
Additive manufacturing of metals — Non-destructive testing and evaluation — Defect detection in parts

*Fabrication additive de métaux — Essais et évaluation non destructifs
— Détection de défauts dans les pièces*





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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

The committee responsible for this document is ISO/TC 261, *Additive manufacturing*, in cooperation with ASTM Committee F42, *Additive manufacturing technologies*, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on additive manufacturing, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438, *Additive manufacturing*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In response to the urgent need for standards for Additive Manufacturing (AM), this document initially indicates Non-Destructive Testing (NDT) methods with potential to detect defects and determine residual strain distribution that are generated in AM processes. A number of these methods were verified. The strategy adopted was to review existing NDT standards for matured manufacturing processes which are similar to AM, namely casting and welding. This potentially reduces the number of standards required to comprehensively cover the defects in AM. For identified AM unique defects, this document proposes a two-level NDT approach: a star artefact as an Initial Quality Indicator (IQI) and *à la carte* artefact where an example shows the specific steps to follow for the very specific unique AM part to be built, paving the way for a structured and comprehensive framework.

Most metal inspection methods in NDT use ultrasound or X-rays, but these techniques cannot always cope with the complicated shapes typically produced by AM. In most circumstances X-ray computed tomography (CT) is a more suitable method, but it also has limitations and room for improvement or adaptation to AM, on top of being a costly method both in time and money.

This document includes post-process non-destructive testing of additive manufacturing (AM) of metallic parts with a comprehensive approach. It covers several sectors and a similar framework can be applied to other materials (e.g. ceramics, polymers, etc.). In-process NDT and metrology standards are referenced as they are being developed. This document presents current standards capability to detect which of the Additive Manufacturing (AM) flaw types and which flaws require new standards, using a standard selection tool. NDT methods with the highest potential will be tested.

Additive manufacturing of metals — Non-destructive testing and evaluation — Defect detection in parts

1 Scope

This document categorises additive manufacturing (AM) defects in DED and PBF laser and electron beam category of processes, provides a review of relevant current NDT standards, details NDT methods that are specific to AM and complex 3D geometries and outlines existing non-destructive testing techniques that are applicable to some AM types of defects.

This document is aimed at users and producers of AM processes and it applies, in particular, to the following:

- safety critical AM applications;
- assured confidence in AM;
- reverse engineered products manufactured by AM;
- test bodies wishing to compare requested and actual geometries.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 11484, *Steel products — Employer's qualification system for non-destructive testing (NDT) personnel*

ISO/ASTM 52900, *Additive manufacturing — General principles — Fundamentals and vocabulary*

ASTM E1316, *Terminology for Nondestructive Testing*

EN 1330-2, *Non-destructive testing — Terminology — Part 2: Terms common to the non-destructive testing methods*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900, ASTM E1316, EN 1330-2, ISO 11484, and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

flaw type

identifiable features that defines a specific flaw

Note 1 to entry: defect term, this word is used when a flaw that does not meet specified acceptance criteria and is rejectable.

Note 2 to entry: Flaw term, an imperfection or discontinuity that is not necessarily rejectable

3.2

lack of fusion

LOF

type of process-induced porosity, in which the powder or wire feedstock is not fully melted or fused onto the previously deposited substrate

Note 1 to entry: In PBF, this type of flaw can be an empty cavity, or contain unmelted or partially fused powder, referred to as unconsolidated powder.

Note 2 to entry: LOF typically occurs in the bulk, making its detection difficult.

Note 3 to entry: Like voids, LOF can occur on the build layer plane (layer/horizontal LOF) or across multiple build layers (cross layer/vertical LOF).

3.3

unconsolidated powder

unmelted powder that due to process failure was not melted and became trapped internally

3.4

layer shift

<E beam> when it is disturbed by a magnetic field a layer or a number of layers are shifted away from the other build layers

Note 1 to entry: see stop/start for PBF laser/E beam.

3.5

trapped powder

unmelted powder that is not intended for the part but is trapped within internal part cavities

3.6

porosity

presence of small voids in a part making it less than fully dense

Note 1 to entry: Porosity may be quantified as a ratio, expressed as a percentage of the volume of voids to the total volume of the part.

[SOURCE: ISO/ASTM 52900:2019, 3.11.8]

4 NDT potential for authentication and/or identification

Some of the NDT methods in this technical report have the additional potential to extract authentication and/or identification apparatus or design embedded in the design of the AM part. Such a potential clearly depends on the material(s), geometry and process selected to fabricate the part, however the design information and AM data file can embed in its geometry or texture ad-hoc devices that potentially could be extracted by NDT techniques. ISO/TC 292 specifies and maintains a number of standards supporting such devices within the ISO referential, and are fully applicable to AM digital information. The specific requirements of design techniques, materials, processes, NDT modalities and applications, however, still require careful evaluation, selection and classification.

5 List of abbreviated terms

AM	additive manufacturing
BAE	British Aerospace and Engineering Systems
EB-PBF	electron beam powder bed fusion
ESFR	European Synchrotron Research Facility
EWI	Edison Welding Institute
FMC	full matrix capture
GE-PD	general electric powder division
HZB	Helmholtz Zentrum Berlin
ILL	Institute Laue-Langevin
IR	infrared
IRT	infrared thermography
J & J	Johnson & Johnson
LNE	laboratoire national de métrologie et d'essais
PBF-LB	laser powder bed fusion
DED-LB	laser directed energy deposition
MTC	The Manufacturing Technology Centre
ND	neutron diffraction
NDE	non-destructive evaluation
NDT	non-destructive testing
NI	neutron Imaging
NIST	National Institute of Standards and Technology
NLA	non-linear acoustic testing
NLR	non-linear resonance testing
PAUT	phase array ultrasound testing
PCRT	process compensated resonance testing
PT	pulse thermography
RAM	resonance acoustic method
ROI	Region of interest
SX	X-ray synchrotron
SHT	step heating thermography

TFM	total focusing method
TMS	the modal shop
UoB	university of bath
XCT	X-ray computed tomography

6 Typical flaws/defects in AM

6.1 Flaw origins/causes

The causes of defects across different types of AM processes can be quite different, but the defects that they generate can be remarkably similar. Detecting the defects also does not depend on the cause, and in general only the size and geometry (and potentially morphology) of the defect matters for detection.

The causes and effects of a number of AM flaws have been reported in the European project AMAZE^[21]. [Table A.1](#) and [Table A.2](#) give explanations of the mechanisms by which these flaws are generated and those mechanisms are linked to the process parameters selected and the resulting processing conditions, see ISO 11484. Understanding the conditions under which flaws are generated and simplifying the terminology used to describe these flaws will aid the drive for quality improvement required for widespread implementation of the technology.

The flowchart displayed in [Figure 1](#) gives an idea of the complexity of flaw generation within the PBF process. As can be seen, the generation of one flaw type can result in an anomalous processing condition, which in turn generates a second flaw. For example, the presence of a thick layer or low laser (or electron beam) power can lead to under-melting, which in turn can lead to unconsolidated powder. Coupled with the tendency of the power source to decrease the surface energy of unconsolidated powder under the action of surface tension, ensuing ball formation may arise due to shrinkage and worsened wetting, leading to pitting, an uneven build surface, or an increase in surface roughness; see EN 1330-2.

Therefore, even when there are multiple causes, a single flaw type or conditions can be generated (excessive surface roughness) causing failure by a single failure mode (surface cracking leading to reduced fatigue properties). Alternatively, it is also conceivable that a single flaw type or condition can cause failure by several different failure modes.

6.2 Flaw/defects classification

Post-built AM flaws have been identified based on a report from the FP7 European AMAZE project. Potential flaws in directed energy deposition (DED) and powder bed fusion (PBF) are listed in [Table 1](#) and [Table 2](#) respectively. A brief description for each flaw type is also given in the tables.

Due to the similarity in manufacturing, defects from welding and casting bear some resemblance to defects from AM processes such as PBF and DED. Defects in post-built PBF and DED parts are identified and listed in EN 1330-2, ASTM E1316 and References ^[22]. As noted in [Table 1](#) and [Table 2](#), both technologies have common defects such as porosity, inclusions, undercuts, geometry, LOF, and a rough surface texture. However, the mechanisms for PBF and DED defect generation are very different, and more importantly, the relative abundance of each defect type will be very different due to the melting and solidification mechanisms involved (and the significantly higher thermal gradients present in DED). DED involves imparting a momentum into the melt pool rather than melting the powder that is already present. The important difference between the two methods is that of timescales.

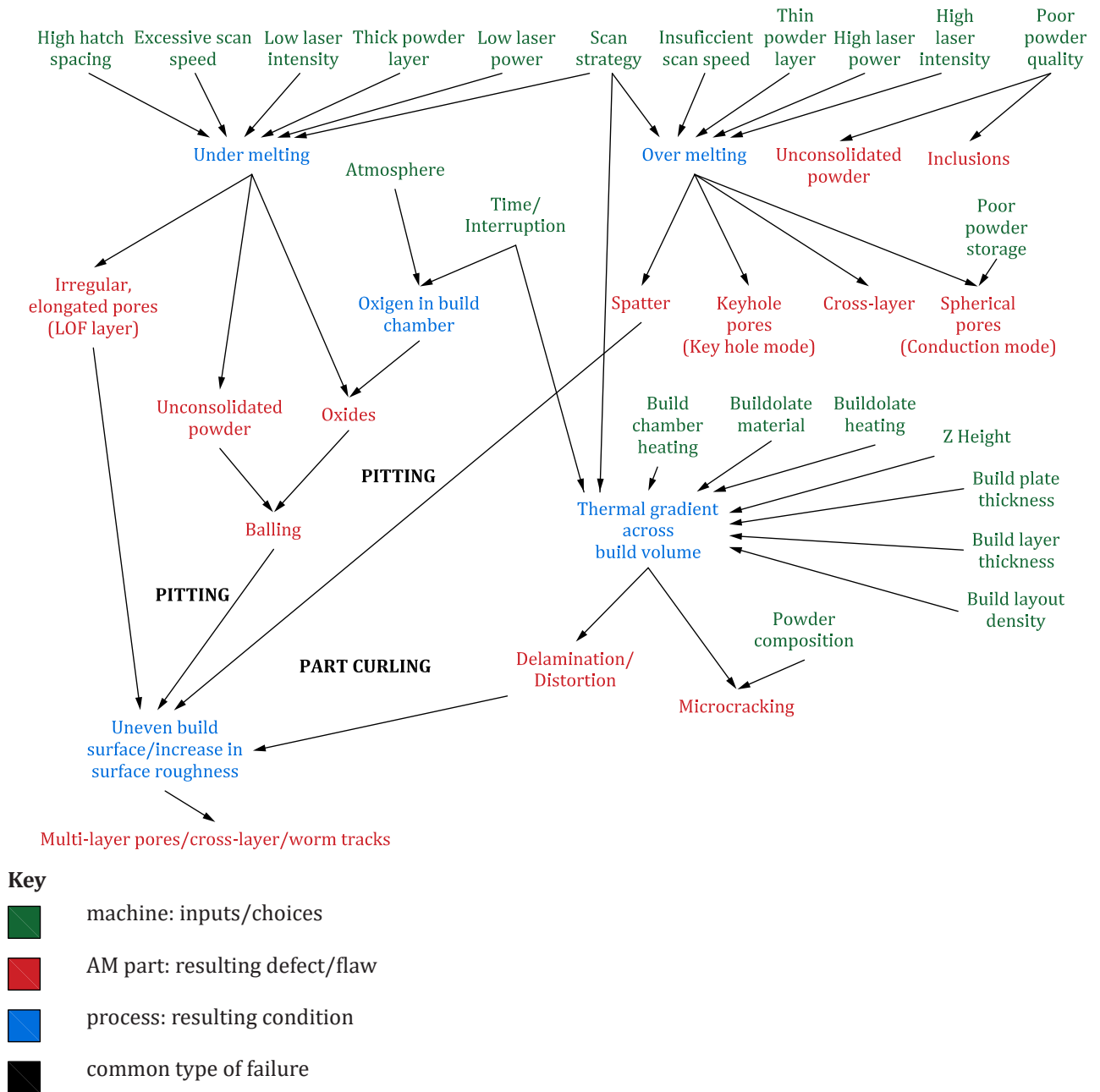


Figure 1 — Causes, mode of failures and defect formation in PBF AM (see ISO/ASTM 52900)

In PBF, there is a balance of timescales between melting and re-solidification. If the melt rate is too low, then the melt pool can become unstable and break into multiple pools. If the melt rate is too high, powder partially melts in front of the melt pool, which can cause defects or heat affected zones. In DED, this balance is not relevant, but the powder (or wire) that is fed into the melt pool can melt sufficiently quickly. The issue of adding cold material (with a given momentum) to a melt pool is not well understood, but has a large effect on the Marangoni convection direction and thermal gradients present. It is likely that the melt pool depth will be much shallower (which may reduce powder surrounding the melt pool) and that the thermal gradients less severe (which cause a flatter melt pool), though this depends on the wetting between substrate (which has no surrounding powder) and the melt pool. This difference in the melt pool dynamics impacts its shape.

This has two important consequences, grain growth and bubble dynamics. Internal defects are attributable to cracking, pores, or lack of material. Cracking has many causes, but is generally related to the grain boundary (apart from solidification cracking). Note that the issue of “spattering” that is

believed to be prominent in DED (or indeed welding) is still a significant issue in PBF. For L-PBF the issue is that of ablation at the surface of the melt pool caused by the large thermal gradients. For EB-PBF the problem occurs from two mechanisms; ablation and charging of the powder.

Table 1 — Typical flaws in directed energy deposition

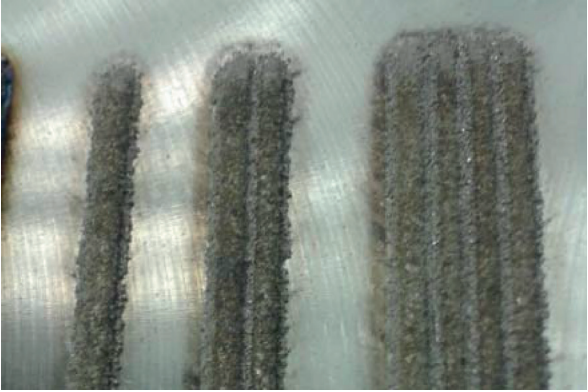
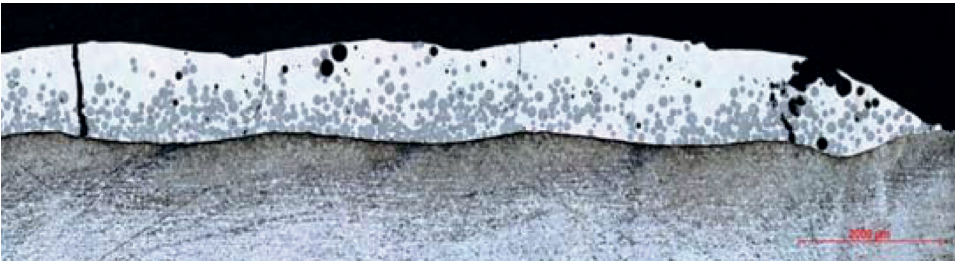
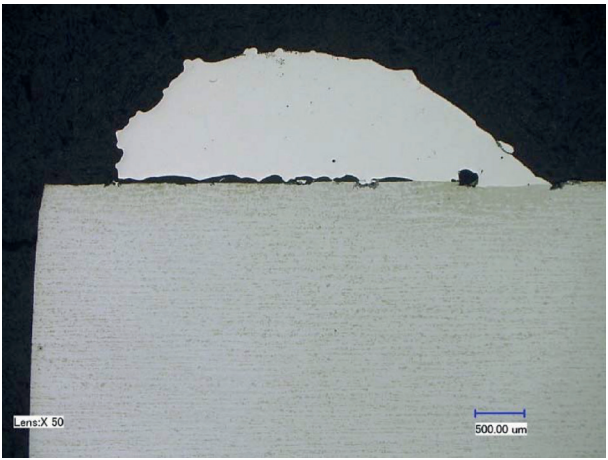
Flaw type	Description
Poor surface finish	The surface roughness on the part does not meet the target specification for the part. Measurement of the surface roughness is considered out-of-scope for NDT however, visual examination can be included. 
Porosity	Typically spherical in shape and contains gas. Porosities can grow in a line to form a chain or elongated porosity. 
Incomplete fusion	Fusion between the entire base metal surfaces and between adjoining welds are not complete. This occurs when new material has been used and the build parameters have not been optimised. Typically, this flaw is eliminated as the process improved when all parameters have been optimised. 
Undercuts at the toe of the welds between adjoining weld beads	A groove melted into the base metal adjacent to the weld toe or weld face and left unfilled by weld metal.

