Efficient volumetric non-destructive testing methods for additively manufactured parts

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Abstract

(100 and 250 words)

The full paper must be written in British English.

As additive manufacturing (AM) moves towards industrial production in critical sectors such as aerospace and medical, the integrity of the fabricated AM parts needs to be ensured in order for these parts to be certified. This requires quality controls, including non-destructive testing (NDT), to be implemented.

AM enables fabricating very complex parts which are not possible to manufacture with conventional manufacturing methods. This can pose a great challenge for existing NDT technologies to perform their inspection. Thus, the existing NDT techniques need to be evaluated with complex AM parts.

This paper presents the evaluation of two promising NDT methods for AM: a resonant acoustics method (RAM) and a phased array ultrasonic testing (PAUT) method involving a full matrix capture (FMC) acquisition procedure, and a total focused method (TFM) to post-process the data and reconstruct the images.

Keywords: Non-destructive testing (NDT), volumetric NDT, additive manufacturing, resonant acoustic testing, phased array ultrasonic testing.

1. Introduction

Considering the complexity of shape that additive manufacturing (AM) enables one to build, and the surface roughness of the as-built parts, some volumetric non-destructive testing (NDT) methods are no longer adequate to control the quality of such parts.

X-ray computed tomography (XCT) remains the most appropriate method to deal with complex shape and rough parts [1]. The spatial resolution is high enough to locate, and even evaluate the dimension of the defects. However, the size and density of the parts matter due to practical limitations of the XCT source power required for X-rays to penetrate the part, and the XCT chamber needs to be big enough to contain the part. In addition, XCT is an expensive and time-consuming inspection technique, not appropriate for routine inspection for mass customised production enabled by AM.

Consequently, alternative methods to XCT are needed. We have investigated several volumetric NDT methods [2, 3] and among them, we have selected two that we consider as efficient for AM parts.

Resonant Acoustic Method (RAM) is a global method, which does not inspect the part in detail, based on the analysis of the natural resonant frequencies of the part. It is particularly interesting for routine production end-of-line testing to identify defective parts. It is easy to use, fast and there is no restriction in part size, shape, and roughness.

Phased array ultrasonic testing (PAUT) is a selective method, which records three dimensional images of the part, using a phased array probe. With PAUT, it is possible to perform inspection of complex shaped parts by just steering the ultrasonic beam without moving the probe. The PAUT system investigated implements a data acquisition method called full matrix capture (FMC) followed by a post-processing reconstruction known as total focusing method (TFM) to improve the image quality. PAUT/FMC/TFM is particularly interesting to identify and locate the type of defect.

This paper will present the principle of these two NDT methods and some inspections of a specific part using these methods. The part investigated with these methods is the so called star artefact designed and fabricated in the ISO TC261-ASTM F42 joint group (JG) 59 related to "NDT for AM parts". Finally, in conclusion the drawbacks and benefits to use these methods to inspect complex additively made metallic parts are reported.

2. Description of the investigated samples: star artefact

The JG59 of the standardisation group related to AM, ISO/TC261-ASTM/F42 works in particular on a guide which will provide recommendations to users to inspect their AM metallic parts with NDT methods. This guide will also provide a list of typical AM defects found in the two main process categories involving metallic powder: powder bed fusion (PBF) and direct energy deposition (DED). In order to provide inputs to the guide, the group has designed and fabricated a test artefact that simulates typical AM defects and then, several companies and academic organizations have used this artefact to evaluate various NDT methods.

This artefact is in the shape of a star (Fig. 1), hence its name: star artefact. It contains the following features simulating defects unique to AM parts:

- Cross-layer defects that are represented by vertical cylinders of different diameters but the same length. These cylinders are connected to each other and open to outside at the bottom of the star, so that powder is released at the largest diameter cylinder;
- Layer-specific defects that are represented by horizontal cylinders of different diameters but the same length, with an open end to release powder;
- Unconsolidated/trapped powder defects that are represented by spheres of different diameters and internal cylinders in various orientations.

