detect various defects at different layers of AM products. Among these defects, porosity is of vital importance. The pores can be either gas pores or lack-of-fusion (LOF) [9]. The numerous AM processes and the different parameters involved with each process make the NDT of additive manufacturing products complicated [10,11]. Complexity in geometry of many AM components requires a pertinent choice of NDT technique to best suit defect detection. In some instances, a combination of NDT techniques has been employed to more effectively detect defects in vital components [12–14].

A number of research reviews have recently been published on NDT [15], quality control [16], and process monitoring and control [11,17,18] of additive manufacturing processes and components. A report has also been published by NASA on the state-of-the-art of nondestructive evaluation (NDE) techniques used in AM [10]. Various nondestructive testing (NDT) methods have been considered for detection and evaluation of defects in AM products [3,10,11]. These techniques have been used both during (in-process) and after the manufacturing process (post-process). Some NDT methods considered in AM include X-ray computed tomography (CT) [19], eddy current testing (ET) [20], infra-red thermographic testing (TT) [21,22], acoustic emission testing (AT) [21], visual testing (VT) [23], and ultrasonic testing (UT) [24]. Among these NDT techniques, CT and UT are the most promising [8]. Ultrasonic testing (UT) is one the most capable NDT methods used for testing of industrial components [25–35]. In recent years, many new advanced ultrasonic techniques have been developed and used in various industrial applications [36–38].

While literature holds a few review articles on the application of X-ray computed tomography (CT) to AM products [19,39], there is a lack

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https://doi.org/10.1016/j.ultras.2020.106227
Received 26 February 2020; Received in revised form 9 July 2020; Accepted 9 July 2020
Available online 15 July 2020

of review articles on the application of ultrasonic testing (UT) techniques for the inspection of AM products, either in-situ or offline. The current manuscript aims to address various UT methods used for detecting defects in AM components.

2. Additive manufacturing

2.1. Processes

In a broad sense, manufacturing techniques can be categorized as formative, subtractive, or additive. In forming processes, for example rolling and forging, the desired product is manufactured by exerting controlled stresses to a body of raw material [40]. In subtractive manufacturing processes, such as drilling, turning and milling, the final product is obtained by controlled material removal [41]. In additive manufacturing, material is deposited precisely at desired spots by using computer-aided-design (CAD) and 3D scanners [4–6]. Various materials, including plastics, metals and ceramics can be used in additive manufacturing. The ISO/ASTM 52900:2015(en) [42] classifies AM into seven distinct processes as follows:

1. **Material extrusion:** Melted material is selectively deposited in a pre-determined path layer-by-layer to produce a 3D object. It uses continuous filament of thermoplastic or composite material as feedstock.
2. **Directed energy deposition (DED):** Focused thermal energy in the form of laser, electron beam or plasma arc, is used to fuse materials (in the form of powder or wire) as being deposited.
3. **Powder bed fusion (PBF):** Regions of a powder bed are fused by thermal energy. The thermal source is usually laser or electron beam.
4. **Material jetting:** The final product is produced by depositing droplets of a photosensitive build material at desired points. Droplet material is consequently solidified through ultraviolet light.
5. **Binder jetting:** Powder materials are selectively joined by a liquid bonding agent to produce a 3D object. A binder is selectively deposited onto a powder bed, bonding the powder particles together to form a solid 3D part layer-by-layer.
6. **Sheet lamination:** The final product is constructed by bonding sheets of materials.
7. **Vat photopolymerization:** Light activated polymerization forms the final product through use of selective curing of a liquid photopolymer in a vat.

Table 1 lists various materials and technologies employed for additive manufacturing.

2.2. Defects

There are two major challenges in additive manufacturing: 1) quality control of the process, and 2) characterization of manufactured products [44]. Various defects may occur in AM components which are categorized into either surface or internal defects. Although ultrasonic testing (UT) is used to detect both surface and internal defects, the capability of UT method in detecting internal defects is of great interest to researchers and engineers in practice.

The most important defect that needs to be detected in metal AM components is porosity [45]. Porosity in AM products acts as a stress raiser leading to crack initiation and reduction of the load carrying capacity in materials [8,46]. Porosity in AM products is divided into gas porosity and lack-of-fusion (LOF) porosity [9]. Fig. 1 shows examples of gas and lack-of-fusion porosities observed in AlSi10Mg samples manufactured by selective laser melting (SLM) [47]. Gas pores are spherical in shape trapped in powder particles or inert gases that are produced during the melting process. LOF porosities are small cavities formed due to inadequate processing parameters leading to improper solidification of the material before it is completely fused to other parts [9]. Thijs et al. [48] examined two Ti-6Al-4V samples manufactured by selective laser melting (SLM) process with 50 μm and 100 μm hatch spacings and found that an increase in hatch spacing promotes formation of LOF porosities. Taheri et al. [8] reviewed the defects that may occur over powder bed fusion (PBF) process and the NDT methods that could be used to detect and evaluate them. They indicated that among various NDT techniques, radiography and ultrasonic testing were most promising. In their experiments, defects such as porosity, cracks and microstructural anomalies were effectively detected by UT. Ultrasonic testing was further used for characterizing mechanical properties of finished AM products.

Table 2 lists various types of defects and deficiencies formed in some metal AM processes [9,45]. Defects such as swelling, warpage and thermal distortion that may occur in AM processes are normally detectable by visual testing techniques and are excluded from Table 2.

Various potential defects appearing in AM products generated by Wire + Arc additive manufacturing (WAAM) processes were discussed in [49]. Since WAAM employs a welding process, its defects are like those of the designated materials and welding processes [50]. Table 3 lists common WAAM materials and welding processes and the defects detected over these processes.

Defects experienced in polymer additive manufacturing processes, such as fused deposition modeling (FDM), were discussed by Günaydın and Türkmen [51]. Most of these defects are visible in the absence of advanced NDT techniques such as ultrasonic testing (UT). However, UT can be used for detecting internal defects, such as voids and missing beads in FDM components. UT is also a very efficient tool in measuring elastic properties of these materials. The present authors have conducted high frequency (50 MHz) phased array ultrasonic tests on FDM samples. The conducted tests revealed the internal structure of different layers of an FDM sample and other defects including manufacturing faults as shown in Fig. 2.

3. Ultrasonic testing

Ultrasonic testing (UT) is one of the most powerful nondestructive evaluation (NDE) methods employed to detect and evaluate surface, subsurface and internal defects. In most metals, flaws as deep as several meters are detectable through UT while the material thickness is a limiting factor for most NDT methods [52]. The sensitivity of UT in detecting flaws highly increases with the testing frequency. In a broad sense, UT techniques can be divided into conventional and advanced techniques.

3.1. Conventional UT

In conventional UT, ultrasonic waves are emitted into a test piece and their interaction with flaws is employed to detect and evaluate defects and to ensure the integrity of the test component. A UT test can be performed in either contact or immersion mode. In contact mode, the ultrasonic probe is directly in contact with the test piece while in immersion testing a column of water lies between the probe and the test piece. In most contact tests, a thin layer of couplant is applied to the test surface to facilitate the transmission of ultrasonic waves into the material. The immersion UT is conducted by immersing both the test piece and probe in a water tank or by other immersion UT techniques where only part of the test piece is in contact with water. In wheel probe immersion UT, a rubber tire filled with water moves over the test piece and the test surface remains dry (also called dry-coupled UT) [53].

Ultrasonic waves are divided into two major categories of (i) bulk waves and (ii) guided waves. Bulk waves are either longitudinal or shear waves [54]. Guided waves have a larger variety, but those which are most popular in ultrasonic testing are surface (Rayleigh) waves and plate (Lamb) waves [55,56]. Guided waves require a wave guide to channelize, i.e. a certain geometry such as a surface or a plate-like

Table 1
Additive manufacturing processes [17,43].