Table 1 (continued)

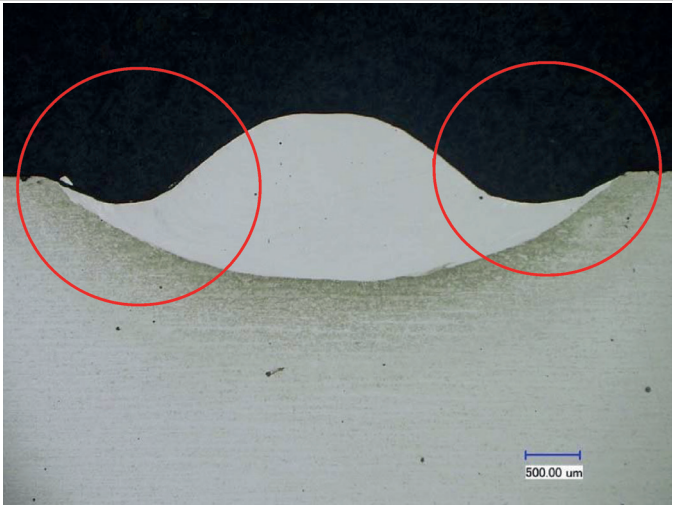
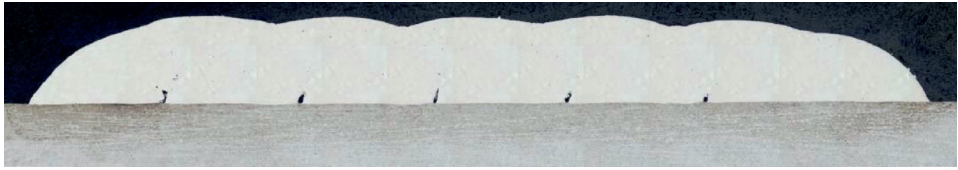
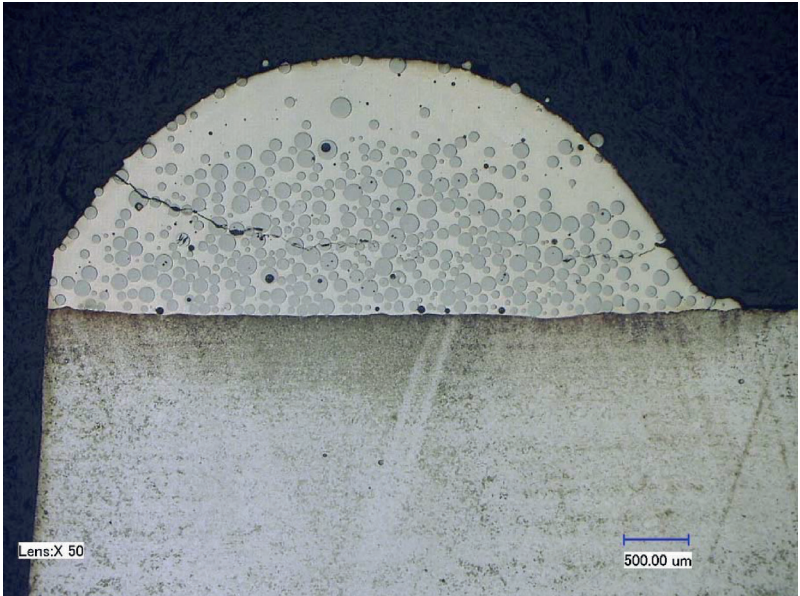
Flaw type	Description
Non-uniform weld bead and fusion characteristic	 These indicate errors in the process which can risk integrity of the build. Internal flaws caused by this can be void, porosity, or incomplete fusion.
Hole or void	Typically occurs internally in the built part as shown in the micrograph below. It is difficult to detect by physical examination of the part. 
Non-metallic inclusions	Inclusions can come from the powder or the wire feedstock. Some inclusions are intentionally added to the powder to improve the process (e.g. for oxidation) but they could also be caused by contaminants in the process.
Cracking	Cracking can develop from internal holes or voids which then grows to the external surface. 
Lack of geometrical accuracy/steps in the part	Variation of the part dimension from the CAD model will not be currently part of the review. Nevertheless, steps and gross variation which can be detected by visual examination are included.

Table 2 — Typical flaws in powder bed fusion

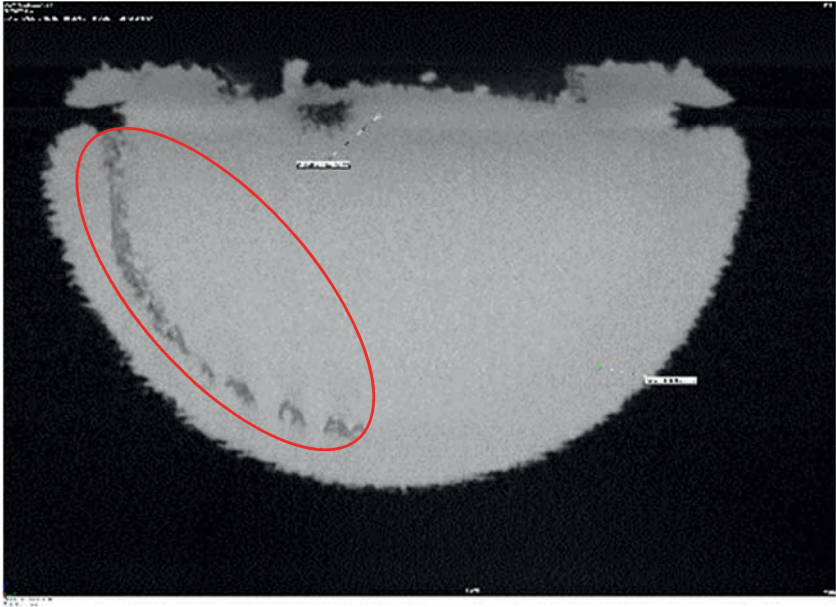
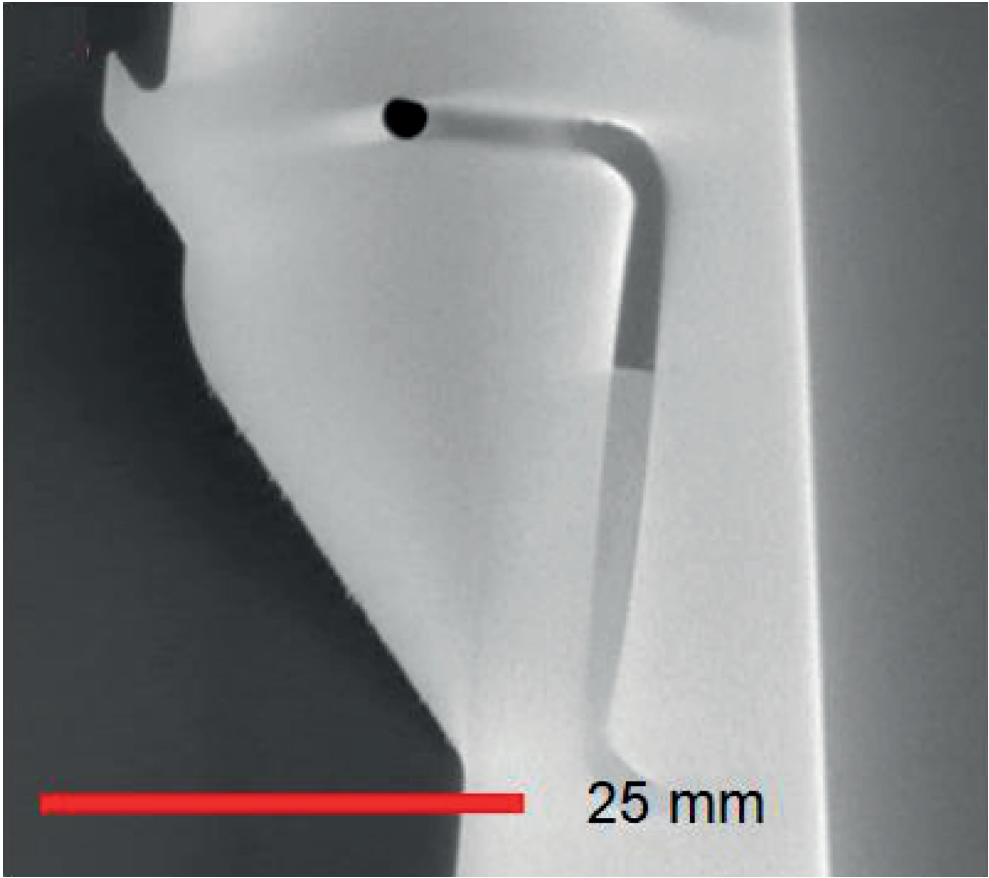
Flaw type	Description
Unconsolidated powder	Unconsolidated powder leading to porosity or voids. The morphology is different to gas generated pores, but the geometry and size are not dissimilar. The image below is an example taken from RASCAL project.  A grayscale micrograph showing a cross-section of a part. A red oval highlights a region of unconsolidated powder, which appears as a lighter, irregularly shaped area with a rough, porous texture. The surrounding material is darker and more uniform.
Trapped powder	Unmelted powder that is not intended for the part is trapped within part cavities.  A grayscale micrograph showing a cross-section of a part. A red oval highlights a region of trapped powder, which appears as a lighter, irregularly shaped area with a rough, porous texture. The surrounding material is darker and more uniform. 25 mm
Layer defect (Horizontal lack of fusion)	Void or porosity with or without unconsolidated powder that grows on the build layer plane in a connected or semi-connected manner. The image below is a vertical slice of an X-ray computed tomography scan.

Table 2 (continued)

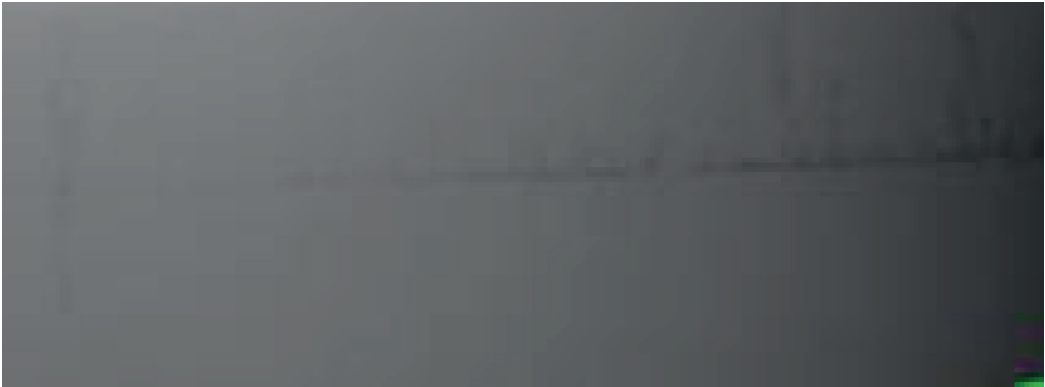
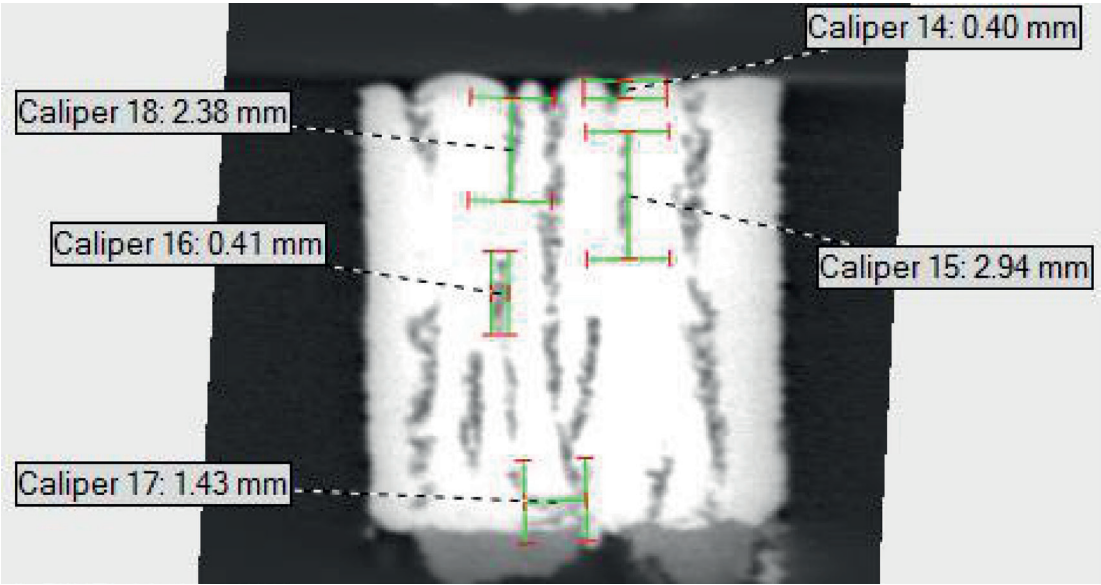
Flaw type	Description
	
Cross layer (Vertical lack of fusion)	Void or porosity with or without unconsolidated powder that grows along the build axis in a connected or semi-connected manner. The images below show vertical and horizontal slices from an X-ray computed tomography scan. Vertical slice view.  Top slice view.

