NDT for qualification of space hardware made by additive manufacturing

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Abstract

X-Ray Computed Tomography (CT) has been established as the preferable Non-Destructive Testing (NDT) method to detect inner defects in Metal Additive Manufactured (MAM) parts such as porosity, inclusions, lack of fusion, etc. Moreover, the usage of this manufacturing technology has grown in the aerospace sector due to the establishment of quality standards and the current maturity of the manufacturing systems, processing route and means of inspection. For instance, the European Cooperation for Space Standardization has developed a specific standard (coordinated by the European Space Agency – ESA) for AM quality assurance, processing, and requirements in space applications (ECSS-Q-ST-70-80C) indicating that CT inspections shall be carried out especially for critical structural and functional components. Similarly, large OEMs (Original Equipment Manufacturers) have developed their own standards considering CT as a mandatory NDT method in critical parts, but also other techniques such as Penetrant Testing (PT), Digital Radiography (DR) or visual inspection (VI) are also considered necessary to assure the quality of the components. This work presents diverse applications examples of different NDTs for hardware qualification: Titanium brackets for CHEOPS space missions; Aluminium helix antenna for PROBA3; Aluminium brackets for JUpiter ICy moons Explorer mission (JUICE), the last; or other aeronautic components like Aluminium fairings for the Clean Sky 2 IADP demonstrator, and structural Titanium flap fittings of the RACER helicopter. The aforementioned cases will be analysed not only from the execution of the inspection, but also from the application of different standards and requirements, specifically developed for AM or adapted to this novel manufacturing technology.

1. Introduction

Additive manufacturing (AM) and especially metal laser powder bed fusion (LPBF) has established as one of the most promising manufacturing technologies allowing excellent mechanical properties for final end-use parts [1-6], especially for complex geometries and optimized designs which are often impossible to realize by other manufacturing methods. One of the biggest advantages of AM components is the weight. 3D printed components need less parts but also less material which makes them considerably lighter.
The current challenge of aerospace industry is to make planes more eco-friendly e.g. consume less fuel [7]. On the other hand, the presence of manufacturing defects or flaws can have a negative influence on mechanical properties of final produced parts, for all production methods, not only additive manufacturing. Therefore, it is important to constantly improve processes and minimize defects which can have such influence, but also to select suitable NDT technique to assure the quality of the additively manufactured component.

The American Society of Testing and Materials (ASTM) discusses the use of different non-destructive testing procedures (UT: Ultrasounds, IRT: Infrared Thermography, PT: Penetrant testing, PCRT: Process Compensated Resonance Testing, MET: Metrology, ET: Eddy Current Testing, CT: Computed tomography) used to inspect metal parts made by additive manufacturing [8]. On this guide, it is shown how Computed Tomography is presented as one of the most valuable techniques since the most common defects due to AM process are pores, voids, inclusions, lack of fusions and cracks, and as CT is mainly independent of the component shape, flaws can be found and represented with high accuracy. For this reason, CT has been selected as the preferable NDT technique when inspecting critical flight components. This study shows some inspections of flight hardware’s taking into account the standards and defects acceptance criteria considered in the aerospace sector. Additionally, since there is almost no geometrical limitation while manufacturing parts additively, new components may have non accessible internal features which need to be inspected without being destroyed. In this context, this study presents some examples in which CT can give some valuable information of interface machining and manufacturing deviations.

2. Materials, equipment and methods

2.1 Materials

All the components presented below are flight components and have been manufactured by LPBF at CATEC facilities:

- Solar panel hosting tools for CHEOPS satellite, manufactured in Ti6Al4V with dimensions of 110x30x38 mm$^3$ (Figure 1.a).
- Helix Antenna for PROBA 3 satellite, manufactured in AlSi10Mg with dimension of 97x107x107 mm (Figure 1.b).
- Horizontal Tail Plane (HTP) fitting for the RACER helicopter, manufactured in Ti6Al4V with dimensions of 80x75x20 mm (Figure 1.c).
- Monitoring camera bracket (JMC) for the JUICE satellite, manufactured in Scalmalloy ® with dimensions of 250x195x125 mm (Figure 1.d).
- Fairings for the CS2 air demonstrator, manufactured in Scalmalloy ® with dimensions of 310x110x95 mm (Figure 1.e).
2.2 Equipment

All the specimens were inspected by micro-computed tomography (μCT) at CATEC to assess the shape and size of the internal defects non-destructively. A custom-made μCT scanner equipped with an X-Ray WorX tube (up to 225 kV) with rotation platform and a 4k flat panel detector (Perkin Ellmer) was used to scan the specimens. VGStudio MAX software was used for CT data analysis. Aerospace standards recommend using a test phantom during CT inspections of components, in order to proof the reliable detection of the required characteristic (porosity, inclusions, etc.), detection limits, and minimal defect sizes that can be detected. In this study, IQI’s of Aluminum (ref: TG-01315, Figure 2.a) and Titanium (ref: TG-TC_01310, Figure 2.b) have been used to establish void detectability. These IQI’s, with dimensions of 10x10x5 mm, contain six artificial internal defects (diameter: 100, 200, 300, 400, 500 and 1000 μm, Figure 2.c).

