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Phased array ultrasonic testing of micro-flaws in additive manufactured titanium block

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Abstract

While titanium components manufactured by additive manufacturing have been widely used in direct molding of complex components, their performance is strongly affected by existing internal flaws generated in the unique manufacturing process. Thus, how to efficiently and accurately characterize geometrical characteristics of internal flaws is critical for enhancing applications of additive manufactured titanium components. In the present work, an effective non-destructive method by using phased array ultrasonic testing is proposed to characterize sub-millimeter artificial deep bottom holes in additive manufactured TC18 titanium block. Specifically, a phased array ultrasonic testing platform integrated with total focusing method-based post-processing algorithm is established. Flat bottom holes with a diameter of 0.8 mm and a depth of 5.0 mm in 55 mm-sized cube titanium block are detected using both linear and annular array transducers. Experimental results show that pre-existing holes can be characterized by both linear and annular transducers, in despite of accompanied high acoustic attenuation. Furthermore, the annular phased array ultrasonic testing has higher detection accuracy and resolution than the linear phased array one, for its stronger capability of sound field focusing. More importantly, the annular phased array ultrasonic testing shows similar high testing accuracy in different relative orientations between forming orientation of the titanium component and sound wave propagation direction. These findings provide an effective strategy for the non-destructive ultrasonic testing of titanium components by additive manufacturing.

1. Introduction

Titanium components are extensively used in fields of biomedicine, aerospace, marine, military and automotive due to their excellent properties of high strength, high corrosion-resistance and high thermal-resistance [1]. Geometrical characteristics of internal flaws in titanium components, such as size, shape and distribution, have a strong impact on their quality and related equipment’s performance. Thus, how to effectively manufacture precision titanium components with eliminated internal flaws is critical. With the rapid advancement of additive manufacturing (AM) technology, titanium components by AM have been widely used in the rapid prototyping of complex-shaped parts, for its high designability, high formability, high rate of stock utilization and low cost [2, 3]. However, there are considerable micro-flaws, such as inclusion, crack and porosity, existed in additive manufactured components due to involved complicated processes of material sintering and cooling, which subsequently deteriorate mechanical properties of as-fabricated components. Thus, how to effectively characterize geometrical characteristics of internal flaws existed in additive manufactured titanium components.
by performing non-destructive evaluation (NDE) is essentially required for ensuring AM quality, as well as facilitating safety and reliability of key equipment.

Ultrasonic testing (UT) is one important method of NDE. In the UT process, the transducer positioned on the specimen surface transforms a voltage pulse into an ultrasonic wave to travel through the specimen. While transmitted ultrasonic waves are reflected back upon encountering discontinuities, the geometrical characteristics of flaws can be detected based on the evaluation of the transmitted and reflected energies.

Recently, increasing interests have been paid on the UT of AM parts. Waller et al. detected embedded voids in AM aluminum parts by using UT with B-scan imaging [4]. Antoni et al. adopted UT with an immersion ultrasonic transducer and a center frequency of 25 MHz to measure internal crack and density map of powder metallurgy parts [5]. Cerniglia et al. demonstrated the efficiency of a laser ultrasonic system-based UT in characterizing near surface micro-defects in Inconel samples [6]. Sun et al. studied the influence of processing parameter on the UT of AM TA15 alloy specimens with different internal micro-flaw sizes [7]. Although considerable work has been carried out to investigate the UT of internal flaws in AM metallic components, further efforts are still needed due to problems of conventional UT, such as poor signal to noise ratio (SNR), low accuracy, shallow detection depth and even inability. Specifically, there are strong distortion and attenuation of sound waves propagation in the layered AM components, due to its anisotropic and inhomogeneous characteristics caused by the unique layer-to-layer deposition process. Zeltmann et al. demonstrated that the conventional water immersion ultrasonic transducer is incapable of detecting pre-existing micro-flaws with size of 0.5 mm in pre-existing AM components [8].