Table 2 (continued)

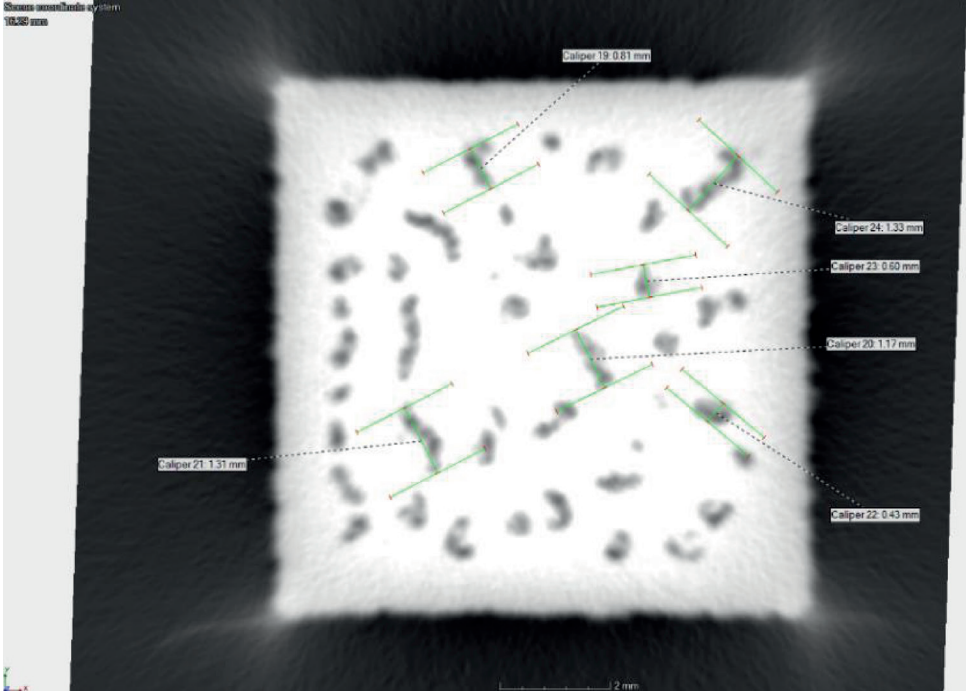
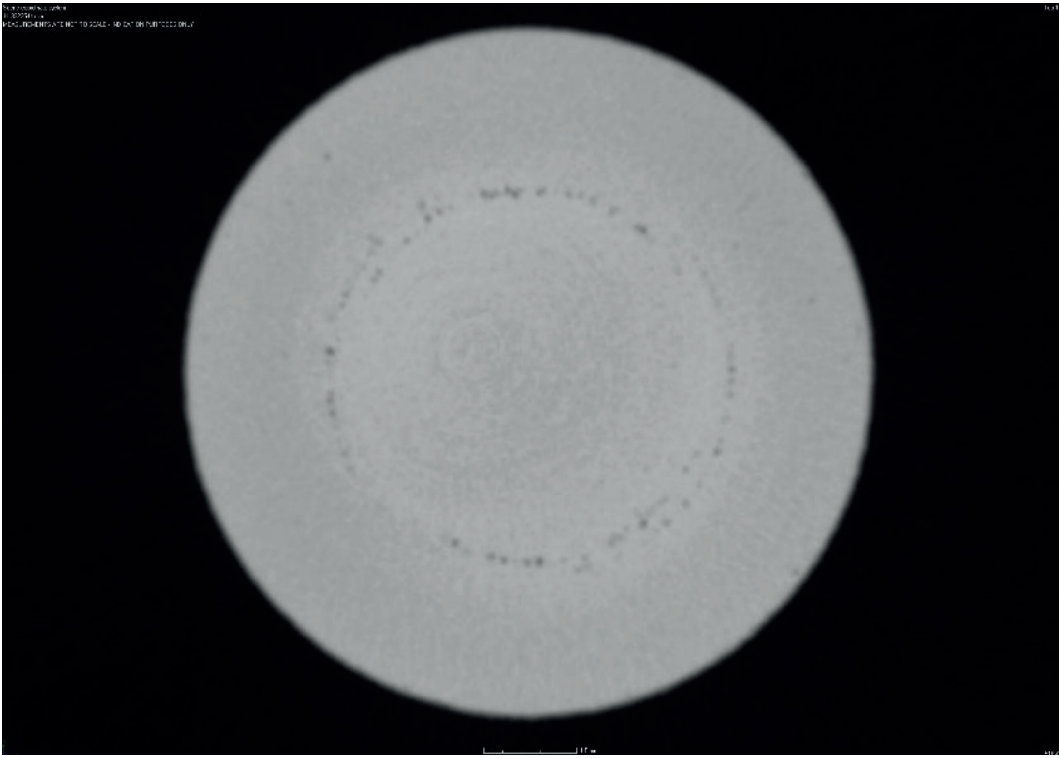
Flaw type	Description
	
Porosity	Typically spherical in shape and contains gas. Porosities can grow in a line to form a chain or elongated porosity. The image below is a horizontal slice of an X-ray computed tomography scan. 
Poor surface finish	The surface roughness on the part does not meet the specification. For example, the surface roughness is higher than acceptable limit^[24].

Table 2 (continued)

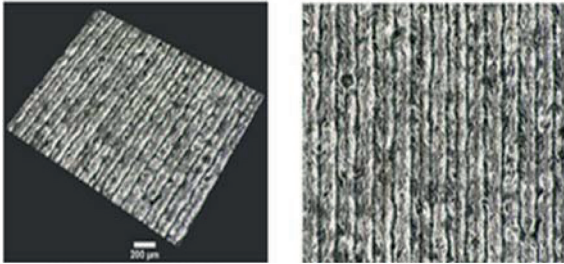
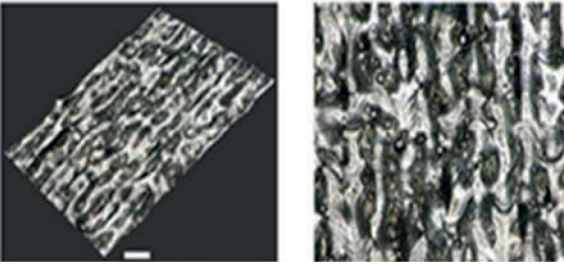
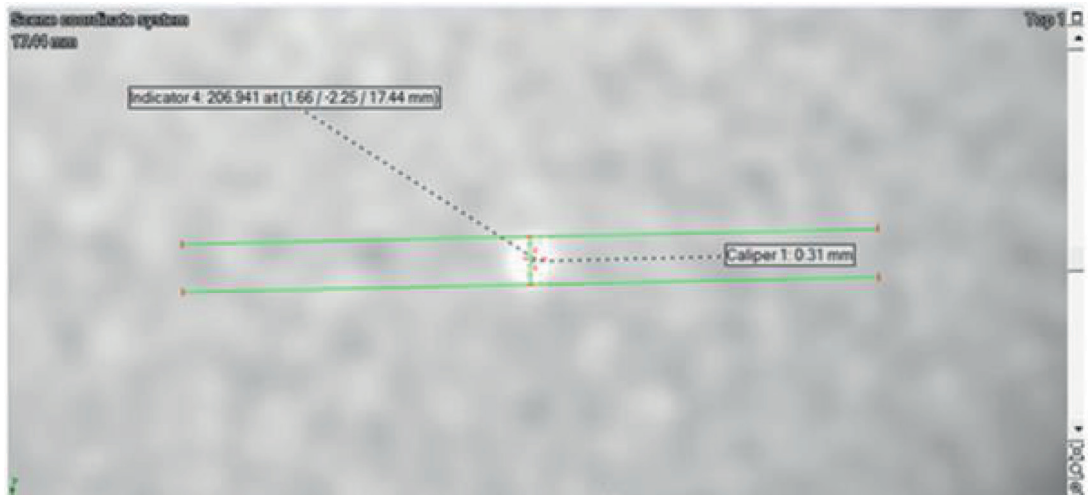
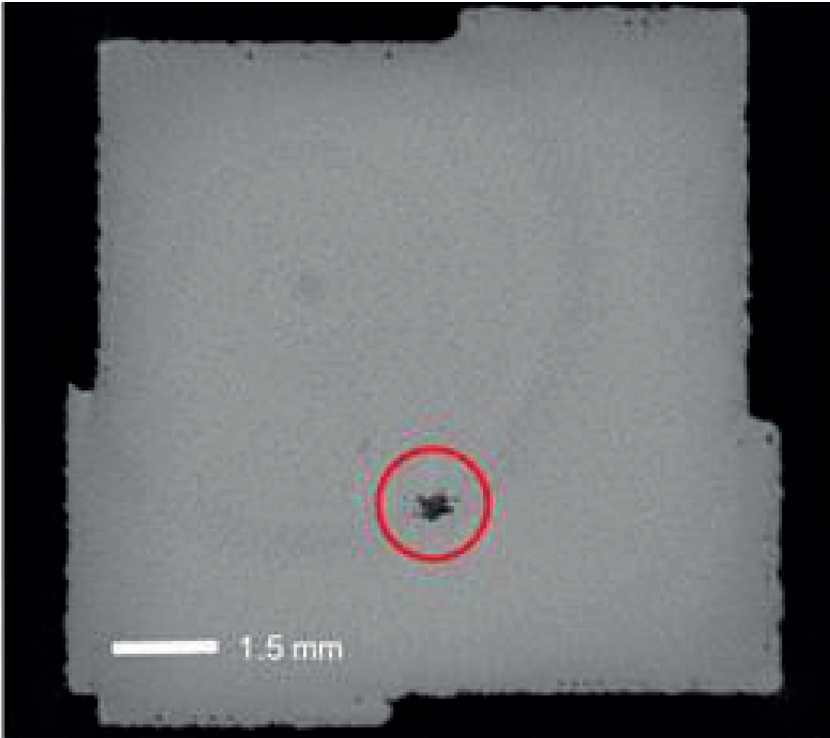
Flaw type	Description
	$P = 50 \text{ W}, V = 200 \text{ m/s}$  $P = 195 \text{ W}, v = 1\,200 \text{ m/s}$ 
Layer shift/ lack of geometrical accuracy/ steps in the part	Variation of the part dimension from the CAD model will not be currently part of the review. Nevertheless, steps and gross variation which can be detected by visual examination are included.
Reduced mechanical properties	A certain region of the part has different mechanical properties to the rest of the part.
Inclusions	Inclusions can come from the contaminants in the powder. The image below is an XCT image of an inclusion taken from project AMAZE 2. 
Void	Flaws created during the build process that are empty pockets or filled with partially or wholly un-sintered powder, or partially or wholly un-fused wire. These pockets can exist in a variety of shapes and sizes. The image below is a horizontal slice of an X-ray computed tomography scan.

Table 2 (continued)

Flaw type	Description
	

6.3 Defect classification strategies for AM

As pointed out in ISO 11484 and Reference [25], there are longstanding NDE standard defect classes for conventionally manufactured cast, wrought, forged, and welded production parts. The defects produced by these conventional processes will generally not be similar to those produced by AM processes. In addition, the NDE signal attenuation characteristics in AM parts may differ from those in conventional parts. Therefore, legacy physical reference standards and NDE procedures can be used with caution when inspecting AM parts[25]. This implies that until an accepted AM defect classification and associated NDE detection limits for technologically relevant AM defects are established, the NDE methods and acceptance criteria used for AM parts will remain part specific to design point. Variation of AM process parameters and disruptions during build may induce a variety of defects (anomalies) in AM parts that can be detected, sized, and located by NDE, see ISO/ASTM 52900.

In addition to defect classification strategies based on NDE detection limits for technologically relevant defects, or acceptance criteria for the minimum allowable defect sizes, a classification strategy based on the physical attributes possessed by defects is also possible and, perhaps, is more intuitive. For example, defect morphology, orientation, size, and location have been found to be useful attributes for classifying defects. Together, physical defect attributes such as morphology, orientation, size, and location provide a powerful framework for classifying defects and can be used to complement defect classification strategies delimited by NDE capability (minimum detectable flaw size) or acceptance criteria (critical initial flaw size). Ultimately, the goal is to determine which of the physical defect attribute(s) play a prominent role in influencing properties and performance.

Further refinement of NDE is possible by looking at still other physical defect attributes related to morphology, orientation, size and location. For example, in Reference [30], tensile tests on 17-4 PH stainless steel AM dogbones were carried out to show effect of defects on its mechanical properties. The results revealed that the number of defects exhibited the strongest correlation to yield strength compared to the other attributes. In addition to the defect attributes of morphology, orientation, size, and location discussed above, the selection of an appropriate NDE method is governed by a range of practical and material considerations[21][22]. Practical considerations include

- a) special equipment and/or facilities requirements,

- b) cost of examination,
- c) personnel and facilities qualification,
- d) geometrical complexity of the part,
- e) part size and accessibility of the inspection surface or volume relative to NDE used (for example the ability to detect embedded flaws), and
- f) process history and post-processing (see ASTM E3166).

While application of conventional NDE techniques is possible for AM parts with simple geometries, topology optimized AM parts with more complex geometries require specialized NDE techniques. The ability of each technique to detect different types of defects, as well as to locate them in the interior or exterior surface of a part is listed. Finally, the NDE techniques are further characterized by the ability to globally screen or detect and locate a defect.

7 NDT standards review

7.1 Post-process NDT standards

In DED, material is fused together by melting as it is being deposited. DED processes are primarily used to add features to an existing structure or to repair damaged or worn parts. DED has many variants of processes. The material deposited can be either powder or wire based. The heat source can be a laser, electron beam, electric arc among others. DED processes have similarities to welding processes, and consequently the flaws generated in DED are expected to be similar to the flaws generated in welding. For this reason, the NDT standards for welding have been used in the review.

In PBF, powder is deposited onto a build platform bed and selectively fused using a localized energy source (typically electron or laser beam) to form a section through the component. The build platform is then lowered and the process is repeated until the part is produced. Unlike DED, PBF processes do not have similarities to welding. However, there are flaws generated in PBF such as voids and porosity that have some similarities to welding flaws. Therefore, the review of NDT standards for welding is still relevant to PBF. In addition to welding, some common casting flaws, gas porosity, cracking and inclusion, are similar to DED and PBF flaws. For this reason, NDT standards for castings have also been reviewed and their applicability to AM flaws is assessed.

7.1.1 ISO review

7.1.1.1 Welding standards

The NDT standards for welding comprise of a number of standards that cover different aspects of inspection in welding. This is described by the tree diagrams in ISO 17635:2016, Figure B.1. The welding quality standards are specified in ISO 5817 and ISO 10042. These standards feed into ISO 17635 which is an interface between the quality levels and the acceptance levels for indications. This standard also describes the NDT method selection process, which splits into six method-specific standards. These are radiographic, eddy current, magnetic particle, penetrant, ultrasonic and visual examination. At this stage, an NDT method has been decided, and a corresponding standard describes the test procedure and the characterisation acceptance levels. Each method has its own limitations and it is possible that, for a given component or a target flaw, a combination of different methods is required.

The method standards are only available for conventional NDT. For radiography and ultrasonic, there are more sub-method standards as shown in ISO 17635:2016, Figures B.2 and B.3. NDT standards for more advanced NDT methods are not available; for example, ultrasonic phased array, X-ray computed tomography, and thermography. It is possible that these methods are not widely accepted and used by NDT operators within the welding industry. However for AM, there are opportunities for new standards to be developed for the advanced methods.

