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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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Contents

Page

Foreword

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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 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 elected 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 hopefully aid the drive for quality improvement required for widespread implementation of the technology.

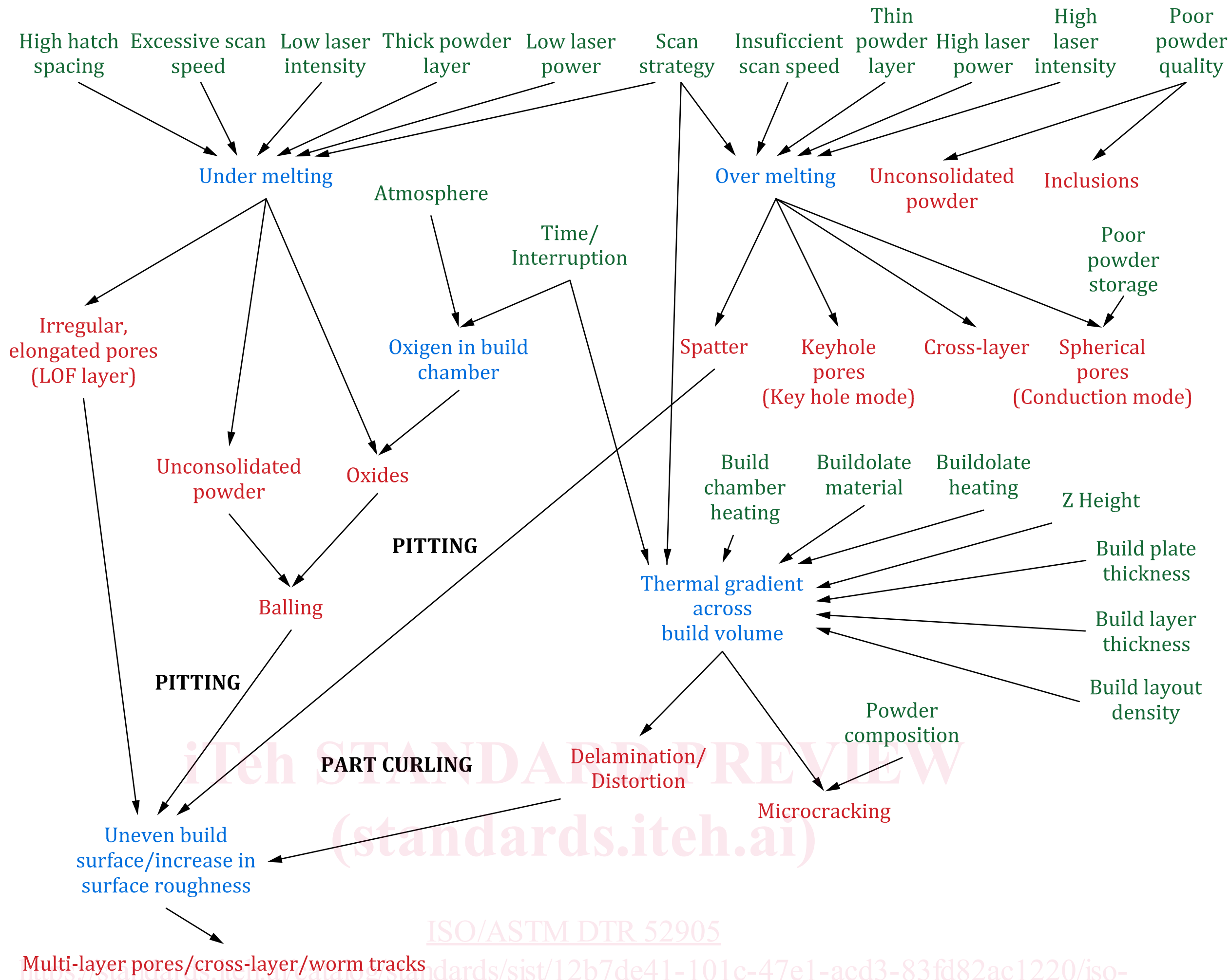
The flowchart displayed in Figure 1 gives an idea of the complexity of flaw generation within the PBF process. As can be seen, the generation of one flaw type can result in an anomalous processing condition, which in turn generates a second flaw. For example, the presence of a thick layer or low laser (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.