In recent decades, phased array ultrasonic testing (PAUT), that uses multi-element transducers to generate sound beam with specific deflection angle and focusing depth, has been proposed to characterize flaws in AM components for its high measuring efficiency, high reliability and sensitivity [9–11]. Lopez et al. demonstrated the effectiveness of PAUT in detecting defects with diameter ranging from 3 to 5 mm in aluminum wire-arc additive manufacturing (WAAM) components with several degrees of surface finish [12]. Taheri et al. adopted PAUT to characterize artificial side drilled holes with diameter of 1 to 2.3 mm existed in an additive manufactured carbon fiber reinforced composite sample [13]. Chabot et al. demonstrated the feasibility of PAUT method in detecting defects with diameter ranging from 0.6 to 1 mm in WAAM aluminum alloy parts [14]. Javadi et al. utilized PAUT to characterize sizes of intentionally embedded tungsten carbide balls in WAAM steel specimen [15, 16]. Taheri et al. performed finite element simulation of PAUT verified by experiments to measure flat bottom holes in additive manufacturing SS17 4PH steel samples [17].

Although previous PAUT work provides valuable insights into the defect characterizing of AM parts, the investigation of PAUT of AM metallic components is far from being completed. Firstly, AM titanium alloy has obvious different internal microstructures from conventional titanium alloy, which may lead to different velocities and attenuation degrees of sound wave propagation. Specifically, sound wave propagations along deposition direction and printing direction may be different in PAUT of AM components. Consequently, this forming orientation dependence induces the asymmetry of ultrasonic energy distribution, which may result into anisotropic acoustic propagation and attenuation in AM components. Secondly, while most of PAUT work uses 1-dimensional linear array transducer for its simple structure and signal processing, the 1.5-dimensional annular array transducer can use fewer number of array elements to achieve a higher acoustic field energy. However, there is rare work reported on the PAUT of AM components using annular array transducer.

Therefore, pre-existing micro-flaws in additive manufactured titanium block are detected by PAUT using both linear and annular array transducers. Flat deep bottom holes with a diameter of 0.8 mm and a depth of 5.0 mm are pre-implemented in 55 mm-sized cube titanium block. A PAUT platform is established, and a new post-processing algorithm based on total focusing method (TFM) especially for the annular array is proposed. Characteristics of sound field distributions accompanied by linear and annular array transducers are interpreted by three-dimensional acoustic field simulation results. Finally, series of PAUT using annular array transducer along both deposition direction and printing direction are conducted to demonstrate the effectiveness of applying annular array PAUT in precisely detecting micro-flaws in AM titanium components.

2. Methods

2.1. Setup of PAUT system

Figure 1 presents the experimental setup of customized PAUT system, which consists of an ultrasonic array excitation/reception board, an array transducer, a computer for data acquisition and an immersion inspection tank. The excitation/reception board for energizing and detecting ultrasonic phased array waves has a maximum transmission speed of 30 MB/s. The model of the board produced by AOS Corporation is ‘OEMPA128-128’. A three-axis moving stage, integrated with an immersion inspection tank, is constructed to fulfill the requirement of automatic testing within a measuring range of 800 mm, 600 mm and 200 mm in X, Y
and Z direction, respectively. And linear encoders are integrated into the stage to achieve a positioning accuracy of 1 μm. A software for data acquisition, processing and image displaying is developed by using API interface function and OpenGL.

A linear and an annular array transducers with the same frequency of 10 MHz are utilized to characterize the AM TC18 titanium alloy block. Especially for the linear array transducer, the aperture size of electronic scanning and the stepping resolution is respectively set as 48 and 0.3 mm, which is equal to the element pitch. Table 1 lists parameters of the two types of phased array transducers. TC18 is of the most widely used titanium alloy in aircraft applications for high structural strength. A TC18 cubic block with a size of 55 mm is manufactured by laser AM, the detailed description of the manufacturing process can be found elsewhere [18]. Three artificial flaws, in terms of flat deep bottom holes with a depth of 5 mm and a diameter of 0.8 mm, are created on three adjacent surfaces of the specimen by drilling, as shown in figure 2(a) and also schematically illustrated in figure 2(b). It is noted that the diameter of 0.8 mm is the minimal value that can be realized in the drilling of difficult-to-machine titanium specimen for a constant depth of 5 mm from the authors’ side. Figures 2(c) and (d) schematically illustrates the C-scan process of the specimen by using annular and linear array transducer, respectively.