7.1.1.2 Casting standards

The NDT standards for casting have a simpler structure to those for welding. ISO 4990 categorises casting flaws into surface discontinuities and internal discontinuities. There are standards for five main conventional NDT methods. Each method is either for surface or internal discontinuities. The five NDT methods are:

- 1) Visual examination ISO 11971 (surface)
- 2) Magnetic Particle Inspection ISO 4986 (surface)
- 3) Liquid Particle Inspection ISO 4987 (surface)
- 4) Ultrasonic examination ISO 4992 (internal) — Part 1 (general purposes) and Part 2 (highly stressed components)
- 5) Radiographic testing ISO 4993 (internal)

Similar to welding, there is no standard available for advanced NDT methods for castings such as X-ray computed tomography, phased array ultrasonic and thermography. These methods are not regarded as standard methods in castings, although they could have been used following company specific internal standards or procedures. Castings typically have simpler geometry compared to AM and welding. Some NDT methods might not be suitable e.g. ultrasonic. Additionally, surface roughness for castings is typically better than as-built AM components.

7.1.1.3 Welding and casting standards applicable to AM flaws

The summary of the review of current standards for welding and casting (see [Table B.1](#)) is shown in [Table 3](#). Flaws that would be covered by other types of inspection e.g. dimensional measurement or material characterisation are categorised as 'non-NDT'. All flaws listed in the table for DED are generally covered by current NDT standards, except for the non-NDT ones. For PBF, seven flaws are not covered by current NDT standards. Three of these are non-NDT, and four are flaws unique to AM (unconsolidated powder, layer, cross layer, and trapped powder). The unique flaws require new NDT recommendations which will be addressed in this document. It will also refer to newly developed standards in other sectors such as aerospace.

As shown in [Table 3](#), the following are the identified flaws unique to AM (PBF only) which require new standards:

- Layer;
- Cross layer;
- Trapped powder;
- Unconsolidated powder;

**Table 3 — Classification of directed energy deposition and powder bed fusion flaws
(Flaws unique to additive manufacturing are in bold)**

Flaw type		Non-NDT	Common in DED & PBF	Covered by current standards	Unique to AM
DED	Poor surface finish				
	Porosity				
	Incomplete fusion				
	Lack of geometrical accuracy/steps in part				
	Undercuts				
	Non-uniform weld bead and fusion characteristic				
	Hole or void				
	Non-metallic inclusions				
	Cracking				
PBF	Unconsolidated powder				
	Lack of geometrical accuracy/steps in part				
	Reduced mechanical properties				
	Inclusions				
	Void				
	Layer				
	Cross layer				
	Porosity				
	Poor surface finish				
	Trapped powder				

7.2 In-process NDT review

Conventional NDE methods such as X-ray, UT, EC, have been used for post build inspection of Additive manufacturing (AM) components. Due to the limited number of studies available and the technical constraints, the capability of these NDE techniques is limited, indicating a technical gap^{[21][27]}. It is foreseen that in-process monitoring can be used to improve control of the process to minimise quality issues. In addition, in-process inspection has the added ability to inspect the part as it is built, which for some very complex AM parts may be the only NDE capable solution.

AM processes offer freedom over other manufacturing methods, such as the integration of multiple parts, which generally increase their geometry complexity. In order for an AM process to be successful, the product quality can first be ensured. Typically, quality inspections are performed after the build of

the full part, which becomes difficult for complex geometries. Taking advantage of the unique layer-by-layer build method, an ideal place to verify the part quality is after a layer or number of layers, with the potential advantage to reduce or eliminate the need to inspect after the full build.

Current AM in-process monitoring relies mainly on surface measurements, potentially missing subsurface defects. LPBF and DED AM processes work at elevated temperatures; therefore, non-contact methods are required.

In powder bed fusion processes, problems with layer-wise coatings and untimely laser melting can lead to porosity, stress and further variations in the built part, or of material properties. Therefore, it is important to not only perform measurements to inspect the finished build, but also to monitor in-process and ultimately implement an efficient feedback system that could compensate time dependent setup deficits, for example decreasing of laser input due to aging/soot pollution or similar effects.

A study that was carried out to map the NDE technologies available for inspection in-situ is reported and discussed in detail by References [22][28]. Also, References [29][30] addressed the matters inside the NDE inspection methodologies compatible with AM process. The topics addressed during this review were:

- optical control methods;
- coating control system;
- in-process control methods;

Only the in-process control methods were covered which involved NDT techniques. The methods reviewed were XCT, Thermography, Laser ultrasonic, Eddy currents, Neutron characterisation, Acoustic emission and X-ray Backscattered. It was concluded that these less conventional inspection methods offer many possibilities for in-situ inspection of AM processes. Cracks have been successfully detected using Ultrasonic, Laser ultrasonic, thermography and X-ray backscatter methods. In particular, X-ray backscatter inspection is not limited by surface finish and, therefore, would be particularly suitable. Residual stress/strain has been identified using neutron beam diffraction.

Infrared thermography not only monitors the melt pool emissions but also enables the user to detect temperature distributions in the powder bed or of the built parts during the build process. Heat distribution variations indicative of process anomalies can be included in error evaluation and, in addition, the measurement of temperatures allows to correlate the measured data to metallurgic properties and therefore to intrinsic material characteristics.

Laser scanning or laser profiling allows closed loop control of Wire DED build height but could also be used in the scanning of powder beds for defects. Laser ultrasound (LU) is another technique which may be used to inspect AM parts. Laser ultrasonic testing is a non-contact inspection technique with potential for in-process defect monitoring of AM processes. It uses lasers to both generate and detect ultrasonic waves which can be used for defect detection, materials characterisation and thickness determination. A pulsed laser is used to generate an ultrasonic wave and a continuous-wave laser interferometer detects the small surface displacement when the waves arrive at the detection point.

LU is capable of working at elevated temperatures of at around 1000 °C, and some systems are capable to work on rough surface samples which are expected to be in AM built parts. LU generates both surface and bulk waves at the same time; therefore, allowing inspection of surface, close to surface and bulk of material. Additionally, surface wave penetration depth can be optimized remotely depending on the process.

LU has shown good capability to detect laser machined notches with dimensions as small as 50 µm × 75 µm × 50 µm (L × D × W) on DED samples as built, that is without any post build surface finishing. The method can be used on curved or difficult to access areas and is capable to work at elevated temperatures, therefore is suitable for Laser-PBF and DED AM processes ([Figure 2](#) and [Figure 3](#))^[31].

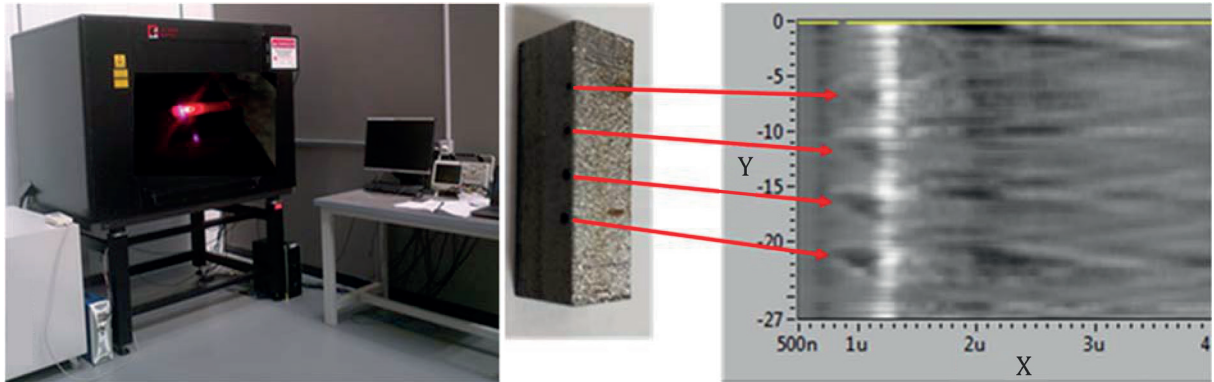


Figure 2 — LU system (left); and L-PBF sample calibration sample with B-Scan results identifying detected features (right)

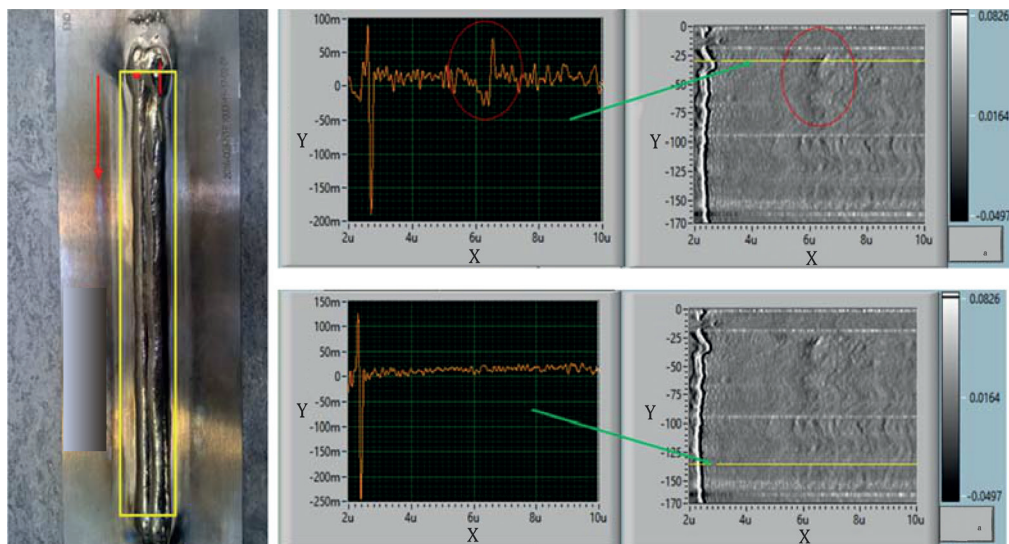
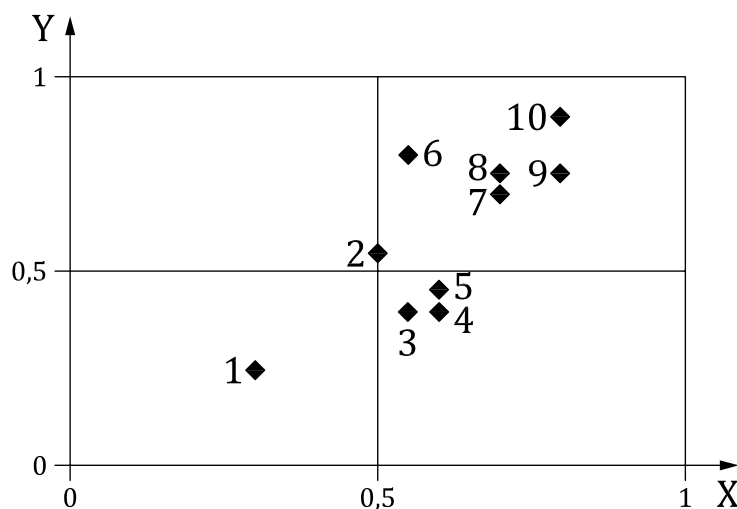


Figure 3 — Photograph of DED sample with scan details (left); A-Scans (centre); and B-Scans showing an area with LOF (right)

[Figure 4](#) summarises the review carried out for NDE technologies applicable for in-situ monitoring and inspection for AM parts. This diagram shows that optical methods are the easiest and capable ones for the in-process monitoring and inspection methods attempted to scope. Nevertheless, other methods such as LU and X-ray based potentially would have better results but integration and development are more complex. A more comprehensive review can be found in ASTM WK73289.

**Key**

X capability

Y difficulty

1 power meter/laser profiler

2 contact ultrasound (PA)

3 surface scanner

4 optical vision

5 IR/thermography

6 X-ray diffraction

7 laser ultrasound

8 X-ray

9 X-ray backscatter

10 X-ray CT

Figure 4 — Quadrant diagram of in-situ monitoring and inspection technologies relative capability vs difficulty to integrate/use

8 Standard selection structure for AM

Based on the review of the current standards, a new structure for NDT standards for AM is proposed as shown in [Figure 5](#). This structure is built on the current welding standards structure shown by the light boxes. The required development of new standards is shown by the dark boxes.

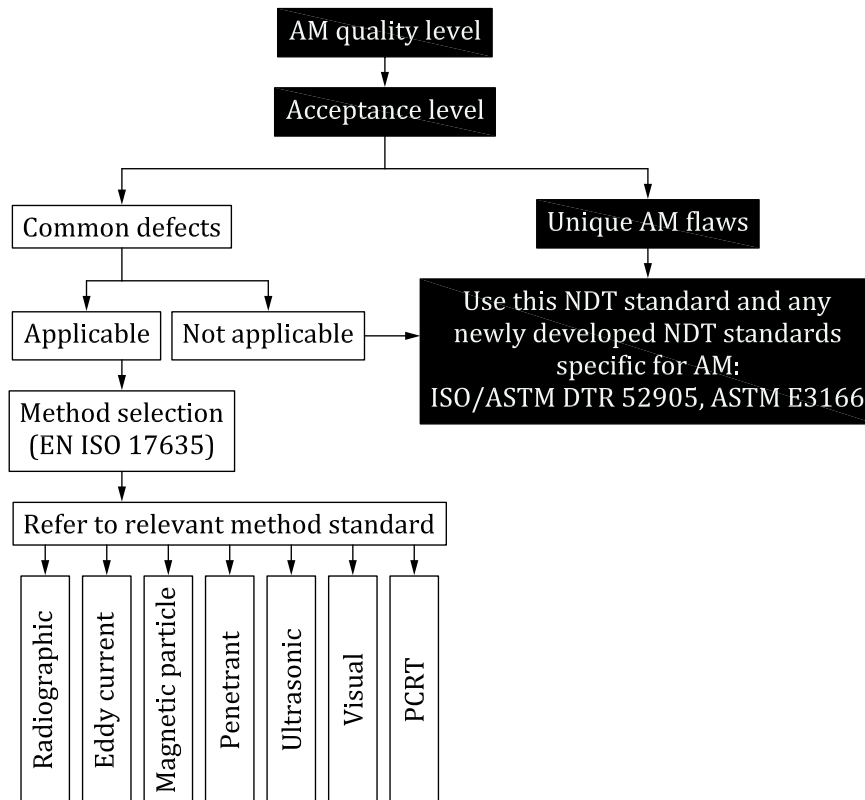


Figure 5 — Proposed NDT standards structure for additive manufacturing. The black boxes indicate development of new NDT standards for AM

9 NDT techniques potential for AM only defects

As discussed in [Clause 6](#), variation of AM process parameters and disruptions during build may induce a variety of defects (anomalies) in AM parts that can be detected, sized, and located by NDE^[32]. NDT is an essential aspect of a fitness-for-service assessment. The NDT technique(s) used for flaw evaluation can be chosen to provide the type of information required to an acceptable degree of accuracy. Such information can include some or all of the following items:

- NDT method;
- geometrical complexity;
- surface finish;
- flaw type.

A study to establish the potential detection capability of the NDE method for post-build and In-process for AM was developed in References [\[22\]](#) and [\[33\]](#). A selector tool has been created in order to demonstrate the capability of each NDT method for inspecting AM parts. This tool considers the micro and macro complexity of the part, and the potential defects of interest as listed in [Clause 6](#). The tool considers a range of component structures and surface finishes, ranging from simple machined blocks/cylinders to inspection of as built EBM (rougher) lattice components. [Figure 6](#) shows an example of the different part categories considered in the matrix of capabilities. From bottom to top the geometric complexity of the part increases, and from left to right the surface complexity increases.