These defects are located into critical areas such as deep sections and hard-to-reach areas, in five different regions. Two versions of the star design, designated as S1 and S2, were used in the evaluation of NDT methods (Fig. 1). In these two versions the defects are of the same size, same height along the part, and the same orientation; the only difference is their locations. The S2 design has the defects in thinner sections of the star branches, while the S1 design has the defects in the thicker sections. All defects are in the range of 100 µm to 800 µm in diameter.

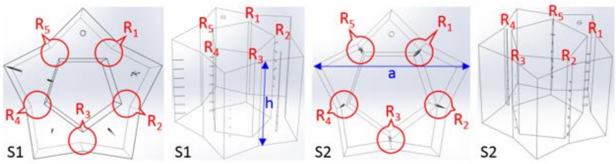

Figure 1. Schematics of the AM star artefacts (design S1 and S2) proposed by the JG59 (where R is a Region in the artefact, “h” and “a” define the height and width of the artefact, respectively)

In order to evaluate statistical NDT methods that required a large number of samples, several half-size star artefacts were also built. However, the sizes of the defects remained the same even though the size of the star was divided by two. In addition, some half-size star artefacts were manufactured with different numbers of defects as well as with no defect (S0 design).

The NDT inspections presented in this paper involved stainless steel (SS), GP1, star artefacts (Fig. 2). They were manufactured using a laser PBF machine EOS M290, and default built parameters for SS: a laser power of 220 W, a speed of 755.5 mm/s, a hatch spacing of 0.11 mm, and a layer thickness of 40 µm.

Figure 2. Stainless steel star artefacts, full-size: h=45 mm and a=60 mm, half-size: h=22.5 mm and a=30 mm

3. Resonant Acoustic Method (RAM)

3.1. Principle of Resonant Acoustic Method (RAM)

RAM belongs to the standardized Resonant Ultrasound Spectroscopy (RUS) methods [4] which are whole-body (pass/fail inspection) comparative methods. Resonant inspection, measures the structural response of a part and evaluates it against the statistical variation from a control set of good (reference) parts to screen defects. Its volumetric approach tests the whole part, both for external and internal structural flaws or deviations, providing objective and quantitative results. This structural response is a unique and measurable signature, defined by a component’s mechanical resonances. These resonances are a function of part geometry and material properties and are the basis for RUS NDT techniques.

A characterization using RUS methods includes several steps:

<u>First step</u>: mechanical impulse of the test part to excite its natural resonant frequencies;
<u>Second step</u>: monitoring, by a sensor, of the response of the test part to record its resonant frequency spectrum;
<u>Third step</u>: comparison of the resonant spectrum of the test part with the spectra of the reference parts:

1) Identification of well-defined resonant peaks based on testing all the reference parts and a few test parts with different structural properties than the reference parts;
2) Selection of a subset of these well-defined resonant peaks that are consistent for all reference parts and have distinct separation with the peaks of the test parts;
3) Evaluation of the ranges in variations in each selected resonant peak frequency of the reference parts to define several “criteria”;
4) Sorting of the test parts with regard to the criteria to evaluate the past/fail test parts.

3.2. Star artefact inspection using Resonant Acoustic Method (RAM)

In RAM testing, the mechanical impulse is generated by an automatic hammer and the response of the test parts is monitored by a microphone (Fig. 3).

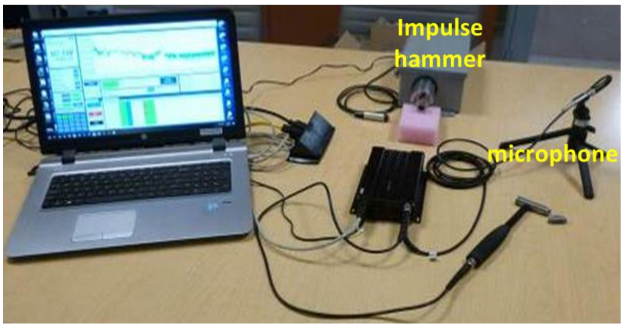

Figure 3. RAM set-up

Eighty-eight half-size star artefacts, S0, S1, and S2 designs, were inspected using RAM. These parts originated from two successive identical jobs (44 parts from the first build and 44 from the second). Among them, forty are reference parts without any internal features (S0) and the rest contain different numbers of internal features (S1: 8 with all defects and S2, 40: 8 with all defects, 8 with only defects in 4 branches, 8 with only defects in 3 branches, 8 with only defects in 2 branches, and 8 with only defects in 1 branch).