### Table 1. Parameters of phased array transducers.

| Probe       | Frequency | Element number | Element pitch | Element width |
|-------------|-----------|----------------|---------------|---------------|
| Linear array| 10MHz     | 64             | 0.3 mm        | 0.2 mm        |
| Annular array| 10MHz  | 16             | 1.3 mm        | 1.2 mm        |

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#### 2.2. Post-processing algorithm

The TFM based on full matrix capturing is a commonly used post-processing algorithm for defects imaging in PAUT [19]. The generation of full matrix of array data is illustrated in figure 3(a). Generally, the imaging area of TFM for a linear array transducer is a two-dimensional section, which introduces difficulty in realizing real-time TFM C-scan detection due to great amount of data. In contrast, the annular array transducer can produce image at any point along each axis based on its axial focusing characteristic, thus enabling real-time 3D TFM C-scan, as illustrated in figure 3(b). In the present work, the single detection zone is set as a linear region along the transducer axis, and point-by-point visual focusing is conducted to achieve infinite focus of the region. For a single detection zone, the annular array transducer sequentially energizes each chip. All chips receive echo signals and keep the receipt signal data. Especially for the annular array transducer, all chips are treated as emit-receive units. Furthermore, ultrasonic echo signals including transmitting and receiving element sequence in the completed time domain are gathered, as shown in figure 3(c). Each chip of annular array transducer has been
excited and \( N \) groups of echo data have been obtained based on the above steps. Since there are fewer chips in an annular array transducer than that in a linear one, the amount of processing data and resulted data used is also less.
The algorithm of annular array TFM for tested rectangle specimen is rationalized in figure 3(d). Through gathering full matrix data and propagation time, the amplitude superposition of each discrete point on the axis is gained. For a single point \((0, z)\) on the axis, the ultrasonic wave is emitted by element \(i\) to the reflector point, and then returns back to the element \(j\). So, the total time for the propagation \(t(0, z)\) is expressed in equation (1):

\[
t(0, z) = \frac{\sqrt{(x_i - x_j)^2 + h^2}}{c_1} + \frac{\sqrt{(x_j - x_r)^2 + h^2}}{c_2} + \frac{\sqrt{x_r^2 + z^2}}{2} + \frac{\sqrt{x_i^2 + z^2}}{2}
\]

where \(c_1\) and \(c_2\) is the velocity of an acoustic wave propagating through the coupling medium and the specimen, respectively, and \(h\) is the height of coupling wedge. The central axis is discretized into multiple focusing points to achieve high imaging accuracy. For a specific detecting point, signals from all elements in the array are superposed at this point. Thus, the intensity of the image \(I(x, z)\) of the detecting point \((x, z)\) is obtained by equation (2):

\[
I(x, z) = \sum_{i=1}^{N} \sum_{j=1}^{N} h_{ij}(t_{ij}(x, z))
\]

where \(h_{ij}(t_{ij}(x, z))\) is the amplitude of focused point excited by chip \(i\) and received by chip \(j\). Therefore, the amplitude of each detecting point can be derived, which subsequently completes the information acquisition of the entire detection area in the sample.

2.3. Acoustic field modeling of phased array
Due to the high scattering and attenuation properties of AM titanium alloys, the combined beam energy of the ultrasonic array is an important factor affecting detection results. Therefore, 3D model of acoustic field is established to study the combined beam energy distribution of commonly used array transducers. The governing equations for pressure acoustics in transient analysis can be written as equation (3) [20]:

\[
\nabla^2 P(x, t) - \frac{1}{c^2} \frac{\partial^2 P(x, t)}{\partial t^2} = -f(x, t)
\]

where \(P(x, t)\) is the acoustic pressure, \(t\) is the time, \(x\) is the displacement in the solid sample and \(f\) is the body force per unit volume. Based on the transformation and derivation calculations according to formulas found in the [20], the acoustic pressure of every array element is obtained by equation (4) [20]:

\[
\varphi(x, t) = \frac{c}{\sqrt{t}} \int_{S_T} \frac{V_n(t - \frac{r}{c})}{4\pi r} dS_T(t)
\]

where \(V_n\) and \(S_T\) is the stimulus and area of the array element, respectively. Considering that N array elements of the transducer are stimulated, the total acoustic pressure of the combined acoustic beam is expressed in equation (5) [20]:

\[
p(x, t) = \sum_{i=1}^{N} \varphi(x, t)
\]