Key

machine: inputs/choices

AM part: resulting defect/flaw

process: resulting condition

common type of failure

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

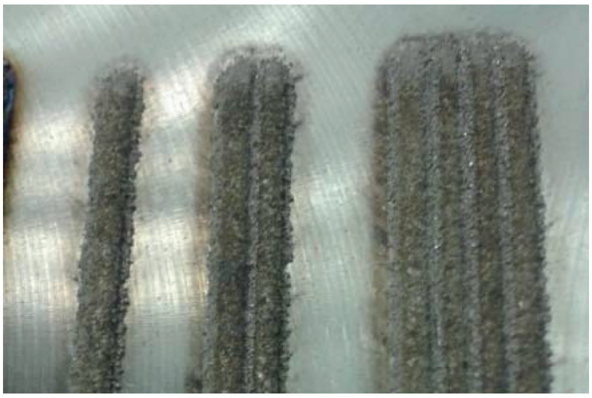
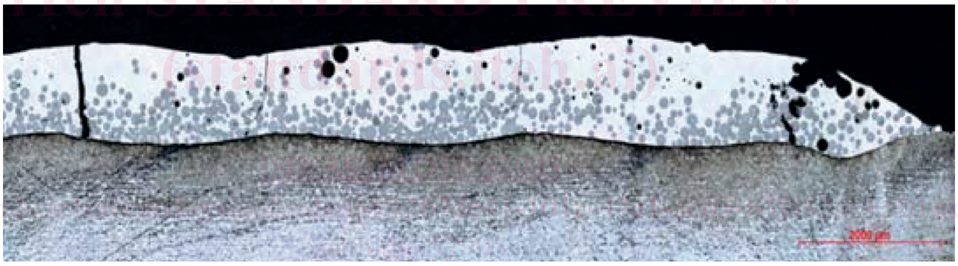
Flaw type	Description
Poor surface finish	The surface roughness on the part does not meet the target specification for the part. Measurement of the surface roughness is considered out-of-scope for NDT however, visual examination can be included. 
Porosity	Typically spherical in shape and contains gas. 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)*

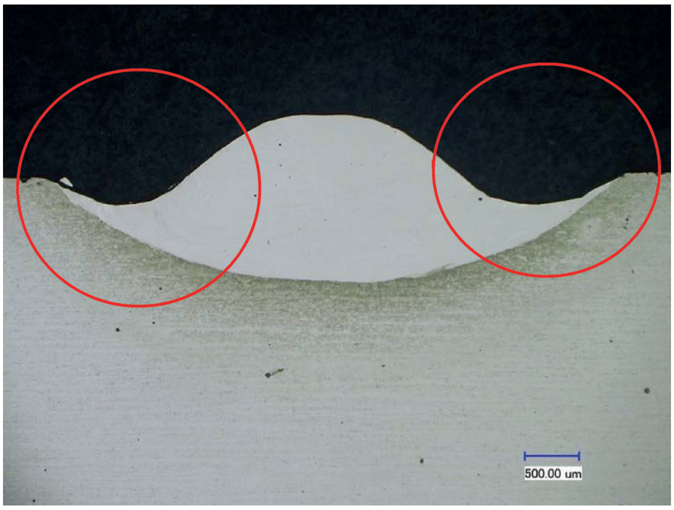
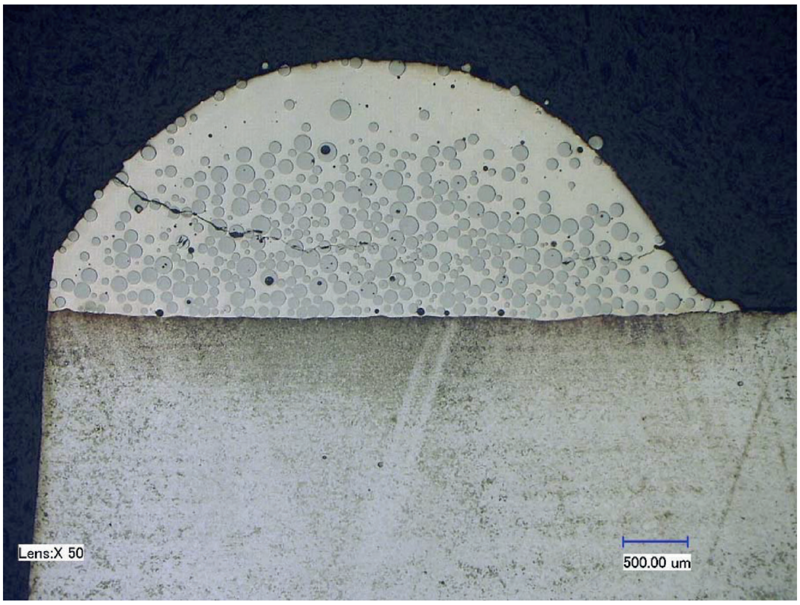
Flaw type	Description
Non-uniform weld bead and fusion characteristic	 These indicate errors in the process which can risk integrity of the build. Internal flaws caused by this can be void, porosity, or incomplete fusion.
Hole or void	Typically occurs internally in the built part as shown in the micrograph 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