Process	Technology	Material
Material extrusion	Fused Deposition Modeling (FDM) Fused Filament Fabrication (FFF) Robocasting	Polymers and plastics
Directed energy deposition (DED)	Laser Engineering Net Shape (LENS®) Supersonic Particle Deposition (SPD) or Cold Spray (CS) Laser Additive Manufacturing (LAM) Laser Powder Deposition (LPD) Wire + Arc Additive Manufacturing (WAAM) Direct Metal Deposition (DMD) Laser Metal Deposition (LMD)	Metal powder, metal wire and ceramic powder
Powder bed fusion (PBF)	Multi Jet Fusion (MJF) Direct Metal Laser Sintering (DMLS) Direct Metal Laser Melting (DMLM) Electron Beam Melting (EBM) Selective Heat Sintering (SHS) Selective Laser Melting (SLM) Selective Laser Sintering (SLS) HP Jet Fusion High Speed Sintering LaserCUSING Direct Metal Production (DMP) Laser Metal Fusion (LMF) Laser Powder Bed Fusion (LPBF)	Metals, plastics, ceramic powders and sand
Material jetting	Polyjet UV Cured Material Jetting Smooth Curvatures Printing (SCP) Multi-Jet Modeling (MJM) Drop on Demand (DOD) Nanoparticle Jetting (NPJ)	Photopolymers, waxes and composites
Binder jetting	3D Printing (3DP) ExOne VoxelJet Powder Bed Printing Drop-on-Powder Binder Jet Additive Manufacturing (BJAM)	Plastics, metals, glass, sand and ceramic powders
Sheet lamination	Laminated Object Manufacturing (LOM) Selective Deposition Lamination (SDL) Ultrasonic Additive Manufacturing (UAM) Selective Lamination Composite Object Manufacturing (SLCOM) Plastic Sheet Lamination (PSL) Ultrasonic Consolidation (UC) Computer-Aided Manufacturing of Laminated Engineering Materials (CAM-LEM)	Plastics, paper and metal sheets
Vat photopolymerization	Stereolithographic Apparatus (SLA) Digital Light Processing (DLP) Continuous Digital Light Processing (cDLP) Scan, Spin, and Selectively Photocure (3SP) Continuous Liquid Interface Production (CLIP)	Photopolymer resins

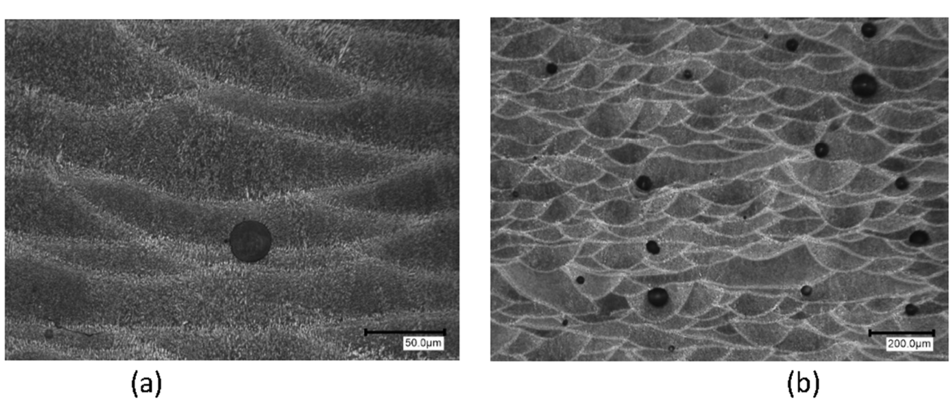

Fig. 1. a) Gas porosity and, b) lack-of-fusion porosity in selective laser melting (SLM) samples [47].

Table 2
Defects in various metal AM processes detectable by UT [9,45].

Process	Porosity	Cracks	Lack of Fusion	Residual Stress
PBF (laser)	Low	Yes	Yes	Yes
PBF (electron beam)	Low	Not typical	Yes	Low
DED (powder)	Low	Yes	Yes	Yes
DED (wire)	Low	Yes	Yes	Yes
Binder Jetting	High	Fragile green	No	Unknown
Sheet Lamination	At Sheet Interfaces	No	Yes	Unknown

structure which could guide the wave through. Most ultrasonic tests are done by using bulk waves through longitudinal or shear waves. Under certain conditions, these two waves can convert into one another. Upon interaction with an interface, ultrasonic waves may be reflected, refracted, diffracted, scattered, or mode converted. Ultrasonic waves are generated and received by different means. The most common way of generating and receiving ultrasonic waves is by using a piezoelectric transducer [57]. Piezoelectric transducers act as both transmitter and receiver. Other methods of generating ultrasonic waves include electromagnetic acoustic transducers (EMATs) [58,59], capacitive micromachined ultrasonic transducers (CMUT) [60,61], magnetostrictive transducers [62] and laser ultrasonics (LU) [63].

3.2. Advanced UT techniques

The advanced UT techniques have lately emerged. Two advanced UT techniques used for testing AM products include (i) phased array ultrasonic testing (PAUT), and (ii) laser ultrasonics (LU).

3.3. Phased array UT (PAUT)

Unlike conventional ultrasonic probes which include a single piezoelectric crystal to generate and receive ultrasonic waves, phased array probes include several small piezoelectric elements arranged in a specific pattern (linear, square, annular or circular). Each crystal is excited individually to enable a phased array (PA) probe to easily steer and focus the ultrasonic beam, see Fig. 3. PAUT has been largely developed over the past couple of decades and various linear and matrix probes have been developed along with new techniques for collection and analysis of data [36,64–66].

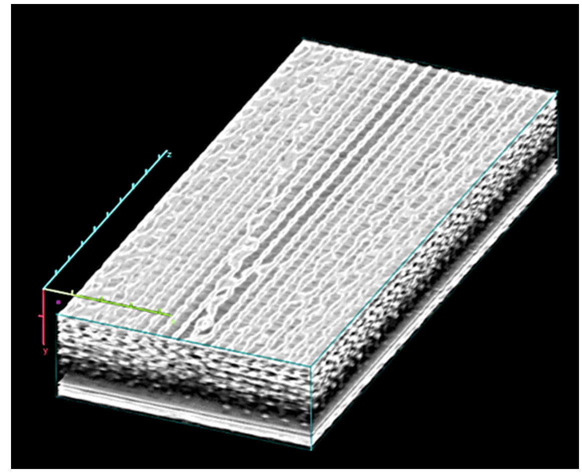

Fig. 2. The fourth layer (from the top) of a 24-layer FDM Polylactic Acid (PLA) sample scanned by a 50 MHz phased array ultrasonic probe by the present authors.

3.4. Laser ultrasonics (LU)

Projection of a laser beam onto a test surface results in a thermal shock leading to rapid expansion of the test surface. This rapid expansion generates ultrasonic waves in the test piece. In general, LU is conducted in either of the two different regimes of thermoelastic or ablation [67]. At low laser powers, the test is conducted in thermoelastic regime and at high laser powers, the ablation regime prevails. Based on the specification and conditions of the test piece, an NDT engineer may decide which LU regime to utilize. Fig. 4 shows different stages of generation and propagation of ultrasonic waves by a laser beam in ablation regime simulated by finite element analysis [68]. In thermoelastic regime, a thermal shock is applied to the surface without causing any damages but in the ablation regime, minor material removal takes place and the technique is semi-destructive. While laser interferometers are common receivers in laser ultrasonics (LU), piezoelectric and EMAT probes have also been considered as receiving elements [69].

4. Ultrasonic testing in additive manufacturing

4.1. In-situ ultrasonic testing

Ultrasonic testing is one of the most capable NDT techniques for in-situ monitoring of AM processes as well as quality control of both metal

Table 3
Major defects observed in WAAM Processes [49].

Material	Welding Process	Defect Type Porosity	Delamination	Crack	Oxidation	Substrate Adherence
Ti-6Al-4V	TIG	–	–	–	Light	Good
Ti-6Al-4V	CMT	–	–	–	Light	Good
Ti-6Al-4V	DCEP-GMAW	–	–	–	Light	Medium
H08Mn2Si steel	DE-GMAW	Low	–	–	–	Good
Copper-coated steel	GMAW	–	–	–	Light	Good
ER4043 aluminum alloy	CMT	High	–	–	Light	Good
AA2319 aluminum alloy	CMT	High	–	–	–	Good
5356 aluminum alloy	VP-GTAW	–	–	✓	–	Good
Inconel-625	PPAD	High	–	✓	–	Good
Inconel-718	GMAW	Medium	✓	✓	–	Good
AZ31 magnesium alloy	PMIG	–	–	–	Light	Medium
Intermetallic Fe-Al	GTAW	High	–	✓	Serious	Medium
Intermetallic Al-Ti	GTAW	Low	–	✓	–	Good
Intermetallic Al-Cu	GTAW	–	✓	–	Light	Poor

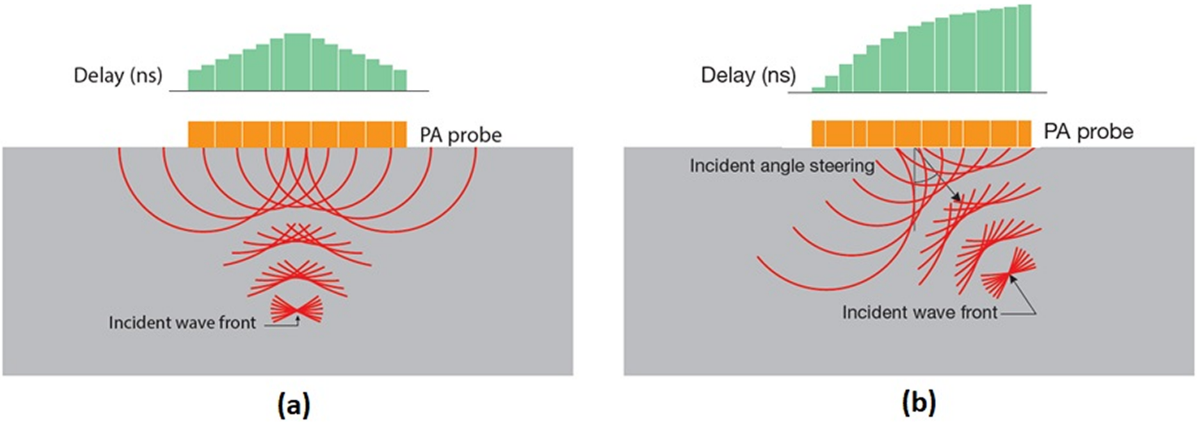

Fig. 3. Focusing and steering of ultrasonic beam in phased array ultrasonic testing (PAUT) is through changing the time delay of excitation pulses sent to each piezoelectric element of the probe, (a) beam focusing, (b) beam steering [36].