Figures 4(a) and (b) shows the acoustic field model of PAUT using a 10 MHz linear array with 32 elements and a 10 MHz annular array with 16 concentric elements, respectively. The output of each element is a five cycle Gaussian windowed tone burst with a center frequency of 10 MHz, and the –6 dB fractional bandwidth is 50%. The detailed description of the acoustic field model can also be found elsewhere [21]. A sampling frequency of 100 MHz is used throughout the modeling.

3. Results and discussion

3.1. Conventional UT versus linear array PAUT
The as-received TC18 titanium block is firstly detected by PAUT using a linear array transducer, and the detailed parameters are listed in table 1. The depth of focus, the aperture size and the scan step size is set to 50 mm, 16 and 0.2 mm, respectively. Meanwhile, the detection by conventional UT using the USIP-40 ultrasonic detector is also conducted for comparison purpose. Table 2 shows parameters of the utilized conventional focusing transducer in the USIP-40.

Figures 5(a) and (b) plots the A-scan curve based on internal echo monitoring method in the TC18 titanium block detected by the conventional UT and the linear array PAUT on printing surface C, respectively. Accordingly, figures 5(c) and (d) presents C-scan images of the TC18 titanium block detected by the conventional UT and the linear array PAUT, respectively. It is seen from figure 5 that the size and the location of holes in the TC18 titanium block can’t be clearly identified by the conventional UT C-scan due to poor SNR. For
the conventional ultrasonic immersion probe with fixed focal length, the internal reflection energy of the specimen with large thickness is insufficient, and there are strong attenuation and scattering of internal signals in AM titanium alloy, which jointly make it easy to produce considerable interference signals and ‘artifacts’ with increasing gain. In contrast, the C-scan detection by the linear array transducer can clearly identify the geometrical characteristics of the internal defects. Although the C-scan image for the linear array transducer has low SNR, there are still high background noises and different degrees of distortions accompanied by defects. Specifically, the flat bottom holes appear to have different extents of distortion. Correspondingly, the defect imaging sizes are far larger than their actual sizes, which is closely associated with the anisotropic acoustic propagation and attenuation of the AM titanium alloy due to the asymmetry of the ultrasonic energy distribution.

A-scan curve of (a) conventional UT and (b) linear array PAUT. C-scan image of (c) conventional UT and (d) linear array PAUT.
Moreover, figures 6(a) and (b) presents C-scan image of the TC18 titanium block detected by the PAUT along deposition surface A and deposition surface B, respectively. Compared with the C-scan image detected in printing surface shown in figure 5(d), the detections in deposition surfaces have a greater extent of distortion and a lower SNR. Therefore, the detection capability of linear array PAUT has a strong dependence on the forming orientation of the AM titanium component.

3.2. Linear array PAUT versus annular array PAUT

In addition to the conventional UT and the linear array PAUT, the as-received TC18 titanium block is further detected by the PAUT using annular array transducer. Figures 7(a) and (b) plots the A-scan curve and C-scan image obtained in the annular array PAUT of the specimen on printing surface C, respectively. Figure 7 demonstrates that the three artificial holes are unambiguously identified using the annular array PAUT. The three defects are measured with the \(-6\) dB method, and the errors for all the imaging sizes are found to be less than 10%. Therefore, it is indicated that the ultrasonic energy distribution in the C-scan imaging by the annular array PAUT has an isotropic characteristic, i.e., the acoustic propagation and attenuation in the AM titanium alloy is independent on the relative orientation between sound wave propagation and layer deposition direction.

The acoustic field distributions in the monolayer medium by the 32-element linear array transducer and 16-element annular array transducer are also examined, which were presented in the recent work [21]. The linear array transducer has a strong beam focusing energy along the direction of element’s arrangement, but the focusing ability of energy distribution is poor in the element’s length direction. Compared to the linear array transducer, the annular array transducer shows better acoustic field focusing performance in both printing and deposition directions. Thus, the annular phased array transducer is more suitable for detecting AM titanium alloy components with high-attenuation and high-scattering property.