The dimensions of the artificial defects are defined for instance as the maximum allowable defect in Airbus Technical Specification for Metal Additive Manufacturing (AIMS03-22-000) during the qualification process of the AM component (200 μm for structural critical parts or non-critical but with fatigue loads requirements, 500 μm for non-structural or structural without fatigue requirements).
2.3 Methods

The tomographic inspections were performed by following ASTM E1570-19 [8] and ISO 15708-3 [9] for operation of the system and interpretation and evaluation of the results.

In terms of defect detectability, it is a common approach to establish the voxel size to detect the minimum defect allowable at least with three voxels in a raw, or by $3^3$ voxels in volume (which means for example a voxel size of 66 μm for a defect acceptance criterion of 200 μm pore diameter) [10].

The acceptance criteria of each component are defined by the end user according to its safety classification (function and requirements). Considering the above information, the inspection resolution (voxel size) of each component was adjust to 123 μm for CHEOPS bracket, 64 μm for PROBA 3 antenna, 54 μm for RACER fittings, 98 μm for JUICE bracket and 98 μm for CS2 fairings.

Additionally, and before extracting the components from the building plate, some inspections were performed with inspection resolution of 144 μm.

3. Results

3.2 Computed tomography inspection added value.

Interface machining of additively manufactured components is often required to obtain higher accuracy than the achieved by AM. For this purpose, the part could be machined while it is still joined to the building plate. Extra material (for instance support structure) could still be present in the building volume which difficulties the dimensional measurement (for instance by scanner or contact probe). Two examples are presented below. Figure 3.b shows the machining drilling input for CHEOPS brackets (extracted from the CT data), and Figure 3.c present a comparison between nominal CAD (red) and inspected component (grey) before machining (JUICE bracket).

On the other hand, CT inspection, while the component is still on the building plate, could be used to better understand the deviation produce during the manufacturing process. Figure 3.a shows the deviation on the upper region of the PROBA 3 Antenna and how this deviation is solve by rotating the component 45 degrees (perpendicular to build plate).

![Figure 3. CT inspection images before part extraction from building plate. (A) PROBA 3 antenna, (b) CHEOPS bracket and (c) JUICE bracket.](image-url)
3.1 Inspection of flight component

This section presents some examples of CT cross section of flight components in the quality assurance stage. All of them have been inspected with its corresponding IQI to assure defect detectability. It can be observed below that all the components show high densification and no defects have been found under inspection resolution.

![Image of flight components](image1.png)

Figure 4. Tomographic cross sections of: (a) JUICE bracket, (b) CS2 fairing, (c) RACER fitting, (d) PROBA 3 antenna, (e) CHEOPS bracket.

3.2 Complementary Non-Destructive inspections

One of the most employed NDT techniques when inspecting AM component, together with CT, is Penetrant testing, which is mainly used to detect and located surface flaws. Due to the roughness that AM could bring, PT is mainly use in machined surface (for instance interfaces). Figure 5.a and 5.b show two examples of PT performed in CS2 fairing and RACER fitting respectively. Once the indications are detected by PT, they are measured by Optical microscope and compare against surface pores acceptance criteria (300 µm for instance).
Figure 5. Image of PT results in (a) CS2 fairing and (b) RACER fitting.

4. Conclusions

A procedure to inspect additive manufacturing parts have been shown, taking into account CT operation standards and aerospace defects acceptance criteria. The usage of IQI has been presented as well as one of the key points to assure defect detectability. Additionally, Penetrant Testing has been introduced as one of the best complementary NDT techniques when detecting AM surface flaws, considering the difficulties that can be found when dimensioning surface indications by Computed tomography. Also, some examples of dimensional analysis performed by CT have been presented, giving solution to manufacturing deviation but also as important input for interface machining.

References

8. ASTM E3188-201: Standard guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build
10. C. Galleguillos, “Comparison of defect detectability between Computed Tomography inspection and CT simulation using a calibrated defect phantom”, 11th Conference on Industrial Computed Tomography, Wels, Austria (iCT 2022),