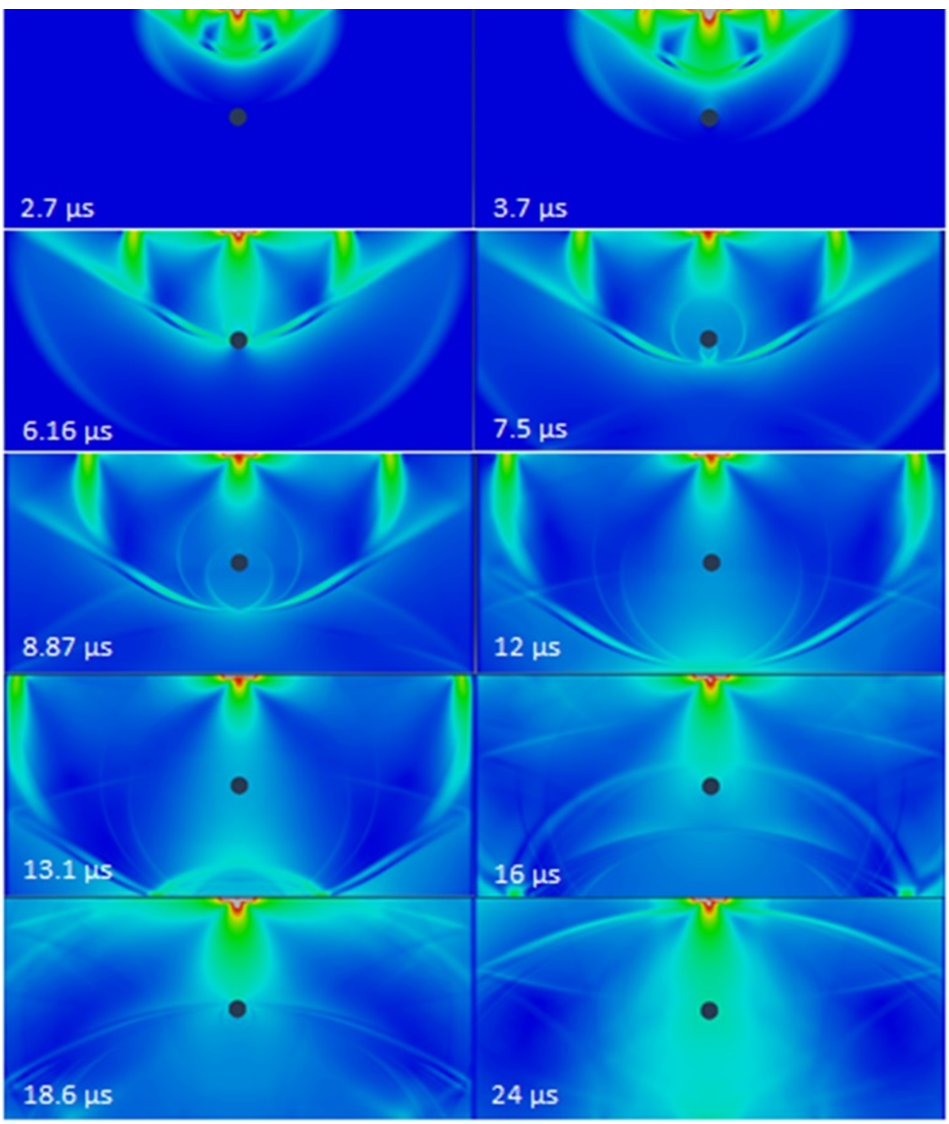

Fig. 4. Finite element modeling of a laser ultrasonics wave reflected from a 3 mm diameter side-drilled hole in thermo-elastic regime. The laser has 57 mJ energy, 10 ns half pulse length and 3.8 mm laser spot [68].

and plastic AM products. The research done on in-situ ultrasonic testing of additive manufacturing products is discussed in this Section.

4.2. Metal AM components

Installation of ultrasonic probes under the build surface has been considered as an online method of monitoring AM processes. Nadimpalli et al. [70] mounted a 5 MHz ultrasonic probe under the build plate of an ultrasonic AM (UAM) machine to measure the quality of the parts during the manufacturing process. Offline measurements were also conducted on the samples by preparing C-scan images from these samples. The C-scan images were prepared by using a 5 MHz immersion probe. They also developed an interfacial spring model to simulate the behavior of the layered components and discussed the effect of layers on ultrasonic signals. In another paper, the same research group conducted further measurements on aluminum UAM samples [71]. They divided the inter-layer defects into type 1 (delamination or kissing bonds), and type 2 (inter-track defects). The ultrasonic transducer was changed from contact to immersion and was installed inside of an oil tank under the UAM build plate. This immersion transducer had a frequency of 10 MHz and a diameter of 6 mm. Six UAM samples were manufactured from 150-μm thick Al 6060-H18 foils on an Al 6060 base plate. Ultrasonic measurements were carried out during the manufacturing process while formation of type 1 and type 2 defects was monitored. The model-based inversion technique developed in [70] was used for assessing the acquired ultrasonic data. The AM samples were then tested off-line and A-scan and C-scan images were prepared to reflect the presence of defects in these samples. A novel solid-state repair technique using friction stir welding was also proposed and implemented for repairing the defects. Rieder et al. [72] installed a 10-MHz, 6.3-mm diameter, longitudinal wave piezoelectric probe under the build platform of an SLM machine for layer-wise monitoring of the product during the manufacturing process. The probe was glued under the build platform after application of grease coupling and measurements were conducted layer by layer in pulse-echo mode. The test sample was a cylinder 20 mm in diameter and 10 mm in height with a 2-mm spherical void defect created in it during the manufacturing process. This sample was made of 250 layers, each 40 μm in thickness. The void was poorly visible due to misalignment of the probe, but an immersion C-scan clearly revealed the presence of this defect. This group of researchers [73] used the same test set-up to investigate the effect of *laser power* on the microstructure of the manufactured SLM components. Cylindrical SLM samples for which the laser power was changed during the build-up of certain layers were monitored by measuring the ultrasonic data during the process. The B-scan image produced from the samples clearly showed the changes in porosity content of the sample due to variations in laser power. X-ray computed tomography (XCT) images validified the outcomes of ultrasonic measurements. In another study, the same group of researchers [74] proposed a test block for calibration of the ultrasonic tests conducted on SLM samples. The semi-cylindrical block had a radius of 50 mm and a thickness of 30 mm. Cylindrical holes with diameters ranging from 2 to 4 mm were implanted at different depths in this block as shown in Fig. 5. The block was used for calibration of wave velocity and was tested by phased array ultrasonic testing (PAUT) technique as well as XCT method.

Pieris et al. [75] used Spatially Resolved Acoustic Spectroscopy (SRAS) technique for online monitoring of SLM samples during production. SRAS is a laser ultrasonics (LU) technique which uses Surface Acoustic Waves (SAWs) to measure elastic properties of materials. They used SRAS to monitor the effect of a change in the laser power used for melting powders in one sample and build scan strategy on another sample. Their results showed that SRAS can be considered as an on-line tool for monitoring SLM processes. Chabot et al. [76] investigated the application of phased array ultrasonic testing through in-situ and real-time inspections of AM components made by directed energy deposition (DED). The DED methods used were laser metal deposition (LMD) and Wire + Arc additive manufacturing (WAAM). They prepared an aluminum alloy 5356 calibration block with dimensions of 140 × 60 × 20 mm with side-drilled holes of different depths and diameters. This block was used for calibrating a 10-MHz, 128-element phased array probe which was utilized for testing a hollow-blade aluminum alloy propeller manufactured by WAAM. A porosity defect with a diameter less than 0.6 mm was detected in this propeller. XCT scanning was used to verify the ultrasonic testing results. A test on a stainless-steel sample manufactured by LMD process was also reported. For this purpose, an 18.5-MHz, 128-element phased array ultrasonic probe was utilized.