The data were collected between 500 Hz and 50 kHz (Fig. 4) in less than five minutes.

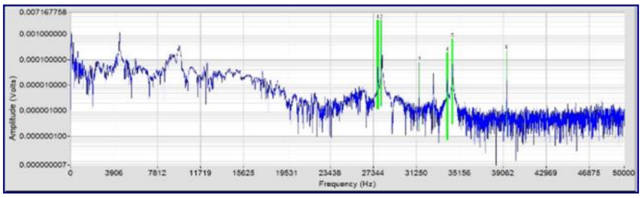

Figure 4. RAM typical spectrum of a SS half-size star artefact (the green vertical lines display the selected criteria)

NDT testing using RAM shows the capacity to sort the parts with internal features (defects) from the reference parts (good parts), however, RAM was unable to distinguish the location or number of internal features in the 'defective' parts.

4. Phased-array ultrasonic testing (PAUT) using full matrix capture (FMC) and total focusing method (TFM)

4.1. Principle of PAUT/FMC/TFM

In standard PAUT, the probe array includes several piezo electric transducers that emit (transmitters) and record (receivers) the ultrasounds all at the same time. In PAUT/FMC/TFM, the first step is a data acquisition procedure, that is full matrix capture (FMC), which consists of emitting with all the transducers of the probe independently and successively while recording with each transducer at a same time generating a graph representing the amplitude of the reflected sound wave as a function of time (A-scan). Consequently, if the probe is made of n transducers, the data will consist in nxn A-scans (Fig. 5).

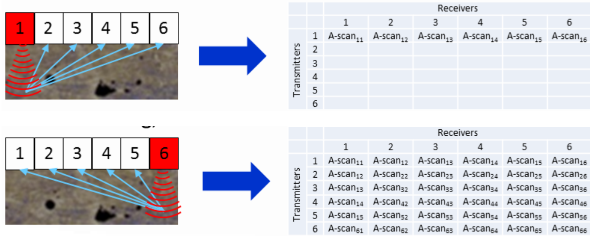

Figure 5. Principle of data acquisition with FMC

The second step consists of numerically post-processing the data with the total focusing method (TFM). This relies on using a reconstruction algorithm which sums all the A-scans over the number of transmitters and receivers to reconstruct the image of the test part [5, 6].

The advantage of this method over standard PAUT is that the ultrasound beam is virtually re-created in such a way that it is focalized in any point in the test part. Thus the resolution of the image is optimized whatever the depth in the test part.

4.2. Star artefact inspection using PAUT/FMC/TFM

Two full-size star artefacts, S1 and S2 designs, were inspected with PAUT/FMC/TFM with the Pioneer device 128 channels (The Phased Array Company, West-Chester, USA). The test part was immersed in a tank full of water and scanned from one side of each branch. Each scan lasts less than one minute. The probe characteristics and experimental parameters used to scan the test parts are summarized in table 1.

Type		Frequency (MHz)	Length (mm)	Number of transducers	Pitch (mm)	Wavelength (mm)	Distance to the test part (mm)	gain (dB)
Linear	ceramic/polymer	10	32	90	0,25	0,6	12,5	40

Table 1. Probe characteristics and experimental parameters used to scan the a SS full-size star artefacts

From the A-scans, B and C-scan images can be extracted. A B-scan shows an image with different grey levels or colors corresponding to the amplitude of the reflection from each reflecting feature or flaw. Position on the Y-axis shows the position of the transducer along its scan path. Position on the Z-axis reflects the depth of each reflecting feature or flaw. A C-scan shows an image viewed from the top (planar view) of a region of interest within the volume of the test specimen. The images display different grey levels or colors corresponding to the amplitude, time of flight, or depth of the signal for different positions of the transducer scanning the surface of the part. A C-scan image is formed in a plane normal to a B-scan image.