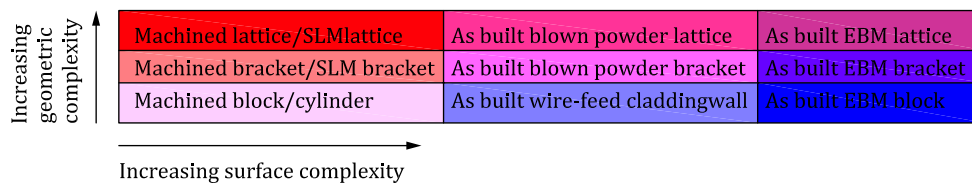


Figure 6 — Examples of different AM parts considered for the capability matrix (parts range from less complexity in the bottom left corner to more complex in the top right)

A matrix of capabilities was created which captures the abilities of each NDT technique for inspecting the various different component conditions. Each NDT method is given one of the following ratings:

- high capability;
- medium capability;
- low capability;
- no capability.

For each type of defect, the inspection method is given a score based on its capability for detecting that type of defect in each of the different build categories. Each build category is colour coded to facilitate simple identification.

The matrix of capabilities is used to populate the selector tool matrices and can be used for reference only. It is worth noting that there are very few NDT techniques that are capable of detecting microstructure variations and residual stresses. These defect types are not often encountered in the majority of NDT inspections, and this is reflected in the reduced range of applicable inspection methods for these defects.

The selector tool may be used as an initial indication to identify the most capable NDT method for inspection of each category of component. To use the selector tool the component under test can first be defined in terms of its geometric and surface complexity, based on the descriptions given in [Figure 6](#). Each category is represented by a number which is used as the input to the selector tool. For each different category the number and type of capable NDT methods vary and each method is given a representation of its inspection capability as is shown in [Figure 7](#).

High capability	H
Medium capability	M
Low capability	L
No capability	

Figure 7 — Capability indicator for the NDT technique shown in [Table 4](#) and [Table 5](#)

To demonstrate the functionality of the selector tool, two examples are given. The first concerns a simple machined block, a component with a simple geometry and surface finish. In this case the selector tool scenario input into the tool would be a 1, resulting in the selector tool output shown in [Table 4](#). The output of the selector tool indicates that the most appropriate NDT method for the majority of defects is ultrasonic contact or immersion, or inspection using Electromagnetic Acoustic Transducer ultrasound. However, the output also indicates that these methods would not be suitable for detection of defects such as near surface residual stress, which the tool indicates would only be detectable using X-ray diffraction.

The second example is at the other end of the spectrum, with a complex geometry and surface condition, such as an as built EBM lattice component, high level of roughness surface. In this case the entry into the selector tool scenario would be a 9, resulting in the output shown in [Table 5](#). With this complex type of component it is immediately apparent from [Table 5](#) that inspection is a more challenging proposition compared to the simple machined block presented in [Table 4](#). Here the most appropriate inspection

method is X-ray computed tomography for the majority of defects, however it does not have good capability for certain defects, such as surface breaking cracks or lack of fusion.

An additional tool has been developed for determining the most appropriate NDT methods for post-build inspection of metal cladding (DED) components. This selector tool operates in the same fashion as the AM tool, with the user entering a number corresponding to the scenario which best describes the component required to be inspected.

Table 4 — Review of NDT technique potential for AM parts. Post built NDE method potential for lowest surface roughness and least complexity geometry, e.g. machined block/cylinder (capability levels are H – High, M – Medium, L – Low and Empty – None)

Class	Type	Sub-type	Including...	Surface breaking cracks / lack-of-fusion	Surface breaking voids	Internal cracks / lack-of-fusion / layer defects	Isolated / clustered porosity	Internal voids, incl. cross-layer defects	Inclusions	Trapped powder (Powder Bed Fusion only)	Near surface micro-structure variation	Sub-surface micro-structure variation	Near surface residual stress	Sub-surface residual stress
Mechanical	Ultrasonic	Contact or near-contact (air-coupled)	Single / twin / array probe, Time of Flight Diffraction	H	H	H	H	H	H	H				
		Immersion		H	H	H	H	H	H	H				
	Vibration analysis	Resonance testing	Acoustic pattern recognition	M	M	L	L	M	M	M				
Optical / visible light	Simple		Aids such as lighting / borescope etc.	M	H					H				
	Dye-penetrant		Fluorescent / visible	H	H									
Radiographic	X-ray	Conventional, 2D	Film / Computed / Real-time / Digital	M	H	M	H	H	H	H				
		Computed Tomography	2D (fan beam) / 3D (cone beam) CT / Laminography	M	H	M	H	H	H	H				
		Diffraction									M		H	L
Thermal	Optically excited	Flash			L			L		M				
		Laser		H	M	L		L		M				
	Electrically excited		Induction-heated	H	H	L		L		M				
	Vibrationally excited		Thermosonics	H	L	H		M						
Electromagnetic	Eddy current		Single / array probe	H	M						H			
	Magnetic field	Magnetic particle		H	H									
		Barkhausen									M	M		
		Alternating Current Field Measurement		H	H									

Table 4 (continued)

Class	Type	Sub-type	Including...	Surface breaking cracks / lack-of-fusion	Surface breaking voids	Internal cracks / lack-of-fusion / layer defects	Isolated / clustered porosity	Internal voids, incl. cross-layer defects	Inclusions	Trapped powder (Powder Bed Fusion only)	Near surface micro-structure variation	Sub-surface micro-structure variation	Near surface residual stress	Sub-surface residual stress
Mixed	Electromagnetic-Mechanical	Electromagnetic Acoustic Transducer Ultrasound		H	H	H	H	H	H	H				
		Laser Ultrasound		H	H	M	L	M	L	L			H	M
	Optical-Mechanical	Spatially Resolved Acoustic Spectroscopy		H	H									
		Shearography	Electronic speckle pattern interferometry	H	H	M	L	M		M				
		Laser Speckle Photometry		L	L	L		L		L	M			
		Grazing Incidence Ultrasound Microscopy		M	M						H			

Table 5 — Review of NDT technique potential for AM parts. Post built NDE method potential for a complex lattice structure with as built surface finish (capability levels are H – High, M – Medium, L – Low and Empty – None)

Class	Type	Sub-type	Including...	Surface breaking cracks / lack-of-fusion	Surface breaking voids	Internal cracks / lack-of-fusion / layer defects	Isolated / clustered porosity	Internal voids, incl. cross-layer defects	Inclusions	Trapped powder (Powder Bed Fusion only)	Near surface micro-structure variation	Sub-surface micro-structure variation	Near surface residual stress	Sub-surface residual stress
Mechanical	Ultrasonic	Contact or near-contact (air-coupled)	Single / twin / array probe, Time of Flight Diffraction											
		Immersion												
Optical / visible light	Vibration analysis	Resonance testing	Acoustic pattern recognition	M	M	L	L	M	M	M				
	Simple		Aids such as lighting / borescope etc.		M					M				
Radiographic	Dye-penetrant		Fluorescent / visible											
	X-ray	Conventional, 2D	Film / Computed / Real-time / Digital		M		M	M	M	M				
		Computed Tomography	2D (fan beam) / 3D (cone beam) CT / Laminography	L	H	L	H	H	H	H				
Thermal	Optically excited	Diffraction												
		Flash						L		L				
	Electrically excited	Laser		L	L	L		L		L				
			Induction-heated											
Electromagnetic	Vibrationally excited		Thermosonics	M	L	M		L						
	Eddy current		Single / array probe											
	Magnetic field	Magnetic particle												
		Barkhausen												
		Alternating Current Field Measurement												

Table 5 (continued)

Class	Type	Sub-type	Including...	Surface breaking cracks / lack-of-fusion	Surface breaking voids	Internal cracks / lack-of-fusion / layer defects	Isolated / clustered porosity	Internal voids, incl. cross-layer defects	Inclusions	Trapped powder (Powder Bed Fusion only)	Near surface micro-structure variation	Sub-surface micro-structure variation	Near surface residual stress	Sub-surface residual stress
Mixed	Electromagnetic-Mechanical	Electromagnetic Acoustic Transducer Ultrasound												
				M	M			L	L				M	M
	Optical-Mechanical	Laser Ultrasound		L	L									
		Spatially Resolved Acoustic Spectroscopy		M	M			L						
		Shearography				L		L		L				
		Laser Speckle Photometry	Electronic speckle pattern interferometry	L	L	L		L		L				
		Grazing Incidence Ultrasound Microscopy												

While application of conventional NDE techniques is possible for AM parts with simple geometries, topology optimized AM parts with more complex geometries require specialized NDE techniques. Following References [22][25][27][33][34], the effect of design complexity on NDE method selection is summarized in Table 6.

Table 6 — AM design complexity groupings^[27]

Group	Design	Description
1	Simple parts	These parts are simple with well-established designs that do not capitalize on the advantages of AM. Such parts may already have consensus NDE inspection procedures.
2	Optimized standard parts	These parts are based on conventional designs, but some of the advantages of AM, such as lighter weight or fewer parts, are incorporated into the design.
3	Parts with embedded features	The added features add complexity to a part, thereby decreasing NDE inspectability. Access is limited to internal inspection surfaces.
4	Design-to-constraint parts	These parts appear to be free-formed without straight lines or parallel surfaces and have no analogue made by conventional subtractive techniques. The presence of detailed external and internal features greatly reduces NDE inspectability because the amount of inspection surface has increased and the vast majority of the structure is detailed and embedded.
5	Lattice structures	These parts consist of a free-form metallic lattices that have a high strength-to-weight ratios, increased surface areas, and tailored stiffness and damage tolerance. The structures pose the greatest challenge for existing NDE technologies, requiring the use of new or creative NDE techniques.

Table 7 lists industrial NDE procedures that are used to inspect AM parts. The ability of each technique to detect different types of defects, as well as to locate them in the interior or exterior surface of a part is listed. Finally, the NDE techniques are further characterized by the ability to globally screen or detect and locate a defect.

Table 7 — General inspection capabilities for selected conventional post-build NDE techniques for AM (adapted from ASTM E3166)

Method	Material and defect types detected	Surface or interior defect sensitivity	Global screening or detect location
CT, macro	In any solid material, any condition and/or defect affecting X-ray absorption, with the exception of reduced mechanical properties	Surface and subsurface, >200 µm resolution	Detects and images defect location; field of view dictated by detector size and distance between test article and imaging plane and x-ray source.
CT, microfocus	In any solid material, any condition and/or defect affecting X-ray absorption, with the exception of reduced mechanical properties	Surface and subsurface, typically 10 µm to 200 µm resolution for parts 10 mm to 200 mm thick	Detects and images defect location; field of view minimized, focal spot may be optimized for resolution at the expense of scan speed
CT, SX	In any solid material, any condition and/or defect affecting hard and soft X-ray absorption, with the exception of reduced mechanical properties	Surface, subsurface and bulk, usually 5 µm resolution for a field-view of 10 mm in 42 mm thick.	Detects and images defect location; field of view minimized, focal spot may be optimized for resolution at the expense of scan speed
Abbreviations used: CT = Computed Tomography, ET = Eddy Current Testing, VI = Visual Inspection, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, TT = Thermographic Testing, UT = Ultrasonic Testing, NI=Neutron Imaging, SX = Synchrotron X-Ray.			

Table 7 (continued)

Method	Material and defect types detected	Surface or interior defect sensitivity	Global screening or detect location
CT, NI	In any solid material, any condition and/or defect affecting Neutron, with the exception of reduced mechanical properties	Surface, subsurface and bulk, usually 10 µm resolution in 42 mm thick. In general it's the size of the field of view divided by 2000, all other elements being optimal.	Detects and images defect location; resolution affects the scanning time. Neutrons have higher penetration to most metals (<i>e.g.</i> , Aluminium, Titanium, Nickel) and are isotope sensitive (light elements).
ET	In electrically conducting and/or magnetic materials for local defects (for example, cracks) and distributed flaws (for example, porosity)	Surface and near subsurface	Detects and images location
VI	In any solid material, any condition and/or defect affecting visible, structured and laser light reflection	Surface	Detects and images location
PCRT	Any solid material. Any defect or condition	Surface and subsurface	Global screening
PT	Any solid material. Discontinuities — cracks, pores, nicks, others	Surface breaking	Detects and identifies location
RT	In any solid material, any condition and/or defect affecting X-ray absorption, with the exception of reduced mechanical properties	Surface and subsurface	Detects and images location but no depth information
TT	In any solid material, any condition and/or defect affecting heat conduction	Surface and subsurface	Detects and images location but limited penetration in metals
UT	In any solid material, any condition and/or defect affecting sound attenuation, propagation, acoustic velocity and/or sensor-part connexion	Surface and subsurface	Detects and identifies location

Abbreviations used: CT = Computed Tomography, ET = Eddy Current Testing, VI = Visual Inspection, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, TT = Thermographic Testing, UT = Ultrasonic Testing, NI=Neutron Imaging, SX = Synchrotron X-Ray.

Based on the analysis performed in the NDE methods, the potential approaches to be used in post-process inspection and in-process of AM components would be those presented in [Table 8](#).

Table 8 — NDT methods with the most potential for post-processing and in-process inspection for AM

Inspection type	NDT methods				
Post-process	X-ray	X-ray CT, Neutron CT	Thermography	UTPA & TFM	PCRT, RAM and NLA
In-process	Laser scan line	Optical imaging	Thermography	X-ray backscattered Digital X-ray	LUT

10 AM artefacts

The objective of the specimen is to cover the AM types of defects not covered by current NDT standards, and unique for the additive process such as layer, cross-layer and unconsolidated powder/trapped powder. Some of these defects (layer and cross-layer) are also being covered in ASTM E3166. A two-level approach is proposed. Firstly to use an extruded star geometry to provide initial image quality indicator (IQI) of AM seeded defects detectability using a specific NDT method, and may be used for relatively simple geometries. The second is an à la carte design with a particularly more representative geometry to the production part, where defects are seeded at geometrically or structurally critical places, required defect sizes and defect types.

10.1 Design

10.1.1 Star artefact

This specimen will be used to assess the detectability of identified AM typical layer defects, cross-layer defects, unconsolidated powder/trapped powder and inclusions. The seeding technique is one of the proposed methods in ISO/ASTM TR 52906, CAD seeding technique. The specimen has a cross-section of a 5 point star as shown in [Figure 8](#). The dimensions shown in the design are general guidance only. The dimensions of the artefact are dependent on several factors including the material, accelerating voltage (kV), and type of filter. The exact dimensions will be determined using XCT Standard: EN 16016-2. For example, using 450 kV, 500 μm Gadolinium oxysulphide scintillation screen and 3 mm Pb filter, XCT can achieve 10 % transmission on 80 mm of aluminium. This level of transmission can give an optimal signal-to-noise ratio in the CT image. In this case, the total material thickness of the artefact can not exceed 80 mm if the scan is rotated on the star axis. The red arrows in [Figure 8](#) indicated the thickness. Details of the preliminary star artefacts design and final design specifying seeded defects location and their distribution are presented in detail in [Annex C, Figure C.1](#) (Preliminary star-shape) and [Figure C.2](#) (Final star-shape).