Recently, Javadi et al. [77] employed an automated weld deposition that was coupled with a robotic ultrasonic testing system for real-time inspection and monitoring of welds. This implementation seems to be promising as a starting point for in-situ inspection of Wire + Arc additive manufacturing (WAAM) products. A tungsten rod with a diameter of 2.6 mm, representing a lack of fusion, was embedded in a multi-pass weld on a 15-mm thick structural steel (S275) plate. A 5-MHz, 64-element phased array ultrasonic probe mounted on a high-temperature wedge and installed on a 6-axis robot was utilized for inspection of the weld during the welding operation. The wedge was equipped with four spring-loaded thermocouples and withstood intermittent temperatures up to 150 °C. By real-time sector scanning of the weld, the tungsten rod was successfully detected in the deposited weld. Another weld sample was also designed to study crack initiation and growth over welding process through use of the robotic phased array UT system. To make sure that no cracks occur in a weld, it was recommended that the root pass of a weld be monitored for at least 36 min after the termination of the welding process.

4.3. Plastic AM components

Laser pulses can be used for both generation and reception of ultrasonic waves on plastic samples; although in many cases they are only used for one of these two purposes. While laser ultrasonics (LU) is used to control a manufacturing process, each layer of the product is tested separately. Koskelo and Flynn [78] conducted in-situ tests on plastic samples manufactured by Fused Deposition Modeling (FDM). Various defects were implanted in these samples. Tests were carried out by attaching an ultrasonic probe to the build plate and layer-wise scanning of the sample surface by a laser doppler vibrometer. The ultrasonic

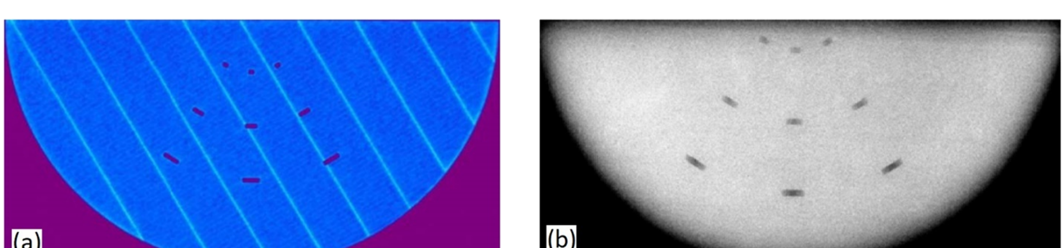

Fig. 5. Smart test block suggested by Rieder et al., a) image recorded during manufacturing, b) XCT image of the test block [74].

probe was excited by a single tone burst at a frequency of 80.5 kHz during the test. Cummings et al. [79] used an in-situ ultrasonic inspection technique for detection of defects in FDM samples. They bonded four piezoelectric crystals to the build plate of the machine and excited these crystals by a chirp signal every 30 s. The frequency response of the sample was then recorded and compared with the frequencies collected from an intact sample.

4.4. Offline ultrasonic testing

Many researchers [12,13,46,52,80–83] have used ultrasonic testing techniques to test and measure various characteristics of metal and plastic additive manufacturing products. The works done on offline ultrasonic testing of AM products are reviewed in this Section.

4.5. Metal AM components

The capability of laser ultrasonics (LU) for testing metal AM components has been investigated by several authors. Cerniglia et al. [52] used laser ultrasonic technique to inspect Inconel components manufactured by laser powder deposition (LPD) where interlayer and intralayer defects may form [84]. An infrared Nd:YAG pulsed laser was employed to operate in the thermoelastic regime. The receiving laser to detect surface displacements was a combination of a continuous-wave laser and an interferometric unit. A numerical model of the process was also developed to help understanding the physics of the technique. Measurements were successfully carried out on a number of samples with implanted defects and near surface micro-defects with diameters of 0.1 mm. Stratoudaki et al. [80] used laser ultrasonic testing for testing an aluminum sample made by selective laser melting (SLM) process. The test piece was $40 \times 20 \times 10$ mm and included several side-drilled holes with diameters of 0.5–1 mm. The test method was called laser induced phased arrays (LIPAs) in which regular laser ultrasonic testing in thermoelastic regime was carried out and the capabilities of phased array were implemented in post-processing of the images. They applied the Full Matrix Capture (FMC) and Total Focusing Method (TFM) schemes to the collected phased array data and were able to discern defects as small as 0.5 mm in size and 26 mm in depth. FMC is a new data acquisition technique and TFM is a new data processing scheme that are used with phased array ultrasonic testing (PAUT). FMC collects the data from every part of the test sample and TFM subsequently processes this data to generate the desired images from test samples. Compared to common PAUT scanning methods, such as S-scan, in which only the focal area of the image appears with high resolution, in this approach, almost all parts of an image appear with optimal resolution [85,86].

Santospirito et al. [81] conducted laser ultrasonic testing on samples made from Inconel by laser powder bed fusion (PBF) process. Holes were drilled in seven different samples by laser drilling and electro discharge machining (EDM). These samples were then tested by both laser ultrasonics (LU) and thermographic testing (TT). Both LU and TT were able to detect defects that were 400 µm in size or larger. Lévesque et al. [82] used laser ultrasonics method for offline testing of AM coupons made from INCONEL® 718 and Ti-6Al-4V by selective laser melting (SLM) and electron beam melting (EBM) processes. They used laser ultrasonics (LU) in ablation regime along with synthetic aperture focusing technique (SAFT). An Nd:YAG laser in its 2nd harmonic, i.e. 532 nm wavelength, was used for generation of ultrasonic waves and another Nd:YAG laser with a wavelength of 1064 nm was used for receiving the signals. Defects such as lack of fusion, lack of bonding, and porosity were successfully detected. The validity of the UT results was further confirmed by micro-computed tomography. Everton et al. [46] used laser ultrasonics for testing $10 \times 10 \times 30$ mm AM blocks made from Ti-6Al-4V by laser powder bed fusion (PBF) process. The laser used for generating ultrasonic waves was a Q-switched Nd:YAG laser with a wavelength of 1064 nm. Powder-filled pores were implanted into the blocks at different depths during the manufacturing process. The laser ultrasonics technique was able to detect the three implanted pores which were also identified by computed tomography (CT). Everton et al. [12] used laser ultrasonics (LU) to test Ti-6Al-4V test blocks manufactured by laser powder bed fusion (PBF) and compared the B-scan images obtained from LU tests with results obtained from X-ray computed tomography (XCT). Their test blocks were $20 \times 20 \times 10$ mm in size manufactured by using different hatch spacings and scan speeds. A defect with a size of $10.0 \times 3.0 \times 0.2$ mm was introduced below the covering layer of the samples. While LU was able to detect the defects, the authors recommend further investigations before LU could be considered as a reliable means for inspecting these kinds of products. Millon et al. [83] used laser ultrasonics (LU) to test a solid block made from 316L stainless steel by directed energy deposition (DED). The block was $80 \times 20 \times 25$ mm with four notches machined by electro discharge machining (EDM) on its top and bottom surfaces. Surface notches as small as 0.1 mm deep and 0.05 mm wide were detectable.

Davis et al. [13] applied laser ultrasonics (LU) on a $60 \times 20 \times 10$ mm block made from AlSi12 powder through selective laser melting (SLM) process. Flat-bottomed holes with radii of 1 mm and depths varying from 2 to 20 mm were implanted in the block during the manufacturing process. The surfaces of the blocks were sand blasted.

Two lasers were used for laser ultrasonic testing of the sample, one for generation of ultrasonic waves and one for detecting the reflected waves. The first laser was a Nd-YAG pulsed generation laser with a wavelength of 1064 nm, pulse duration of 9.80 ns, and maximum energy of 210 mJ/pulse. The detecting laser was a continuous wave fiber laser with a wavelength of 1550 nm and maximum capacity of 2 W. The tests were done in through-transmission mode. A-scan, B-scan, and C-scan images were obtained from the sample. They also conducted CT scanning and immersion ultrasonic testing with 1 MHz, 5 MHz, and 15 MHz probes and compared the results with those obtained by LU. The results showed that LU is a promising NDT technique for testing AM products.