The images corresponding to all the features that can be seen in the full-size SS star artefact, S1 and S2 designs, are presented on Figures 6 to 12.

In S1 design, only four of the cylinders with different orientations (∅ 0.30 mm, L 2 mm) are seen (Fig. 6); six of the vertical cylinders (∅ 200 µm, 300 µm, up to 700 µm are seen, ∅ 100 µm and 150 µm are not seen) (Fig. 7); four of the sphere are seen (∅ 400 µm, up to 700 µm) (Fig. 8); the horizontal cylinders open to outside and located on the inner and outer sides of the star artefact are not seen.

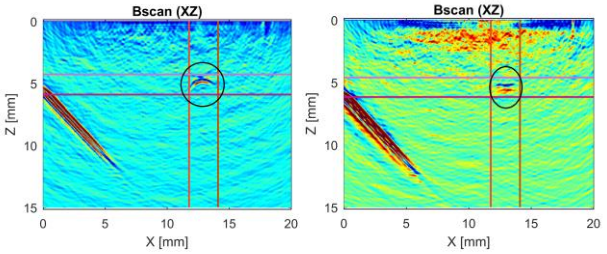

Figure 6. PAUT/FMC/TFM images of the cylinders with different orientations (∅ 0.30 mm, L 2 mm) of the SS full-size star artefact, S1 design

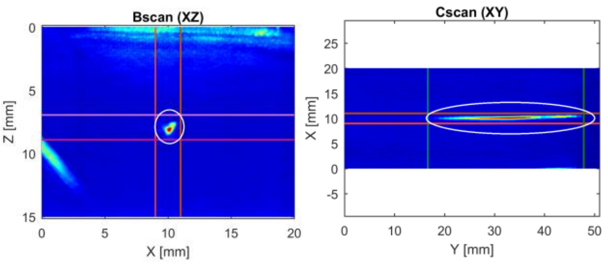

Figure 7. PAUT/FMC/TFM images of the vertical cylinders from the top (left) and from the side (right) of the SS full-size star artefact, S1 design

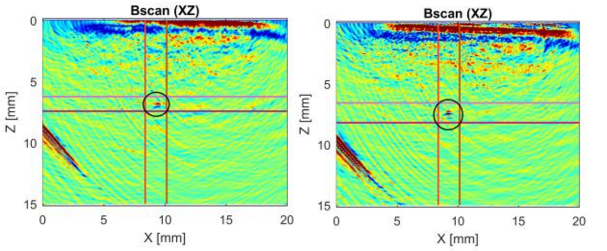

Figure 8. PAUT/FMC/TFM images of the spheres of 700 µm (left) and 400 µm (right) of the SS full-size star artefact, S1 design

In S2 design, three of the inner (Fig. 9) and four of the outer (Fig. 10) horizontal cylinders open to outside and located on the sides of the star artefact are seen; six of the vertical cylinders (∅ 200 µm, 300 µm, up to 700 µm are seen, ∅ 100 µm and 150 µm are not seen) (Fig. 11); only one of the cylinders with different orientations (∅ 0.30 mm, L 2 mm) is seen (Fig. 12); the spheres are not seen.

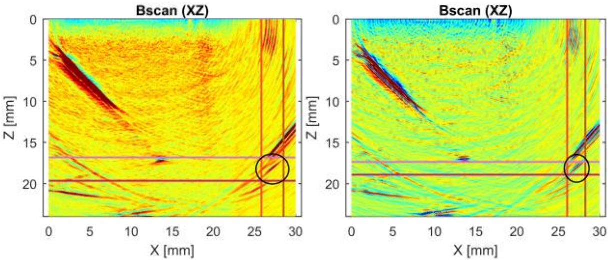

Figure 9. PAUT/FMC/TFM images of the horizontal cylinders, of 700 µm (left) and 500 µm (right), open to outside and located on the <u>inner</u> side of the SS full-size star artefact, S2 design