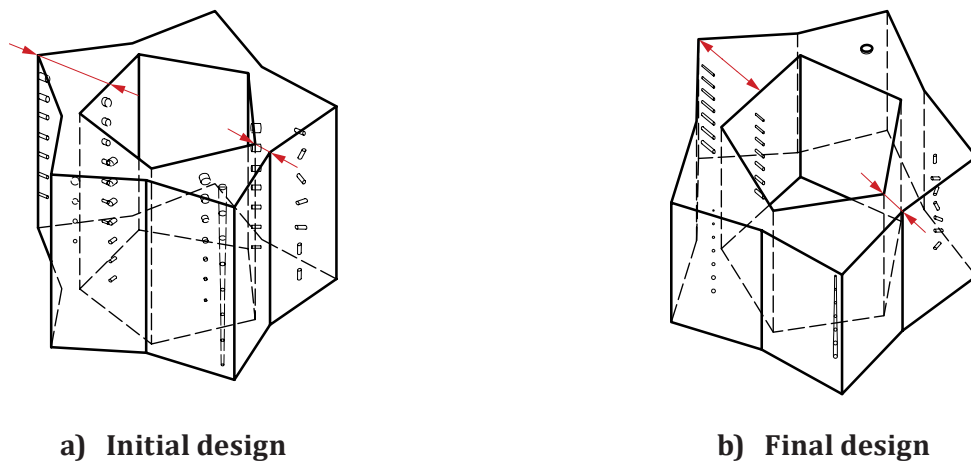


Figure 8 — Proposed specimen designs to assess the detectability of layer defects, cross-layer defects, unconsolidated powder and trapped powder (the red arrows indicated the maximum and minimum material thickness of the specimen)

For the preliminary star-shape artefact design labelled as SP, those stars have been seeded with artificial defects unique to AM process represented by cylinders and spheres. The sizes of the defects vary between 0,02 mm to 1,5 mm in diameter and 0,5 mm to 6,4 mm in length. Six titanium artefacts and four Inconel^{®1)} artefacts have been built. For titanium stars, four of them were built using the L-PBF process, and two of them were built using the EBM process. Two of the L-PBF built artefacts did not have artificial defects and were intended for reference.

1) Inconel is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

For the new star artefacts design proposed by MTC, the defect sizes vary between 0,1 mm to 0,7 mm in diameter and 2,0 mm to 5,0 mm in length. Three versions of star artefacts have been created based on the initial design showing in numeral 9.1 (size of seeded defects changed). The three design are:

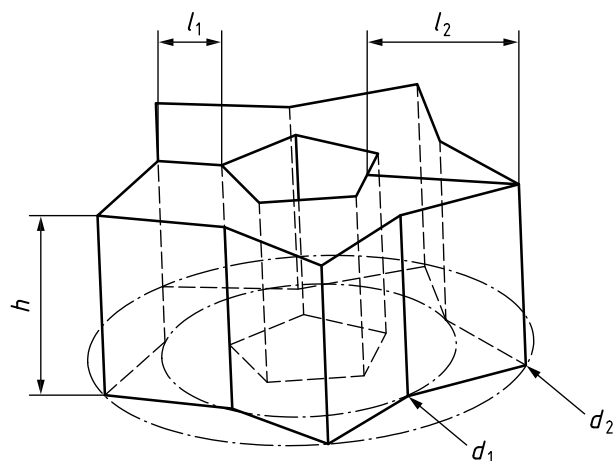
- Reference S0 — No nominal defects.
- Version S1: Defects are positioned close to the tip and on the surface of the internal pentagon, as first design but with the very small defects removed.
- Version S2: Same defects as S1 but positioned at the corner, away from the tip. This position has minimum material on.

The type of seeded defects and their dimensions assessed during the trials are summarised in [Table 9](#), for the preliminary design, while [Table 11](#) presents the values for the final design. Detailed information of the process, manufacturers and builds is specified in [Annex D, Table D.1](#).

Table 9 — Defects dimension and location for star artefact preliminary design 1 and design 2

Design	Description ^a	Diameter ^a ϕ_1 mm	Length l_1 mm	Total seeded defects Q_{ty} number
SP ^b	Region 1. Vertical cylinders inter-connected and open at both top and bottom.	0,02, 0,05, 0,1, 0,2, 0,5, 1,0 and 1,5	6,4	7
	Region 2. Cylinders in various orientations (Unconsolidated/trapped powder). Orientation offsets of 45° and 90° relative to the first instance	0,3	2,0	7
	Region 3. Reference section.	ND ^c	ND ^c	ND ^c
	Region 4. Horizontal cylinders open at the outside edge (Layer defects).	0,02, 0,05, 0,1, 0,2, 0,5, 1,0 and 1,5	2,0	7
	Region 5. Spheres (Voids/porosity, unconsolidated/trapped powder).	0,02, 0,05, 0,1, 0,2, 0,5, 1,0 and 1,5	2,0	7
	Region 6. Horizontal cylinders, open at the inside face (Layer defects).	0,02, 0,05, 0,1, 0,2, 0,5, 1,0 and 1,5	1,5	7
	Region 7. Horizontal cylinders open at the inside face (Layer defects).	0,02, 0,05, 0,1, 0,2, 0,5, 1,0 and 1,5	2,0	7
	Region 8. Reference section.	ND ^c	ND ^c	ND ^c
	Region 9. Horizontal cylinders, open at the inside face (Layer defects).	0,02, 0,05, 0,1, 0,2, 0,5, 1,0 and 1,5	0,5	7
	Region 10. Horizontal cylinders, open at the inside face (Layer defects).	00,02, 0,05, 0,1, 0,2, 0,5, 1,0 and 1,5	2,0	7
^a The defects order from TOP to BOTTOM are as follows: smaller defects is number 1 (20 µm) increasing to number 7 (1 500 µm). It is with the star face up where the reference holes are set. ^b SP abbreviation to indicate the star artefact correspond to the preliminary design ^c Abbreviation used: ND = Not defect				

To achieve the 10 % transmission of X-ray energy, the dimensions are modified based on material density. The overall star geometry is driven by two diameters that control the positions of the vertices on the outer star profile. The sketch views in [Figure 9](#) and [Figure 10](#) give a clearer indication of the diameters and pentagon dimension needed to achieve the desired wall thickness. The height of the star is kept constant. [Table 10](#) shows the dimensions of the star artefact build for the different materials tested here. The STL build files are available at the following ISO link: <https://standards.iso.org/iso/tr/52905/ed-1/en/>.



Key

- d_1 inner star diameter
- d_2 outer star diameter
- h height
- l_1 thin wall section
- l_2 thick wall section

Figure 9 — General sketch showing the main dimension of the start artefact to be achieved for 10 % transmission of X-ray accomplish based on material density

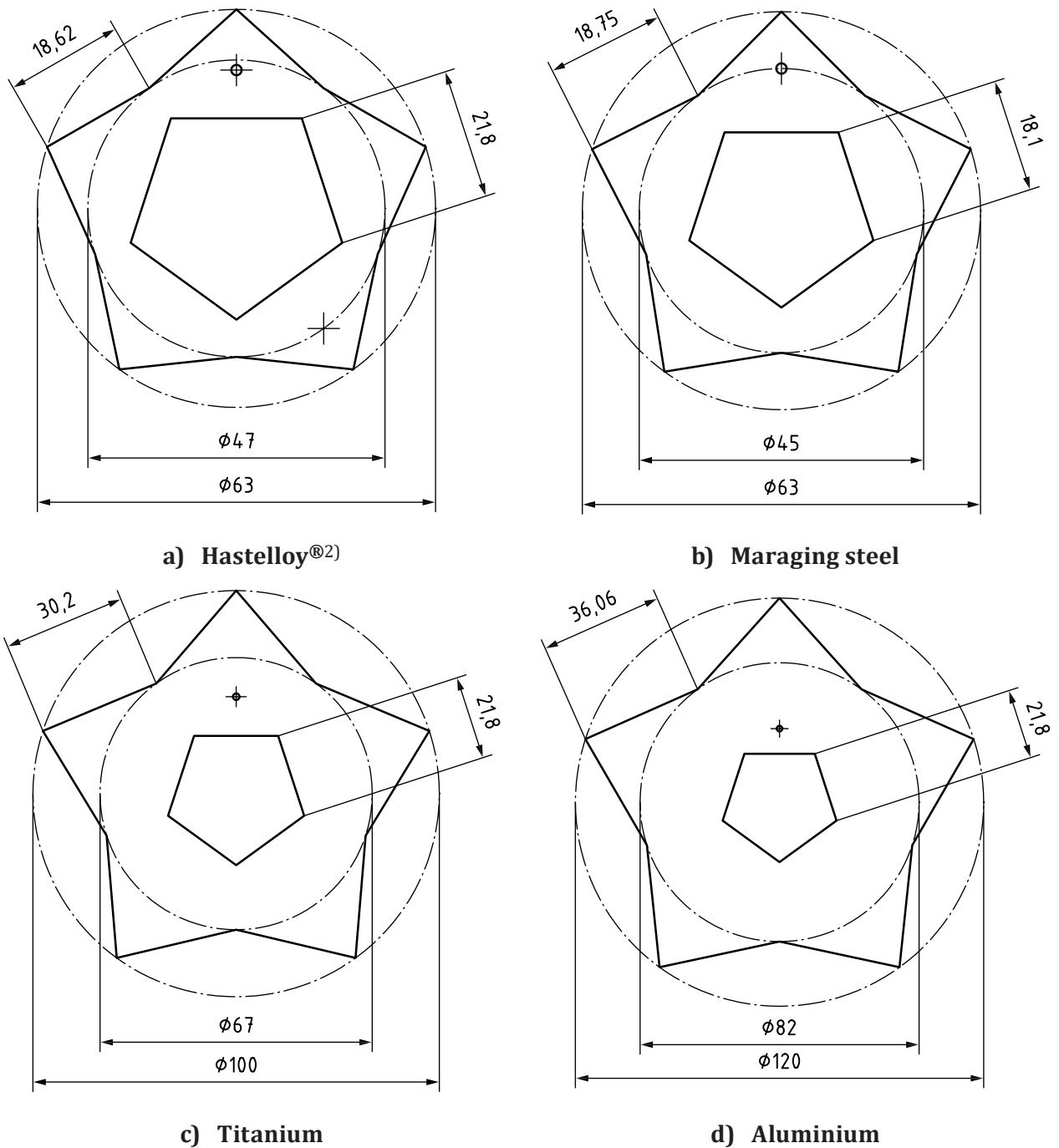


Figure 10 — Artefact material design comparison for the new star design

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Table 10 — Star artefact dimensions based on material density

Material	Density ^a ρ g/cm ³	Height ^b h_1 mm	Material group	Ideal scale factor	Actual scale factor	Ideal cumulative wall thickness mm	Cumulative wall thickness mm	Thin wall section l_1 mm	Thick wall section l_2 mm
Hastelloy®1)	8,89	45	Nickel	–	1	21,46	21,46	4,96	16,5
Inconel®2)	8,5	45	Nickel	0,96	1	20,52	21,46	4,96	16,5
Cobalt-Chromium	8,50	45	Nickel	1	1	21,46	21,46	4,96	16,5
Maraging steel	7,87	45	Iron	1,08	1,09	23,18	26,14	7,1	19,04
Stainless steel 17-4	7,8	45	Iron	1,09	1,09	23,39	26,14	7,1	19,04
Titanium CP	4,51	45	Titanium	1,88	1,92	40,45	39,96	4,96	35
Ti6Al4V	4,43	45	Titanium	1,92	1,92	41,18	39,96	4,96	35
Aluminium	2,80	45	Aluminium	3,04	3,04	65,15	67,46	45	22,46

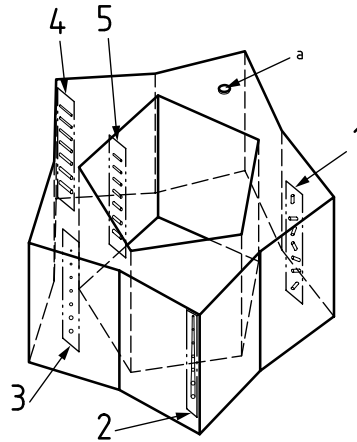
^a Density source (<https://www.matweb.com/search/MaterialGroupSearch.aspx>).

^b The height of the star artefacts for full size is constant.

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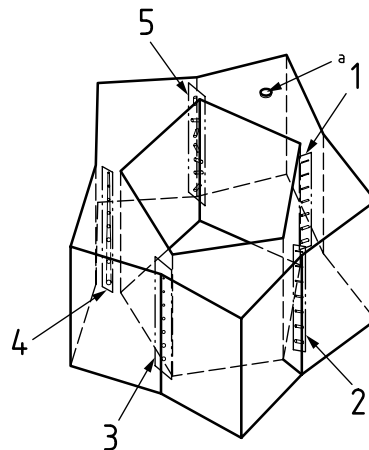
Inconel is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

[Figure 11](#) shows the defects on the tip sections of the star, which covers the region (1) to (5), while [Figure 12](#) shows the defects on the inner pentagon, which covers the region (1) to (5) too. However, noted the position of the seeded defects varied with design 1 shown in [Figure 11](#). [Table 11](#) show the dimensions of the defects seeded on the star artefacts.



NOTE Details of the defects on the tip sections are shown in region (1) to (5).

Figure 11 — Proposed specimen design 1 (S1) to assess the detectability of layer defects, cross-layer defects, unconsolidated powder and trapped powder



NOTE Details of the defects in the inner pentagon are shown in region (1) to (5).

Figure 12 — Proposed specimen design 2 (S2) to assess the detectability of layer defects, cross-layer defects, unconsolidated powder and trapped powder

Table 11 — Defects dimension and location for star artefact final design S1 and design S2

Design	Description ^a	Diameter ^a ϕ_1 mm	Length l_1 mm	Total seeded defects Q_{ty} number
S0	Reference star without defects	ND ^b	ND ^b	ND ^b

^a The defects order from TOP to BOTTOM are as follows: smaller defects is number 1 (0,1 mm) increasing to number 7 (0,7 mm). It is with the star face up where the reference holes are set.