3.3. Forming orientation dependence of annular array PAUT

Given the manufacturing algorithm of layer-to-layer deposition in AM, there are lamellae characteristics in the as-manufactured TC18 titanium block. In addition to printing surface C, annular array PAUT of the as-received TC18 titanium block on different deposition surfaces is also carried out. Figure 8 shows the C-scan signals based on the back-wall echo monitoring method on different surfaces, which indicates that the attenuation laws of back-wall
echo of AM titanium alloy vary greatly with detection surface: back-wall echo along the printing direction for printing surface C distributes as spot and grid, while it distributes as belt along the deposition direction for deposition surface A or B. This strong forming orientation dependence in the annular array PAUT of the AM titanium alloy can be primarily attributed due to the strong columnar crystal growing along the deposition direction in the manufacturing process. Correspondingly, ultrasonic waves are scattered at the lamellae interfaces, resulting in different attenuation laws of the bottom echo amplitude on different surfaces [22]. It is proved that the attenuation characteristic of the AM material is closely related to the forming orientation. Therefore, it is essentially needed to consider the forming orientation of AM titanium alloy in PAUT process.

Figure 9 shows the results of A-scan and C-scan detection when the annular phased array transducer is placed on different surfaces. It is seen from figure 9 that the resolution and SNR of the annular array ultrasonic C-scan placed on the printing surface are significantly better than that placed on the two deposition surfaces, mainly due to that the acoustic wave produces a certain ultrasonic attenuation when it propagates to the macro-layer interface. Thus, the stronger sound beam focusing energy and higher detection accuracy makes the annular array PAUT more suitable than the linear array one for the inspection of high attenuation material with uneven internal microstructures, such as the AM titanium alloy components. It should be noted that the computed tomography (CT) method may provide higher detection accuracy of defect size than the annular array PAUT, as it produces 2-D and 3-D fine cross-sectional images of an object from flat x-ray images, in despite of its higher requirement on the testing equipment.

Above results demonstrate the priority of annular array PAUT over both linear array PAUT and conventional UT in detecting deep holes with a depth of 5 mm and a diameter of 0.8 mm in AM titanium specimen. Furthermore, the annular array PAUT possesses similar detection accuracy, regardless the ultrasonic incident detection on deposition surface or printing surface of the AM titanium specimen. It is known that the minimal detectable defect size is closely determined by the wavelength the wavelength of the ultrasound, which varies inversely with the frequency of the probe as the speed of ultrasound is constant in a specific material [23]. In particular when the defect size is close to half-wavelength, there will be significant diffraction phenomenon accompanied with negligible reflected echo. And the detection accuracy prompting by increasing probe frequency is accompanied with increased attenuation and decreased SNR, which is not applicable for the detection of deep holes. Therefore, defect size on the order of half-wavelength can be theoretically inspected. In the present work, the frequency of the probe is 10 MHz and the velocity of the ultrasound in titanium is about 6100 m s⁻¹, thus the minimal detectable defect size is expected to be 0.610 mm, which is very close to the diameter of 0.8 mm detected. It should be noted that the characteristics of internal defects existed in AM titanium components may vary in different additive manufacturing processes. Thus, in the future work systematic investigation based on large number of specimens with various defect size, shape and position is needed to further validate the theoretically-established limitation of detection accuracy of the annular array PAUT.

4. Summary

In summary, PAUT is carried out to characterize internal micro-flaws in TC18 cubic block manufactured by AM. The TC18 cubic block sized in 55 mm contains three flat bottom holes with a diameter of 0.8 mm and a depth of 5.0 mm in three adjacent surfaces. A PAUT system using both linear and annular array transducers is established, and a TFM-based post-processing algorithm is integrated especially for the annular array transducer. While conventional UT is incapable of characterizing the flaws due to high attenuation characteristics of sound waves in the AM titanium specimen, both linear array and annular array PAUT integrated with TFM C-scan can detect the geometrical characteristics of flaws. Furthermore, the annular array
PAUT has higher detection accuracy and resolution than the linear array PAUT, regardless of the ultrasonic incident detection on deposition surface or printing surface of the AM titanium specimen.

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