Pieris et al. [87] used Laser Induced Phased Array (LIPA) for remote ultrasonic testing of a $20 \times 40 \times 10$ mm block made from AlSi10Mg by selective laser melting (SLM). Six through holes with diameters of 0.5 and 1 mm were implanted in the sample at various depths. A pulsed Nd:YAG laser with a wavelength of 1064 nm, pulse energy of 0.1 mJ, and repetition rate of 5 kHz was used to generate the ultrasonic pulse in thermoelastic regime. The receiver was a continuous-wave laser vibrometer with a wavelength of 633 nm, power of 1 mW and focal spot of 0.04 mm. To reduce the noise, each signal was averaged 500 times. LIPA combines the benefits of laser ultrasonics (LU) and the advanced imaging capabilities of phased arrays. The LU scanning was made under the build plate and the collected data was synthesized in post-processing. Five of the six implanted defects were successfully detected in the test sample. The results obtained through LIPA were then verified by comparison with XCT scans and ultrasonic measurements made by using a 10 MHz, 128-element phased array (PA) ultrasonic probe. Both XCT and PA probe were able to detect all six defects in the test sample. The authors suggested that LIPA can be used for in-situ process monitoring of AM components made by SLM. Yu et al. [88] inspected a Ti-6Al-4V test block manufactured by selective laser melting (SLM) by using laser ultrasonics (LU). The test block was $50 \times 10 \times 5$ mm and four through holes with diameters ranging from 0.4 to 2 mm were implanted in it as representative defects. A Q-switched Nd:YAG laser with a wavelength of 532 nm was used for generating ultrasonic waves in thermoelastic regime and a scanning LDV with a wavelength of 532 nm and a resolution of 0.2 mm was used as the detecting device. The smallest hole that was discernable in B-scan and C-scan images was the 0.8-mm hole while the 0.4-mm hole could not be detected. The ultrasonic test results were verified by comparison with X-ray computed tomography (XCT) images.

Some researchers used ultrasound to measure various properties of AM products. Foster et al. [89] used ultrasonic testing to evaluate elastic constants of AM samples made by ultrasonic additive manufacturing (UAM). Longitudinal and shear wave velocities were measured in Al 3003-H18 samples with different percentage areas of bonding. From these measurements, the elastic constants of the samples were found and compared with a cold-worked aluminum sample. They reported that the manufactured components possess orthotropic properties and the elastic constant values may reduce up to 48% due to the presence of voids in the final UAM components. They also reported that as the bonding area increased, the elastic constants of samples approached those of the bulk sample. Slotwinski et al. [24,90] tried to establish a correlation between the wave velocity and porosity content of AM samples. They conducted ultrasonic wave velocity measurements on sixteen samples made from CoCr through powder bed fusion (PBF) process. Test samples were made as cylindrical disks, 10 mm thick and 40 mm in diameter. By varying the hatch speed and hatch spacing during the build, various amounts of porosity ranging from 0% to 70% were introduced into these samples. The samples were then tested by a 5 MHz probe in pulse-echo mode. The variations in ultrasonic wave velocity were found to be linearly correlated with the porosity percentage of samples, see Figs. 6 and 8. They concluded that the ultrasonic velocity measurement method enabled detection of small changes, approximately 5%, in porosity and can be used as an in-situ method to monitor the porosity content of SLM products.

Hanks et al. [91] investigated the effect of surface roughness on ultrasonic testing of Ti-6Al-4V samples manufactured by electron beam melting (EBM). They found promising results for tests conducted with frequencies as high as 10 MHz on as-manufactured surfaces, while lower frequencies of 2.25 MHz and 5 MHz were found incapable to detect damages. Witkin et al. [14] conducted both ultrasonic and computed tomography (CT) tests on selective laser melting (SLM) samples made from Al10SiMg. Cubic samples with different thermal histories and sizes were tested and their elastic modulus, E, and Poisson's ratio, ν, were calculated by measuring the wave velocities in samples. Elastic properties of samples that were heat-treated differently were further examined and changes in properties were discussed. Javidrad and Salemi [92] measured the elastic constants of Inconel 625 samples that were manufactured by laser powder-bed fusion (LPBF). Eight samples were prepared with different process parameters that included laser power, scan speed and hatch spacing. Longitudinal and transverse wave velocities were measured in these samples. Longitudinal wave velocity was measured by a 4-MHz, 12-mm diameter normal beam transducer while transverse wave velocity was measured by a 4-MHz, 8 × 9 mm angle beam probe. The elastic constants of samples were then calculated from the measured wave velocities. Tensile tests were used to verify the ultrasonic results.

Sealy et al. [93] used conventional ultrasonic testing for measuring the glocal integrity on 420 stainless steel samples manufactured by laser engineering net shaping (LENS®). Glocal integrity refers to cumulative surface integrity that is enabled by a secondary process during the AM process. Cylindrical samples 12.7 mm in diameter and 25.4 mm in height were manufactured. In some of these samples, approximately 17 out of 85 layers were treated by laser peening. The surfaces of the samples were machined before performing the longitudinal wave velocity and attenuation measurements. It was shown that ultrasonic testing is a suitable choice for mapping the glocal integrity of these samples.

Several researchers have conducted ultrasonic tests on samples with implanted defects. Roy et al. [94] conducted ultrasonic tests on a 30-mm diameter cylindrical sample made from powdered-aluminum alloy by selective laser melting (SLM). Three spherical defects in the form of un-sintered spheres of 2-mm diameter were implanted along the axis of the sample. They measured the time-of-flight of ultrasonic waves by using a 5 MHz normal-beam probe. Farrell and Deering [95] conducted ultrasonic tests on metal test blocks made from M300 steel by laser directed energy deposition (DED) process. Test blocks were made with dimensions of 150 × 60 × 3 or 4.5 mm. Evenly distributed defects were introduced into the blocks through altering the hatch speed and spacing. The defect density varied between 1% and 5%. The percentage of porosity in blocks were tested by different means including ultrasonic testing. The ultrasonic tests were carried out in pulse-echo mode using a 5 MHz probe with a diameter of 6 mm. While the wave attenuation for the intact specimen was low, it showed a significant increase for the block with 1% of porosity content such that almost no returned echoes, except the initial pulse, was observable. They also reported a direct relationship between the gain setting (80% FSH) of the ultrasonic flaw detector and the density of the specimens. Prevorovsky et al. [96] employed nonlinear ultrasonic spectroscopy techniques to test Ti-6Al-4V prismatic samples made by electron beam melting (EBM) process. Defects in the form of side-drilled holes and stochastic porosity were introduced into the samples.

Sol et al. [97] conducted ultrasonic tests on AlSi10Mg samples manufactured by selective laser melting (SLM). They prepared several samples to measure longitudinal and shear wave velocities in different directions. The longitudinal wave was measured by using a 20 MHz probe with a diameter of 3.175 mm. The shear wave was measured by using a 5-MHz probe having a diameter of 12.7 mm. A cast AlSi10Mg sample was used as reference. Samples were subjected to various heat treatment processes. In addition to wave velocity measurements, they also measured the attenuation in samples. These measurements were conducted by frequency depended attenuation analysis and exponential fitted attenuation. They resulted in ignorable changes in longitudinal wave velocity, while changes in shear wave velocity were noticeable.

Immersion ultrasonic tests have also been considered by several researchers. Song et al. [98] conducted immersion ultrasonic tests on a 316L stainless steel sample manufactured by selective laser melting (SLM) process. The sample was 40 × 40 × 15 mm and had a porosity volume of 0.38%. The ultrasonic tests were carried out in pulse-echo mode in a water tank using a 15-MHz focused transducer. Through statistical analysis, the C-scan images were analyzed for the presence of defects in the tested sample. These results were further compared with those obtained through destructive tests. Ladewig et al. [99] conducted ultrasonic C-scan imaging on AM samples made by selective laser melting (SLM) process to detect defects such as lack-of-fusion. Karthik et al. [100] carried out immersion ultrasonic tests on EOS GP1 stainless steel samples manufactured by sheet lamination process. Durkee et al. [101] conducted ultrasonic tests on Ti-6Al-4V blocks manufactured by electron beam melting (EBM) process. Blocks with dimensions of 91 × 25 × 25 mm containing six spherical voids at different depths were prepared. The ultrasonic tests were carried out in an immersion tank by using a 10-MHz, 0.5-inch focused transducer. B-scan images were prepared from all tested samples. These images were then processed by Hough transform and SURF processing. They concluded that UT is not fully capable of detecting voids at different depths.

Ibrahim and Zhuang [102] carried out numerical modeling and experimental measurements of the ultrasonic testing of fatigue cracks in aluminum alloys repaired by supersonic particle deposition (SPD). SPD is a directed energy deposition (DED) technique in which micron-sized particles are accelerated through the nozzle of a spray gun at supersonic velocities. These particles consolidate upon impacting the component surface to from a permanent coating. They used ultrasonic testing and thermoelastic stress analysis to detect fatigue cracks under SPD coatings and recommended the combination of the two inspection techniques for effective results.