^b Abbreviation used: ND = Not defect

Table 11 (continued)

Design	Description ^a	Diameter ^a ϕ_1 mm	Length l_1 mm	Total seeded defects Q_{ty} number
S1	Region 1. Cylinders in various orientations (Unconsolidated/trapped powder). Orientation offsets of 45° and 90° relative to the first instance.	0,3	2,0	7
	Region 2. Vertical cylinders interconnected and open at both top and bottom.	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,7	5,0	7
	Region 3. Spheres (Voids/porosity, unconsolidated/trapped powder).	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,70	–	7
	Region 4. Horizontal cylinders open at the outside edge (Layer defects).	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,7	2,5	7
	Region 5. Horizontal cylinders, open at the inside face of the pentagon (Layer defects).	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,7	2,0	7
S2	Region 1. Horizontal cylinders, open at the inside face of the pentagon (Layer defects).	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,7	2,0	7
	Region 2. Horizontal cylinders open at the outside edge (Layer defects).	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,7	2,5	7
	Region 3. Spheres (Voids/porosity, unconsolidated/trapped powder).	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,70	–	7
	Region 4. Vertical cylinders interconnected and open at both top and bottom.	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,7	5,0	7
	Region 5. Cylinders in various orientations (Unconsolidated/trapped powder). Orientation offsets of 45° and 90° relative to the first instance.	0,3	2,0	7
^a The defects order from TOP to BOTTOM are as follows: smaller defects is number 1 (0,1 mm) increasing to number 7 (0,7 mm). It is with the star face up where the reference holes are set. ^b Abbreviation used: ND = Not defect				

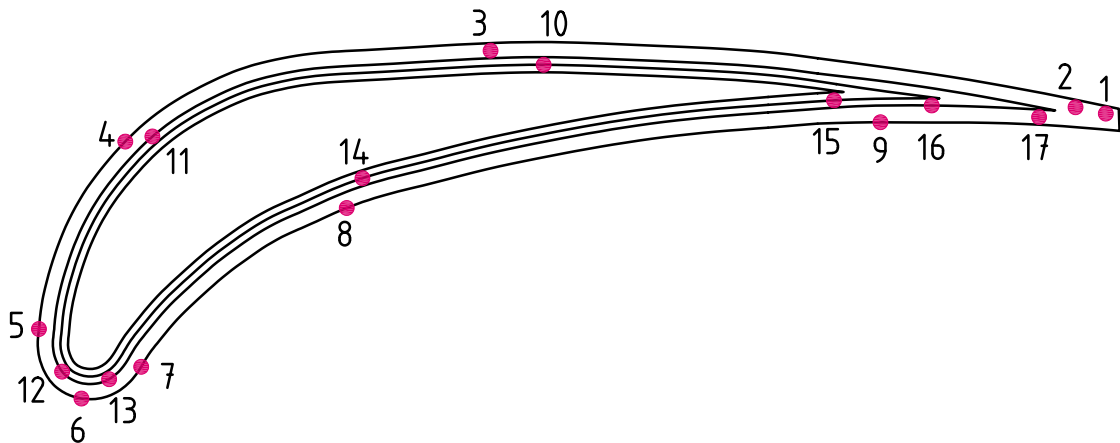
10.1.2 À la carte artefact

For cases where geometry is considerably more complex than the design in the previous section and further validate an NDT method, it is recommended to use an à la carte approach. In this case, the actual part geometry design is recommended to be built, inserting typical or expected defects at strategic locations such as critical places (geometrical/structural), deep sections, hard to reach sections, close to surface, surface regions and any other region required. Using the part geometry, the recommended steps to follow in the à la carte framework are:

- Identify structurally critical defect locations and sizes to be required for detection, ideally through modelling or mechanical test;
- Seed those defects to the part in the identified critical areas;
- Build the part which is now the NDE test/calibration artefact;
- Test the built calibration artefact with NDE methods (UT, XCT, resonance, any other novel NDE method that may have become available) to qualify it is capable for the part quality requirements.

Figure 13 shows an example based on à la carte generic airfoil geometry. CAD seeded cylinders with openings at the surfaces are located on various locations on the airfoil (shown by red circles), as examples of potentially critical regions and hard to detect by XCT. The primary focus of this is to determine the sensitivity of the XCT detection of the same defects (sizes and shapes) at various locations

on the airfoil. The STL build file for this geometry is also available at the following ISO link: <https://standards.iso.org/iso/tr/52905/ed-1/en/>.



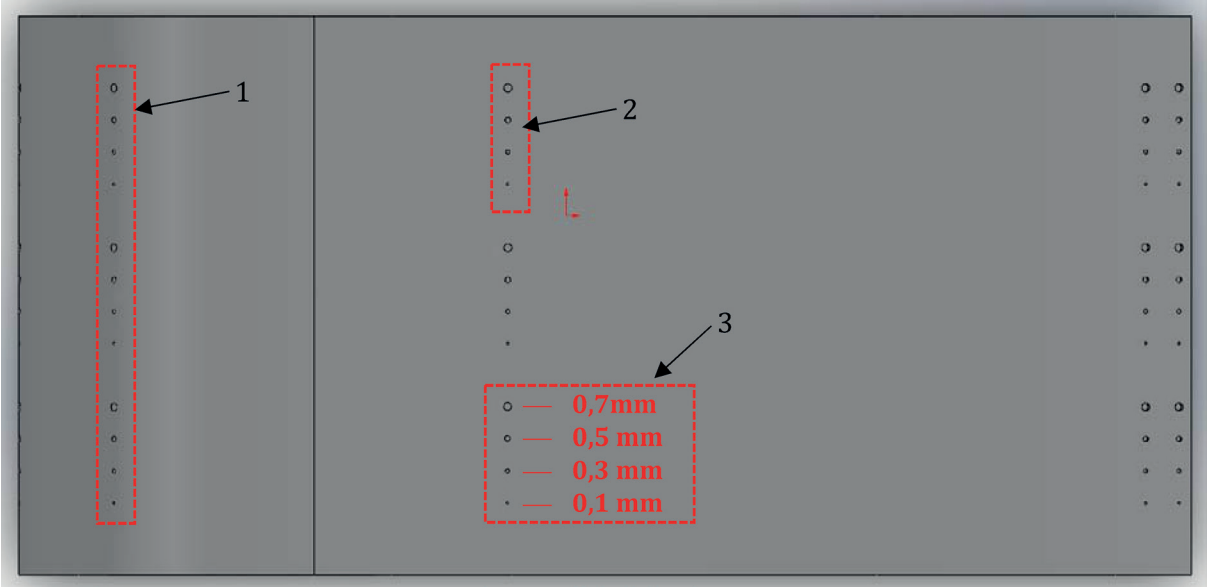
Key

- | | | |
|---|---------------------|--------------------------------------|
| 1 | holes set 1 to 5 | located at the external concave side |
| 2 | holes set 10 and 11 | located at the internal concave side |
| 3 | holes set 7 to 9 | located at the external convex side |
| 4 | holes set 14 to 17 | located at the internal convex side |
| 5 | hole set 6 | located at the external curve side |
| 6 | holes set 12 and 13 | located at the internal curve side |

NOTE Holes location are indicated by red diamonds.

Figure 13 — Generic airfoil geometry with critical defects locations inside and outside of the concave and convex side

The airfoil contains 17 sets of holes at various locations with each set containing three (3) clusters of holes. Each cluster has four holes with diameter of 0,1 mm, 0,3 mm, 0,5 mm and 0,7 mm as is shown in [Figure 14](#). The depth of each holes is the same as the diameter, however, the material thickness varies depending on the location on the airfoil. The holes were designed in this way in order to have sensitivity relative to location, such that defects of the same size will give contrast at different locations. This is summarised on [Table 12](#) based on [Figure 13](#) layout.



- Key**
- 1 sets of holes containing 3 cluster
 - 2 number of holes per cluster
 - 3 holes dimensions per cluster

Figure 14 — Top view of the CAD model showing an example of the rows, sets and dimensions of the holes in the airfoil

Table 12 — Dimensions of the seeded defects in the à la carte design of the generic airfoils

Region	Side	Number of sets ^a	Holes ^b <i>d</i> ₁ mm
1	Concave outside	5	0,1, 0,3, 0,5 and 0,7
2	Concave inside	2	0,1, 0,3, 0,5 and 0,7
3	Convex outside	3	0,1, 0,3, 0,5 and 0,7
4	Convex inside	4	0,1, 0,3, 0,5 and 0,7
5	Curve outside	1	0,1, 0,3, 0,5 and 0,7
6	Curve inside	2	0,1, 0,3, 0,5 and 0,7

^a Total number of sets 17.

^b Total number of holes 204.

10.2 Manufacturing

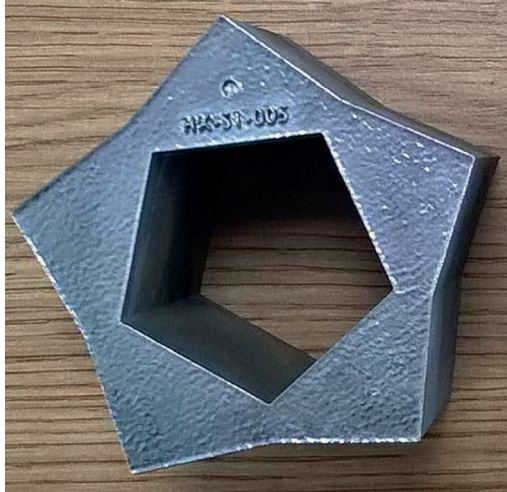
10.2.1 Star artefact

The goal of the star artefacts is to represent the defects/flaws unique to additive manufacturing represented by seeded geometries to replicate them as follows:

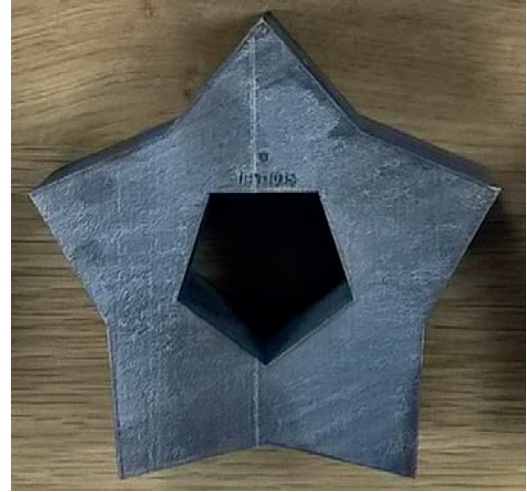
- Cross-layer defects: Vertical cylinders of different diameter but the same length. Those are connected by a small link to release powder at the largest diameter.
- Layer defects: Horizontal cylinders of different diameters but the same length. Open end to release powder.

- Unconsolidated/trapped powder: Internal spheres of different diameter and cylinders in various orientation with the same length and diameter.

The defects are located in critical areas or locations at a different depth to ensure they are representative of flaws that can be generated during the AM process. [Figure 15](#) shows examples of the star artefact builds for Hastelloy^{®3)} and Titanium.



a) Hastelloy[®]



b) Titanium

NOTE Sample star design S1 showing size difference due to diameter variation to achieve 10 % transmission X-ray energy.

Figure 15 — Hastelloy[®] and titanium star artefact build using EOS system

The star artefacts built during this study are summarised as followed:

10.2.2 À la carte artefact

In this section, a build example is shown in [Figure 16](#) for an à la carte specimen made from Inconel^{®4)} by GE power. The selected geometry was a generic air foil seeded with defects which were selected in regions of interest as presented in [10.1.2](#).

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4) Inconel is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

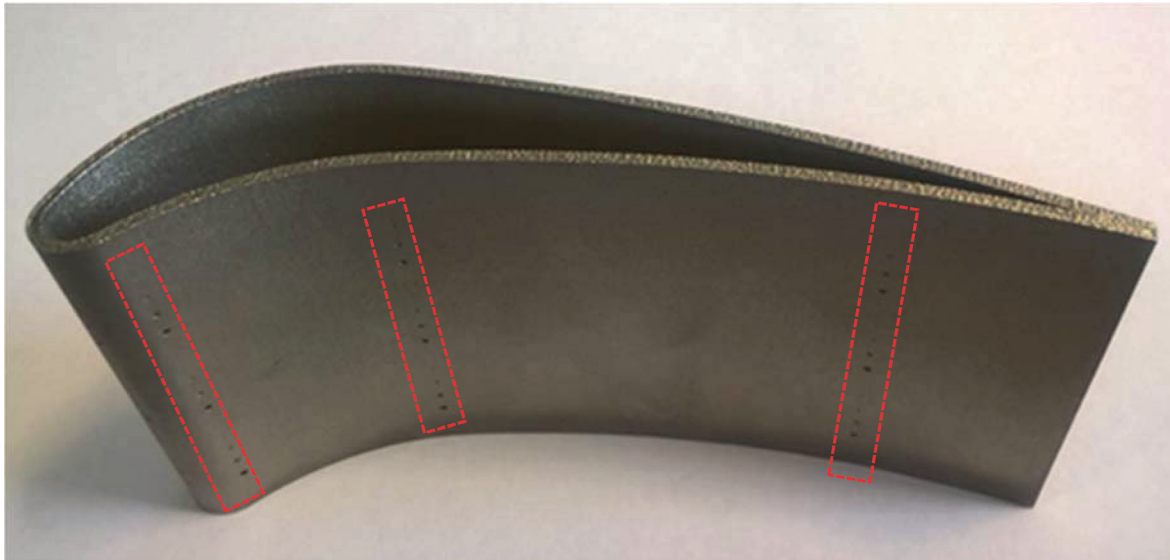


Figure 16 — Generic airfoils build as à la carte design provided by GE power (red rectangles show simulated defects manufactured by PBF)

11 NDT method trials and validation using star artefact

Following the review from [Clause 9](#) for NDT approaches, the methods with the most potential for AM were selected. Trials of these methods will be presented in this clause, which can include material extracted from collaborators' reports including background, experimental, results and analysis.

11.1 Experimental trials

The experimental trials in this section compile the main information of the test as well as main outcomes from the analysis performed in the star artefacts built (S0, S1 and S2 design) using different alloys such as Inconel®, Hastelloy®, Maraging steel, stainless steel, titanium, cobalt-chrome and Aluminium alloys. Details of the star artefact manufactured, NDT technologies and collaborators are presented in [Table D.1](#) and [Table D.2](#). Some of the findings reported are based on trials performed on the preliminary star designs while others were on new star versions.

The scope of the trials is to assess the capability of detection of the NDT technique involved. These trials are giving information on the presence of the defect rather than sizing them. If dimensions of the seeded defects are measured, it is considered as an additional information or capability of the technique used. Seven NDT techniques were involved in the trials carried out as follows:

- x-ray computed tomography (XCT);
- neutron Imaging (NI);
- synchrotron radiography;
- synchrotron CT;
- neutron CT;
- thermography;
- process compensated resonance testing (PCRT);
- non-linear resonance testing (NLR);
- conventional ultrasonic testing (CUT);

- pulse-echo ultrasonic testing (PE);
- phase array ultrasonic (PAUT);
- phase array ultrasonic and full matrix capture/total focus method (FMC/TFM);
- neutron diffraction (ND).

11.1.1 X-ray Computed Tomography – XCT (MTC & GE & EWI)

X-ray computed tomography (XCT) is one of the most common Nondestructive evaluation (NDE) techniques for additive manufacturing parts. XCT technique can produce 2D (fan beam) and 3D (Cone beam) cross-sectional images of an object from flat X-ray images. X-ray computed tomography consists of probing a test part with X-ray at different angular positions of the part, recording the interactions of these waves with the test part for each angle independently, and post-processing these data with a reconstruction algorithm to give a volumetric image.

All trials have used the 3D XCT method. Characteristic of the internal structure of an object imaging is visualised through a process known as reconstruction. Object dimensions and shape, internal defects and density are the typical information obtained by XCT.

11.1.1.1 Summary of procedure

The general procedure for the XCT inspection includes the following steps:

- Position of the star artefact on the table oriented on the X-axis and sample faced up with the reference point.
- Scan of the star artefact.
- Reconstruct the star artefact rotational image.
- Analyse XCT data to determine seeded defects detected.
- Obtain XCT images of the area of interest to link it with the nominal CAD.
- Report.

For the XCT scan trials, three systems have been used, belonging to EWI, GE and MTC. The material used by EWI was Stainless Steel, Cobalt-Chrome, while GE and MTC used Inconel^{®5)}, Hastelloy^{®6)}, Maraging steel, and Ti6Al4V. A summary of the samples built is presented in [Table 13](#).