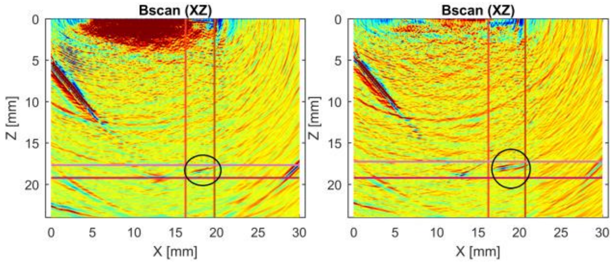

Figure 10. PAUT/FMC/TFM images of the horizontal cylinders, of 700 µm (left) and 400 µm (right), open to outside and located on the <u>outer</u> side of the SS full-size star artefact, S2 design

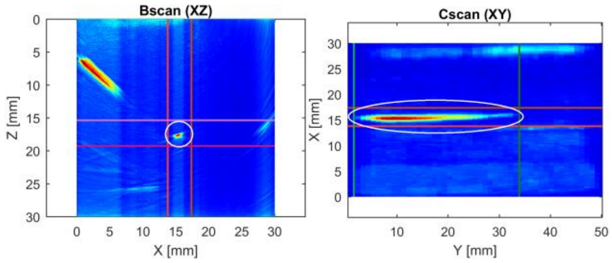

Figure 11. PAUT/FMC/TFM images of the vertical cylinders from the top (left) and from the side (right) of the SS full-size star artefact, S2 design

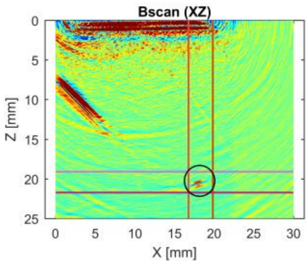

Figure 12. PAUT/FMC/TFM images of the cylinders with different orientations (∅ 0.30 mm, L 2 mm) of the SS full-size star artefact, S2 design

This PAUT/FMC/TFM method has enabled to see most of the internal features inside the star artefacts but not the ones smaller than 200 µm. However, the method relies a lot on the experience of the operator as it is very much interpretative. The interpretation of the images would have been even more complicated if the location of the features (simulated AM defects) would have not been known.

5. Conclusions and perspectives

The two described methods present benefits and drawbacks.

<u>Benefits of RAM</u>:

- Easy to use;
- Fast;
- Objective;
- Not restrictive in shape (appropriate for lattice structures);
- Not restrictive in size;
- No part preparation required (fixturing, coupling materials, etc.);
- Identification of defective parts.

Drawbacks of RAM:

- Global method: pass/fail inspection;
- No identification of the type of defects;
- No location of the defects in the part.

Benefits of PAUT/FMC/TFM:

- Selective method: scanning inspection providing images;
- Part inspections without scanning by steering the beam;
- Faster than conventional UT method;
- Less restrictive in shape than conventional UT method;
- Less restrictive in size than XCT;
- Identification of the type of defects;
- Location of the defects in the part;
- Discretization in size with a better spatial resolution than conventional UT and PAUT methods.

Drawbacks of PAUT/FMC/TFM:

- Requires more experience and training than RAM and conventional UT;
- Slower than RAM;
- More restrictive in shape than RAM and XCT (not appropriate for lattice structures);
- More restrictive in size than RAM;
- Part set-up required;
- More expensive than RAM and conventional UT.

RAM is very appropriate for routine and as a first level inspection method to sort defective (bad) parts from acceptable parts. However, on a second level, if the defects in the bad parts need to be identified and located, PAUT/FMC/TMC is more appropriate.

Nevertheless, the outcomes of these two methods should be improved to make them more effective. Concerning RAM, statistical tools, which could enable sorting the parts regarding the number of defects, should be developed. Concerning the PAUT/FMC/TFM method, more numerical signal processing on ultrasound images to discretize the defects should be studied to ameliorate the spatial resolution of the images. Then the reliability of these two methods should be evaluated.

Furthermore, blind tests should be performed in order to consolidate the capabilities of these two inspection methods.

We are not yet at the end of our efforts to refine the existing NDT methods and develop new ones to inspect parts as specific as those that can be fabricated in AM in order to ensure their integrity. One potential focus that is currently under assessment concerns non-linear acoustic methods. These methods should enable to detect smaller defects.

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