Wang et al. [103] incorporated phased array ultrasonic testing (PAUT) for inspection of a TC18 titanium alloy cubic block with side lengths of 55 mm. Coarse grains and anisotropy make the ultrasonic testing of this material quite challenging. Three flat-bottomed holes, 0.8 mm in diameter and 5 mm in depth, were drilled on three surfaces of this block, Fig. 6. The ultrasonic measurements were carried out by both conventional and phased array ultrasonic techniques. A 10-MHz, 0.5-mm diameter, focused immersion ultrasonic transducer was used for conventional measurements and a 10-MHz, 64-element linear array

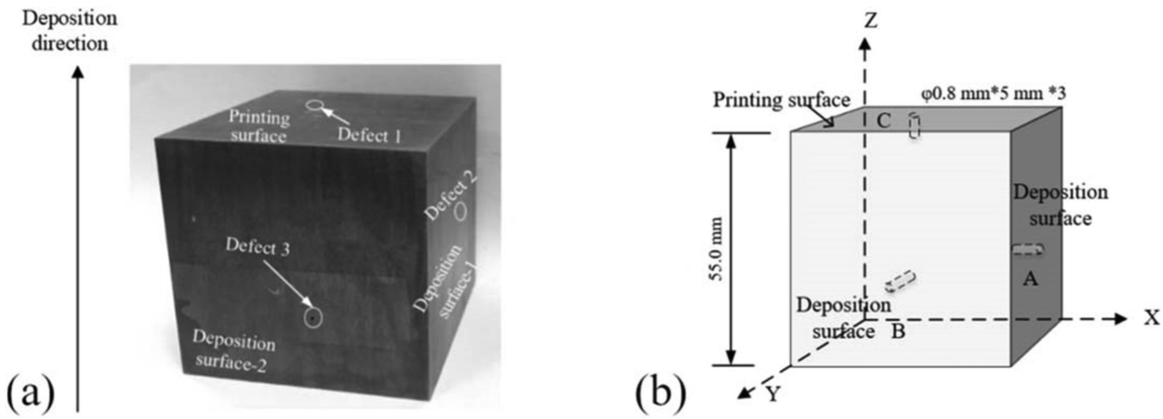

Fig. 6. a) Solid TC18 titanium block, b) schematic illustration of flat-bottomed holes machined in the block [103].

transducer and a 10-MHz, 16-element annular phased array transducer were used for phased array ultrasonic testing. Full matrix capture (FMC) and total focusing method (TFM) were used for collecting and analyzing the ultrasonic data. Phased array systems, especially the annular transducer possessed better accuracy and resolution as compared to conventional UT techniques, see Fig. 7. The same group of researchers, Li et al. [104], reported further investigations on ultrasonic testing of AM TC18 titanium samples. They modeled the three-dimensional acoustic fields of both linear and annular phased array transducers. Ultrasonic group velocities were also measured in TC18 titanium sample at different propagating angles and C-scan images were prepared by both linear and annular phased array probes. Results showed that the annular phased array probe has higher accuracy in quantifying the defects.

Wire + Arc additive manufacturing (WAAM) falls under directed energy deposition (DED) AM techniques. A few works on the application of ultrasonic testing to WAAM technique has been reported in the literature as follows. Lopez et al. [105] used phased array ultrasonic testing (PAUT) for inspection of Wire + Arc additive manufacturing (WAAM) components made from aluminum AA2319. Three samples were tested. The surface of one of the samples was machined and the other two sample surfaces were tested as is. Two phased array ultrasonic probes with frequencies of 3.25 and 5 MHz were used for testing. Tests were simulated by the CIVA [106] simulation software package. In simulations, a lack of fusion with a size of 3 mm at a depth of 3.5 mm was detectable. In experiments with up to 91.55 µm average surface waviness profile, detection of defects with sizes ranging between 2 to 5 mm was found to be feasible. It was concluded that PAUT technique can be used for testing WAAM products. Dryburgh et al. [107] used Spatially Resolved Acoustic Spectroscopy (SRAS), which is based on the

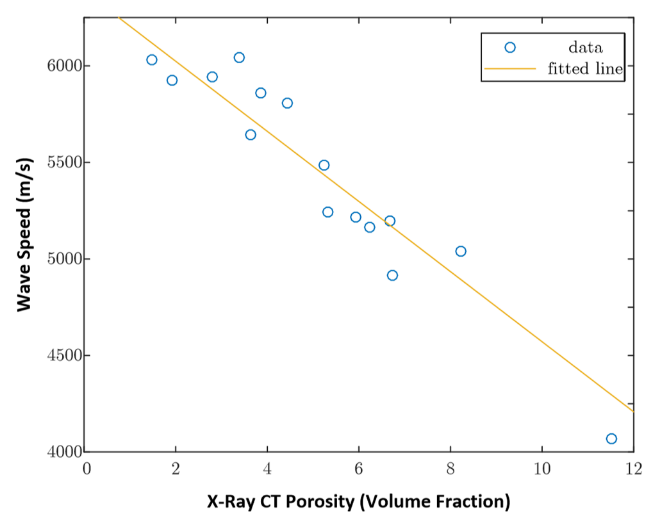

Fig. 8. Correlation between measured ultrasonic wave speed in SLM samples as a function of measured porosity in the CoCr disks as determined by X-ray CT measurements [24].

analysis of laser-generated Rayleigh waves on the surface of a specimen to examine the effect of rolling on Wire + Arc additive manufacturing (WAAM) products. The specimens were made from Ti-6Al-4V welding wire feedstock by a pulsed gas tungsten arc welding torch with argon shielding. Each welded layer had a width of approximately 6 mm and a height of approximately 24 mm. After cooling of each layer, it was rolled by a 100 mm diameter roller. Two rolling forces of 50 kN and 75

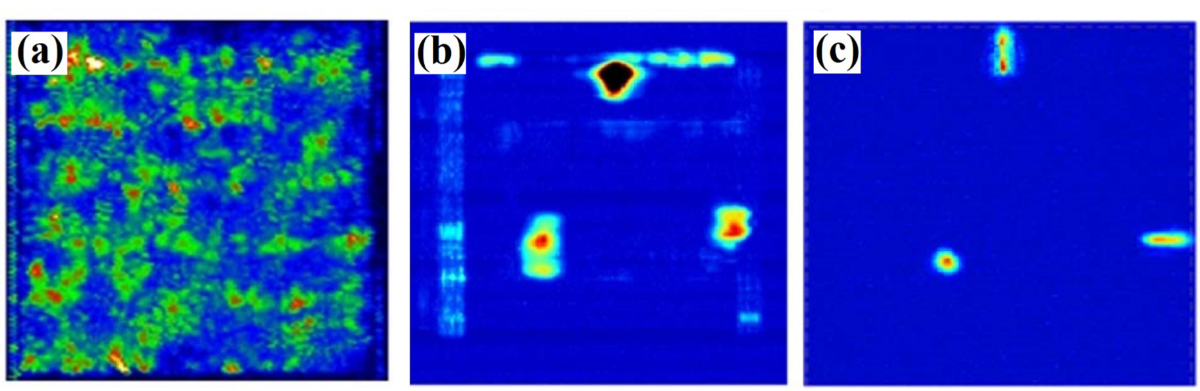

Fig. 7. C-scan images for the TC18 titanium block shown in Fig. 6, a) conventional UT, b) linear array PAUT, c) annular array PAUT [103].

kN were applied. Small specimens were cut from the manufactured part by electrical discharge machining and mounted for SRAS tests. Test results indicated that grains within microstructure were refined through rolling process in cross-sections and side walls. Javadi et al. [50] employed phased array ultrasonic testing for inspection of a steel block manufactured by WAAM. The block was manufactured by using a Gas Metal Arc (GMA) welding torch mounted on a six-axis robot. Tungsten-carbide balls with diameters ranging from 1 to 3 mm were embedded at different depths in this test block. The block was then tested by a 5-MHz, 64-element phased array transducer. By employing the full matrix capture (FMC) and total focusing method (TFM), most of these embedded defects were detected. A calibration method and a testing procedure for testing a WAAM steel sample with a lack-of-fusion (LOF) defect was also developed and the results were verified by destructive testing. It was concluded that while TFM was able to detect most of defects, incorporation of meander scanning would result in better sensitivity. The same research group [108] conducted phased array ultrasonic testing on aluminum samples manufactured by WAAM. Side-drilled holes with diameters ranging from 0.5 to 3 mm were machined in these samples. Samples were first scanned by a wheel probe that was mounted on a robot, but the results were not acceptable. Then, 5- and 10-MHz phased array probes along with full matrix capture (FMC) and total focusing method (TFM) were utilized for inspecting the samples. It was shown that the combination of the conventional and phased array ultrasonic techniques can identify all implanted defects. Mohseni et al. [109] conducted phased array ultrasonic testing on titanium samples made by WAAM process. Four samples with linear structures were manufactured. Two of these samples were built using parallel deposition and contained defects in the form of lack of fusion (LOF) and keyhole. The other two samples were built using oscillated deposition with no intentional defects. These samples were tested in pulse-echo mode by three different linear array ultrasonic probes from their machined and original surfaces. The frequency and element size of these probes were: 1) 5 MHz-64 element, 2) 10 MHz-128 element, and 3) 10 MHz-32 element. A 2-mm diameter side-drilled hole (SDH) which was machined in one the walls was used for calibration. Best results were obtained by using the 5-MHz, 64-element linear array probe. It was concluded that the phased array technique could be a suitable choice for inspection of titanium WAAM products.