11.1.1.2 Apparatus/settings

The XCT systems used for GE, MTC and EWI were 450 kV systems. The systems used an X-ray generator as a radiation source. The parameters used for each system for the inspection are shown in [Table E.1](#) and [Table E.2](#), while the set up used by MTC and GE is shown in [Figure E.1](#) and [Figure E.2](#).

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6) Hastelloy is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

Table 13 — Summary of the star artefacts version used during the XCT trials

Material	Version S0	Version S1	Version S2
Hastelloy® (HX) ^{b,c}	HX-S0-001 to HX-S0-005	HX-S1-001 to HX-S1-005	HX-S2-001 to HX-S2-005
Maraging steel (MS) ^{b,c}	MS-S0-001 to MS-S0-005	MS-S1-001 to MS-S1-005	MS-S2-001 to MS-S2-006
Stainless Steel (SS)	NT ^d	SS-S1-001	SS-S2-001
Cobalt-Chrome (CoCr)	NT ^d	NT ^d	CoCr755-S2-001
Inconel® ^a (IN)	NT ^d	IN-S1-300A	IN-S2-300A
Ti6Al4V ^a	NT ^d	S _{LB} -001 ^f	S _{EB} -001 ^e
^a The star artefact correspond to the preliminary design. ^b Nikon XT H 450 kV system reflection target. System located in the UK. ^c Nikon XT H 450 kV system reflection target. System located in Germany. ^d NT = Not tested. ^e S _{EB} : Star artefact manufactured by EB-PBF process. ^f S _{LB} : Star artefact manufactured by L-PBF process.			

11.1.1.3 Significance of data/interpretation of results

The results of the XCT trials performed by GE and MTC for the preliminary star artefacts version are summarised in [Table 14](#). Examples of the XCT image scan are also shown in [Annex E](#).

The XCT results showed that the EBM artefact was successful in creating all the artificial defects. The smallest unconsolidated powder or trapped powder detected was between 0,3 mm to 0,5 mm in diameter. The smallest layer defect detected was between 0,2 mm to 0,5 mm in diameter. The smallest cross-layer defect detected was 0,05 mm in diameter.

The XCT results for the preliminary star artefacts designed by MTC (SP) did not show any indication of unconsolidated powder or trapped powder (see [Figure C.1](#)). It is not clear whether this is due to the XCT detection limit or the limit of L-PBF built. Therefore, validation is required through cut-ups and observation under the microscope. The SP artefacts were successful in creating layer and cross-layer defects. The XCT results showed the smallest defects detected was between 0,3 mm to 0,5 mm in diameter. In addition, the data also revealed some indications of defects that were not designed in the artefact.

Table 14 — Summary of the smallest defects detected in the star artefact built in Inconel®⁷⁾ and Ti6Al4V alloys by XCT scan

Defects dimensions in millimetres

Design ^a	Defect region	MTC		GE	
		Inconel 300A	Ti6Al4V	Inconel 300A	Ti6Al4V
SP	1	0,5	0,02	0,2	TBU ^c
	2	ND ^b	All detected	ND ^b	TBU ^c
	3	Reference	Reference	Reference	TBU ^c
	4	0,5	0,5	0,2	TBU ^c
	5	ND ^b	0,5	ND ^b	TBU ^c
	6	0,5	0,5	0,2	TBU ^c
	7	0,5	0,5	0,2	TBU ^c
	8	Reference	Reference	Reference	TBU ^c
	9	0,5	0,5	0,2	TBU ^c
	10	0,5	0,2	0,2	TBU ^c
^a The CAD file of the star artefact corresponds to the preliminary version design by MTC. ^b ND = Not detected. ^c TBU = To be updated.					

For the inspection with the new version of the stars (S0, S1 and S2) a summary of the findings is presented in [Table 15](#) and [Table 16](#). The smallest defect per region is given, however, details of individual outcomes are included in [Table E.1](#) to [Table E.9](#) and [Figure E.3](#) to [Figure E.11](#), [E.3](#), numeral 2.

Table 15 — Summary of the smallest defects detected in the final star artefact design by XCT scan in Stainless Steel and CoCr

Defect dimensions in millimetres

Design ^a	Defect region	EWI ^b	GE ^b
		Stainless steel ^b	CoCr755
S0	All	NT ^d	NT ^d
S1	1	All detected	NT ^d
	2	0,1	NT ^d
	3	0,4	NT ^d
	4	0,2	NT ^d
	5	0,3	NT ^d
S2	1	0,2	0,3
	2	0,2	0,3
	3	0,3	0,5
	4	0,1	0,3
	5	All detected	All detected except horizontal (tangential)
^a The CAD file of the star artefact correspond to the new design version S0, S1 and S2 supplied by MTC. ^b The analysis was performed in one sample per each design. ^c ND = Not detected. ^d NT = Not tested.			

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Table 16 — Summary of the smallest defects detected in the final star artefact design by XCT scan in Hastelloy^{®8)} and Maraging materials

Defect dimensions in millimetres

Design ^a	Defect re- gion	GE-UK ^b			MTC ^c	
		Hastelloy ^{®d}	Hastelloy ^{®b}	Maraging steel ^b	Hastelloy ^{®c}	Maraging steel ^c
S0	All		ND ^e	ND ^e	ND ^e	ND ^e
S1	1	NT ^f	All detected	All detected	All detected in 4 stars and 6 in two stars	All detected in 5 stars and 6 in one star
	2	NT ^f	0,1	0,1	0,1	0,2
	3	NT ^f	0,4	0,3	0,4	0,5
	4	NT ^f	0,3	0,3	0,1	0,2
	5	NT ^f	0,3	0,2	0,1	0,2
S2	1	0,3	0,3	0,2	0,1	0,1
	2	0,3	0,3	0,2	0,3	0,1
	3	0,3	0,3	0,3	0,1	0,3
	4	0,1	0,3	0,3	0,1	0,1
	5	All detected	All detected	All detected	All detected in 2 stars and 6 in three stars	All detected in 1 star and 6 in four stars
^a The CAD file of the star artefact correspond to the new design version S0, S1 and S2 supplied by MTC. ^b The analysis was performed in one sample per each design. ^c The analysis was performed in 6 Hastelloy [®] stars (design S1) and 5 stars (design S2). The nominal features diameter size reported correspond to the average of the diameter detected using the set sample per each design. ^d Test carry out using the DYN 41 detector -100 in one sample. ^e ND = Not detected. ^f NT = Not tested.						

11.1.1.4 Comments/observations

The XCT analysis performed on the Hastelloy^{®9)} X, Maraging steel and stainless steel star artefacts design S1 and design S2 clearly showed that the observable defects on the three materials are very similar. Although EWI attempted to use similar parameters used from previous imaging experiments carried out at the MTC, since the Nikon 450 kV systems were the same, the results achieved are slightly different in contrast, resolution and accuracy.

EWI found that challenges with scattering resulted in the detectability being rather limited for the spheres with trapped powder (0,3 mm to 0,4 mm). Also, after several attempts at imaging the star face-up, tilted, and face-on, it was determined that imaging the star face on resulted in the least amount of scattering and beam hardening, thus producing the best results. Therefore, it would be recommended that pursuing CT imaging of these stars would also perform the imaging face-on.

The XCT scan carried out by GE using the Dynamic 41 100 um detector was not used to increase nominal resolution by a factor of two, but to enable sharper imaging at a lower magnification and only a more marginal increase in nominal resolution. Detectability is not dependent only on nominal resolution but a combination of factors. It was found that the quality of the image is enhancing substantially and increasing resolution capability.

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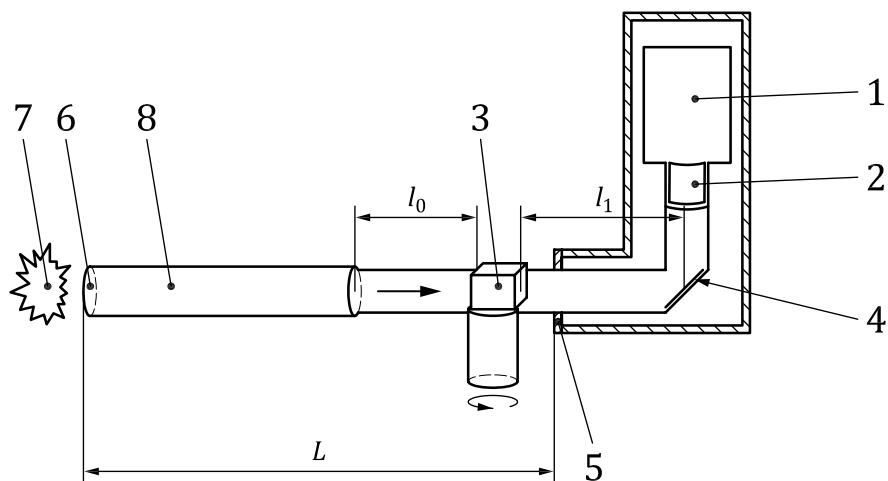
11.1.2 Neutron Imaging — NI and Synchrotron radiation — SX (HZB & ESRF)

The ability of neutrons to penetrate easily through materials such as steel and titanium, revealing interior details of engineering components such as coolants channels or verifying the absence of defects such as cracks or pores made NI a unique and valuable tool. At the same time, the advent of synchrotrons enabling focalised high-energy x-rays has revolutionized tomographic methods, pushing boundaries of spatial and temporal resolution to the nanometre and microsecond.

Neutron imaging is complementary to X-ray imaging. Whereas x-rays are scattered and absorbed by the electron of an atom, neutrons interact with the atom nuclei. Therefore, some features easily visible with neutron imaging can be very challenging or impossible to be detected with X-ray imaging. Neutrons have more sensitivity than X-ray to light elements and their degree of attenuation depends on the neutron energy. For metals, a strong energy dependency of the attenuation is observed due to Bragg scattering from the crystal lattice. Even though, it is mentioned that X-ray resolution is better than neutron method it is highly dependent on the system used and on the material, for example, new neutron imaging instruments combined with high flux sources, the resolution achieved is at the same scale (50 μm). However, a particular advantage of neutron imaging is the high penetration depth, allowing to inspect large samples with a medium resolution, which X-ray cannot do^{[35][36]}.

As with radiography, visualisation of the sample in three-dimensions is available by neutron imaging. For the tomography technique, the resultant digital projectional radiographs taken at defined rotational steps of the sample are reconstructed using algorithms similar to those used for classical X-ray computed tomography, taking into account specific beam geometry characteristics. The concept of Neutron Imaging (NI) is shown in Figure 17, but the basic set-up is very similar to that used by X-ray synchrotron radiation (SX) source. Neutron transmission through the sample leaves a neutron imprint on the scintillator screen which transforms it into photons. A mirror downstream of the scintillator reflects these photons towards a camera (CDD or sCMOS for example) placed at 90° which transforms the photons into an ensemble of digital grey scale signals (the camera is protected from the primary beam to ensure its lifetime). The whole or only the optical part is placed in a black box (enclosure sealed to light).

The resultant digital projectional radiographs taken at defined rotational steps of the sample are then reconstructed using algorithms similar to those used for classical x-ray computed tomography, taken into account specific beam geometry characteristics.



Key

- | | |
|---------------------------|--|
| 1 camera CCD/CMOS | 7 radiation source |
| 2 lens | 8 collimator |
| 3 sample of thickness X | l_0 distance collimator to sample |
| 4 mirror | l distance sample to detector |
| 5 scintillator | L distance aperture source to the detector |

Figure 17 — Sketch showing the basics of neutron imaging (adapted from Reference [35])

Figure 17 also gives the general transmission law for photons and neutrons through the material, known as the Beer-Lambert Law. X-ray interacts with an atom's electron clouds and the probability of interaction, given by the attenuation coefficient (or the mass attenuation coefficient) is directly proportional to the element's mass number. Of course, high energy x-rays (250 keV) such as those used on ID19 have a far higher penetration than XCT laboratory machines. For neutrons, the interactions are also energy-dependent (a rule of thumb being that their absorption cross-section is inversely proportional to their speed) and can take several forms but in general absorption and scattering by the atom's nucleus are predominant. Unlike x-rays, there is no direct dependence on mass number. Therefore, the interaction of x-rays and neutrons with the material is different and complementary. For example, in transmission (radiography), light elements like H, Li, B and C absorb neutrons more readily than x-rays, and the reverse is true for heavy elements (for example metals like Fe, Al, Cu and W — with the notable exception of Gd). In addition, the neutron absorption cross-section isotopically varies for some elements, for example, $1\text{H}/2\text{H}$ or $3\text{He}/4\text{He}$, which is not the case with x-rays.

11.1.2.1 Summary of procedure

One Cobalt-Chrome star version S2 (LNE & NIST) and two Ti6Al4V samples labelled as $S1_{\text{EBM}}$ and $S1_{\text{SLM}}$ were tested (MTC). Details of the samples can be found in [Annex D, Table D.1](#), while a sample and drawing are shown in [Figure F.1](#) and [Figure F.2, Annex F](#). Samples were positioned face up and the beamline was aligned with the X-axis of the sample. Titanium star S_{EB} and S_{LB} were scanned using cold neutrons and Synchrotron radiation, while CoCr star was inspected only using monochromatic SX. A CCD camera recorded the XCT projections and those were acquired for 3D reconstruction using a mathematical algorithm. Details of the parameters used for the NI and SX test can be found in [Table F.1](#), while the set up for NI test are shown in [Figure F.3](#), and [Figure F.4, Annex F](#). $S1_{\text{SLM}}$ sample was manufactured by L-PBF while $S1_{\text{EBM}}$ was build built using L-EBM as is shown in [Figure F.5](#) and [Figure F.6, Annex F](#).

11.1.2.2 Apparatus

For these tests, the neutron scans were led by ILL and carried out at the Helmholtz Zentrum Berlin (HZB) by beam time exchange policy (https://www.helmholtz-berlin.de/forschung/oe/ce/materialforschung/methoden/n-tomo_en.html), while the synchrotron test was performed at the European Synchrotron Research Facility (ESRF), <http://www.esrf.eu/>. The HZB institute has a cold neutron energy spectrum, whereas the ESRF owned the state-of-the-art micro-tomography instrument ID19.

11.1.2.3 Significance of data/interpretation of results

The results of the neutron and synchrotron test are discussed in this subclause. For the reconstructed 3D images of the titanium stars, the analysis covered first the quality of the imaging results, followed by the capability to detect the seeded defects in the region of interest (ROIs), followed by other defects noted – cracks and porosities-, and finally geometrical comparison with the 3D CAD drawing. For the CoCr star-shape, the analysis covered only the seeded geometries for the star artefact design S2 on the ROI. Comprehensive results of the analysis carried out on the titanium samples are presented from [Figure 18](#) to [Figure 22](#), while [Figure 23](#) to [Figure 24](#) show the findings for the CoCr star artefacts.

The relative quality of images is due to various parameters such as beam-hardening caused by sample geometry and thickness, along with those inherent in the use of these imaging techniques (e.g. light diffusion from neutron or X-ray/photo conversion scintillators), both sets of data underwent correction/optimisation processing to minimize artefacts. This procedure is normal and is applied to most data sets to enhance image clarity. It is clear from the images that those obtained from ID19 are superior in quality — both in resolution and in signal quality. This is due to three main imaging parameters already mentioned: the number of projections through 360° (for best spatial voxel resolution in a tomography