Ma et al. [110] used a laser opto-ultrasonic dual detection approach, called LOUD, to conduct simultaneous optical and laser ultrasonics (LU) tests on Wire + Arc additive manufacturing (WAAM) components. They first tested a 12-mm thick laser-welded aluminum alloy A6061 block which contained a 2-mm diameter side-drilled hole as an artificial defect. The surface of the sample was ablated by an Nd:YAG laser beam with a wavelength of 532 nm and a pulse energy of 60 mJ to generate both ultrasound and optical spectra. The ultrasonic wave was picked up by a 15-MHz ultrasonic transducer mounted under the test specimen and the optical spectra was detected by a charge-coupled device (CCD) spectrometer as presented in Fig. 9.

The results showed that LU can detect the implanted defects and the residual stress in the test sample. Digital radiography was used to confirm the LU results. Both the LU and spectroscopy results were compared with measurements made by other techniques and were found to have less than 10% relative error. In the next step, a 5-mm thick WAAM test sample was tested by LOUD which revealed the presence of a porosity defect. The relative errors in measurements of Cu content, defect and residual stress were estimated to be less than 15%. A possible experimental setup was proposed for in-situ testing of WAAM components.

4.6. Plastic AM components

Na and Oneida [111] used a special immersion ultrasonic imaging system with 20 MHz focused transducers to test polymeric samples made by fused deposition modeling (FDM). The test sample was made from ULTEM™ 9085 thermoplastic filament with dimensions of 76.2 × 76.2 × 3.3. mm. The tests were conducted in both pulse-echo and through-transmission modes. Fig. 10 shows the C-scan image obtained from the test sample in through-transmission mode. A specific sample with cavities, holes and varying wall thicknesses is also suggested as a standard block for calibration of AM manufacturing systems, as presented in Fig. 11.

Jin et al. [112] conducted immersion ultrasonic tests on 3D printed samples made from acrylonitrile butadiene styrene (ABS) by fused deposition modeling (FDM). They prepared two samples with varying densities and scanned them by a conventional 1-in, 0.5-MHz immersion ultrasonic transducer. By using a specific imaging algorithm, they prepared images that showed the effective density variations along the samples. It was suggested that this technique could be combined into FDM machines for in-situ monitoring of the manufacturing process.

Yap et al. [113] used ultrasonic testing to measure elastic constants of a Polycarbonate-Acrylonitrile Butadiene Styrene (PC-ABS) sample manufactured by fused deposition modeling (FDM) process. They

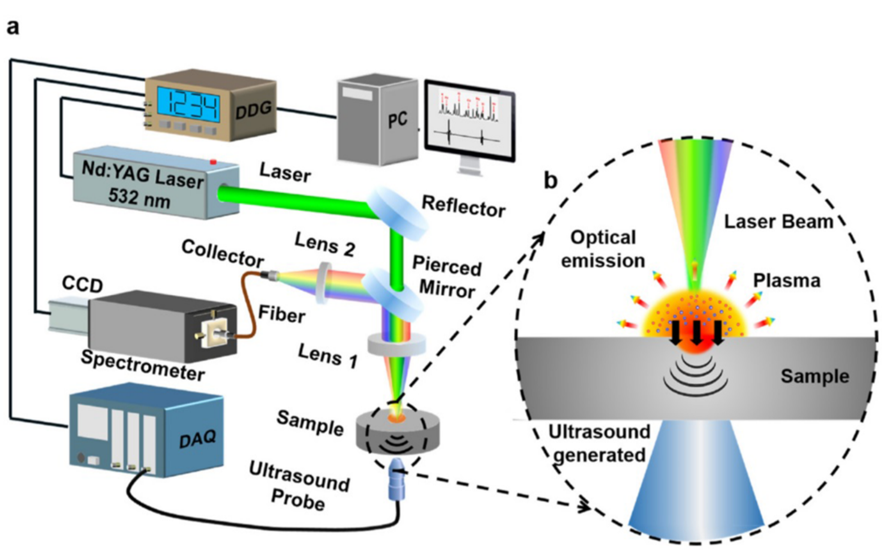

Fig. 9. (a) The experimental setup for LOUD detection. (b) The schematic of LOUD detection. The plasma is generated by laser ablation which consequently generates the optical spectra and ultrasonic waves [110].

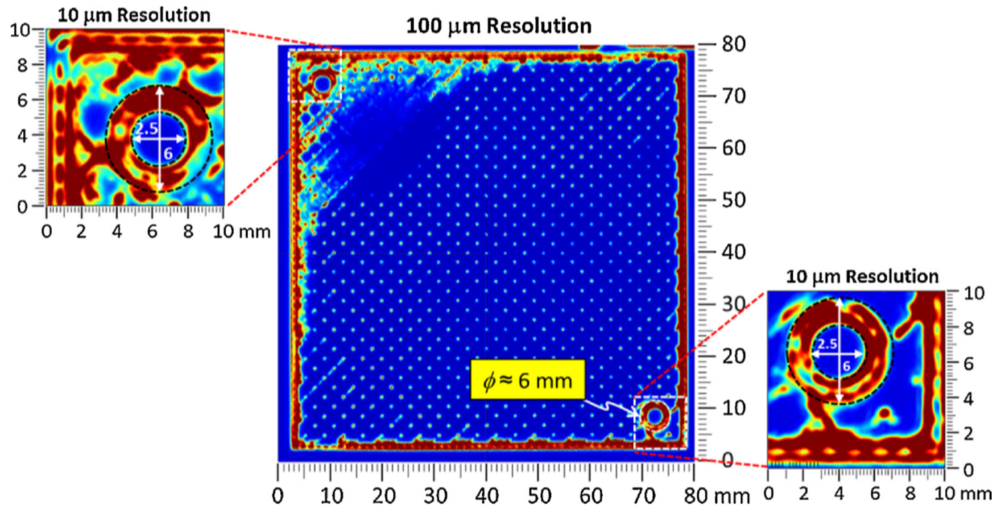

Fig. 10. C-scan image of the FDM test sample [111].

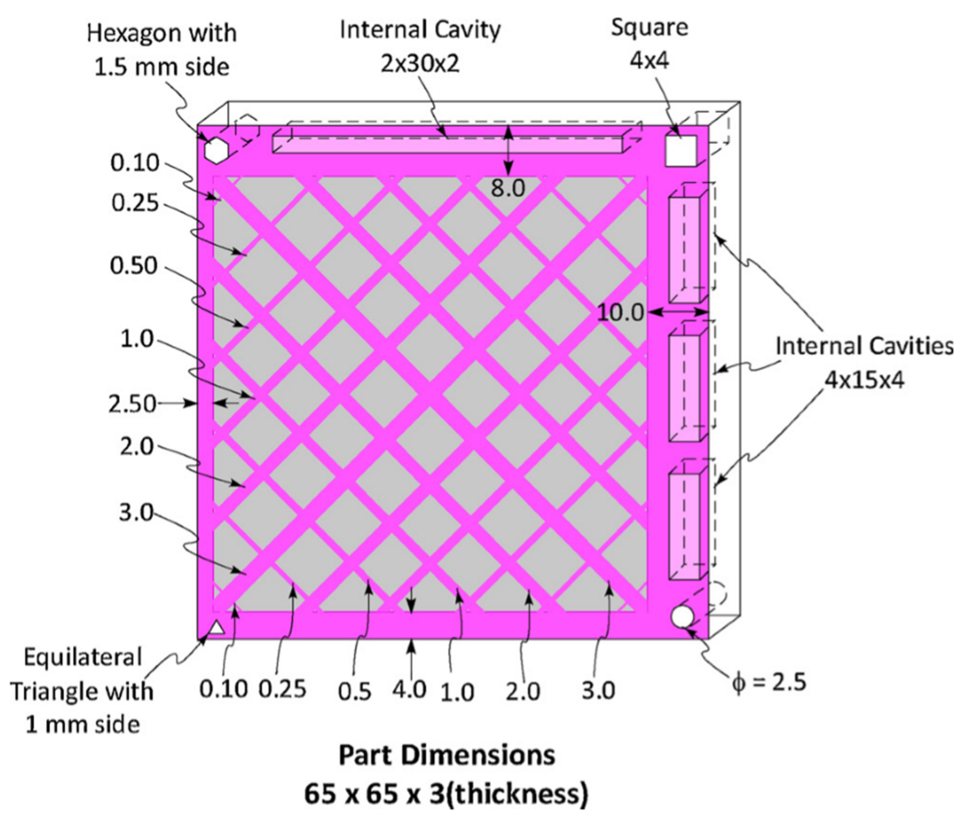

Fig. 11. Reference block proposed for calibration of FDM systems [111].

assumed that the sample is orthotropic and measured its longitudinal and shear wave velocities along different directions in order to find the nine elastic constants. The frequencies used to measure the longitudinal and shear wave velocities were respectively 5 MHz and 2.25 MHz. Fig. 12 shows the layout of two of their FDM samples.

Tatarinov and Panov [114] conducted ultrasonic tests on plastic phantoms made from hard plastic by material extrusion process to mimic bones with varied cortical layers, intracortical porosity, and low mineralization. The tests frequencies were 75 and 500 kHz. Caminero et al. [115] conducted phased array ultrasonic testing on both CFRP composites and 3D printed continuous glass fiber reinforced thermoplastic composites. Impact tests were also carried out on the 3D printed samples according to ASTM D 7136 [116]. The phased array ultrasonic testing (PAUT) results indicated that the extent of damage was larger in the 3D printed samples as compared to CFRP ones.

5. Codes and standards

There are currently no codes or standards for ultrasonic testing or even nondestructive testing of AM products. However, technical groups at both ASTM and ISO are working to regulate and set policies on UT testing methods. ASTM working group WK47031 [117] is currently developing guidelines for NDT of metal AM products. The guideline is particularly prepared for AM parts that are used in aerospace applications. The requirements and policies developed in this guideline are more rigorous as compared to those used for general purposes. This

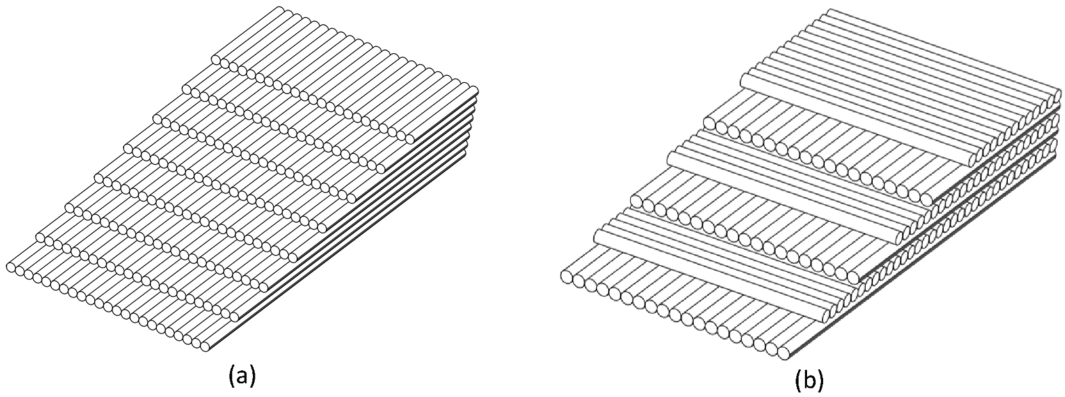

Fig. 12. Raster configuration for samples used by Yap et al. [113], (a) 0 degrees, and (b) 0/90 cross-ply.

guideline will include a section on ultrasonic testing of AM products as well. An ISO technical group has also prepared a guideline for testing AM products [118]. This guideline is intended for metal AM parts, and similar principles are anticipated to develop for polymeric and ceramic AM products.

6. Summary and future outlook

A major concern in additive manufacturing is the appearance of defects over the manufacturing and loading processes of finished products which necessitates to develop pertinent nondestructive testing (NDT) techniques to detect these defects [7–9,119]. Nondestructive testing methods are favorable for testing AM products since they do not incur any damages to the product during the test. Various NDT methods are categorized based on their capabilities, applications, advantages and disadvantages. Among these NDT techniques, ultrasonic testing has high potential for testing AM products [8]. The present study intended to review principles of ultrasonic testing methods and their applicability for in-situ and offline examination of additive manufacturing products. Based on open literature, several research works have been conducted on offline ultrasonic testing of AM components. In these works, solid samples holding implanted defects are tested by various ultrasonic testing techniques. Researchers have also developed calibration blocks to calibrate ultrasonic instruments and to evaluate defects [74,111]. Literature is yet to offer a universally accepted calibration method.

The UT method has been employed for both in-situ monitoring of AM processes as well as testing of final products. Various UT techniques including laser ultrasonics (LU), phases array UT (PAUT), guided waves (GW), and immersion UT have been considered. Ultrasonic testing results are presented in the form of time domain signals, 2D images and 3D images. Some shortcomings of ultrasonic testing techniques can be overcome through using signal and image processing techniques [37,120–122].

The major advantage of additive manufacturing is its ability to produce components with extremely complex geometries at high precision and material efficiency. Nondestructive testing of such complex geometries is not easy, and most NDT techniques fall short in providing the desired performance. That is why, up to now, ultrasonic testing methods have only been applied to relatively simple geometries of AM components. It takes much effort to develop new ultrasonic techniques and to regulate procedures that could handle the more complicated components that are of interest in additive manufacturing. Currently, most of the ultrasonic testing techniques used for testing AM components are at their early stages of development and it would take more time and effort for these techniques to become suitable for industrial applications. Moreover, in many AM processes, such as selective laser melting (SLM), the build chamber has a complex environment filled with fumes and un-melted powder particles that make the use of ultrasonic methods such as laser ultrasonics (LU) difficult [17]. The presence of high energy sources used for melting powders in the build chamber of an SLM machine may also interfere with the more delicate signals picked up by LU interferometers leading to noisy and distorted signals. Therefore, one should be aware of these limitations when using such techniques as laser ultrasonics for in-situ testing and monitoring of AM processes.

While X-ray micro- and nano-CT are utilized for testing components with complex geometries, these tests are time consuming and expensive. For thick samples, attenuation of the X-rays and their limited depth of penetration become challenging factors. Ultrasonic waves, however, penetrate as deep as several meters through most metals. For components with complex geometries, CT techniques may be more efficient than ultrasonic techniques in damage detection. It should also be noted that nondestructive testing methods are considered to complement each other and not to replace one another. Therefore, NDT techniques could be combined to address shortcoming and disadvantages each individual testing method might have in measuring certain features of a product. With the quick development of data fusion techniques in NDT [123], it is also possible to combine the results of two or more NDT methods to gain a deeper insight into the integrity and health of a manufactured product.

Simonetti et al. [124,125] recently suggested the use of ice for encapsulating AM components. The ice fills the internal vanes and channels of the test sample and allows the ultrasonic waves to reach all parts. This technique, referred to as cryo-ultrasonic NDE, offers a viable solution to testing complex AM components. Simonetti and coworkers used the migration data processing technique [126], which is a well-known signal processing technique in seismic studies, to extract the desired information from the collected ultrasonic data. The interesting approach proposed in [124] may suggest the use of magnetorheological and electrorheological fluids in place of ice, especially if the acoustic properties of these materials could match with the acoustic properties of the test material. The magnetorheological and electrorheological fluids transform into a solid when subjected to a magnetic/electric field. By removal of the magnetic/electric field, they transform back into their fluid state. Therefore, the empty vanes and channels of the test piece can be filled with a magnetorheological or electrorheological fluid and when the magnetic/electric field is applied, the whole component turns into a solid part that can be easily tested by ultrasound.

Advanced UT techniques such as phased array ultrasonic testing (PAUT), laser ultrasonics (LU), and guided waves have shown pertinent potential in testing AM products and it is worthwhile studying their capabilities through a detailed investigation. While the current study emphasizes the use of UT techniques to evaluate damage and defects in AM products, testing of raw materials, such as powders, filaments and wires in AM are also important challenges. Testing of these materials requires a comprehensive analysis and investigation. Authors believe that further testing and analysis are required to address important key parameters in on-line UT techniques including variables such as test sample geometry, defect size, defect depth, testing frequency, and elastic properties of filaments and wires used in AM processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge the cooperation of FUJIFILM Visualsonics Inc. and Dr. Kazem Fayazbakhsh from Ryerson University in conducting phased array ultrasonic tests on the FDM sample shown in Fig. 2. The financial support through Natural Sciences and Research Council (NSERC) of Canada is also appreciated.

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