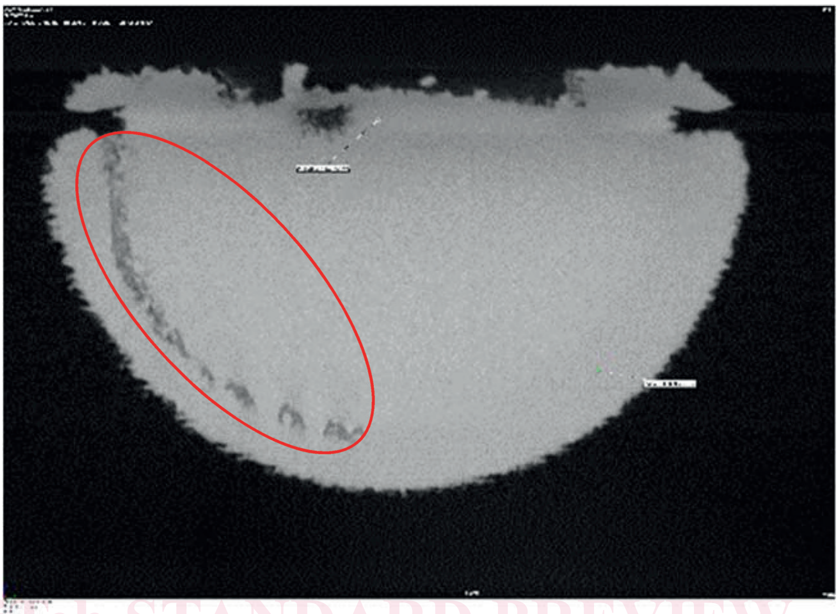
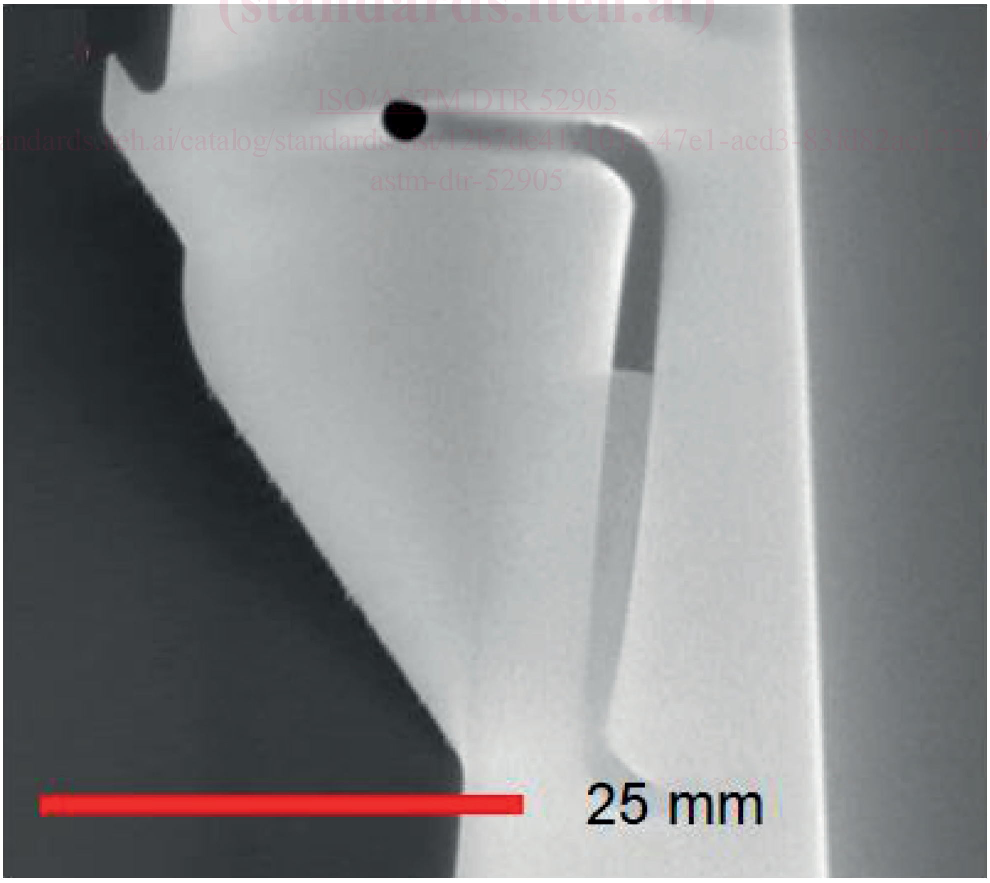
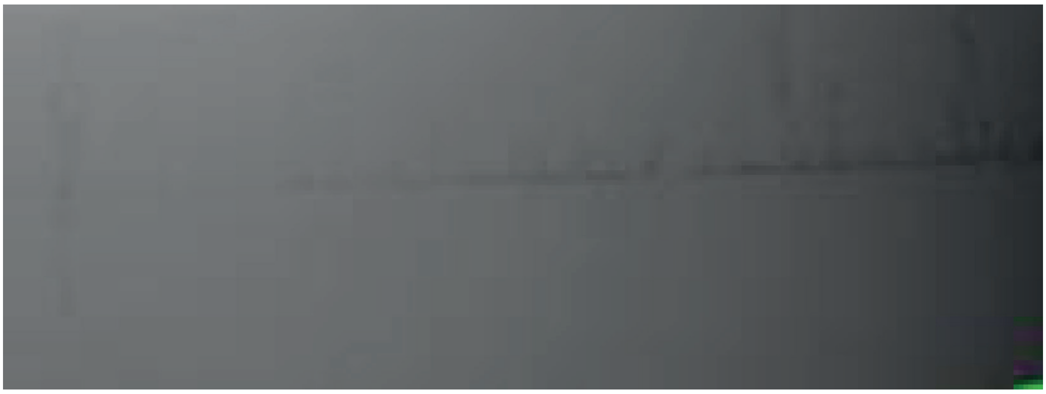
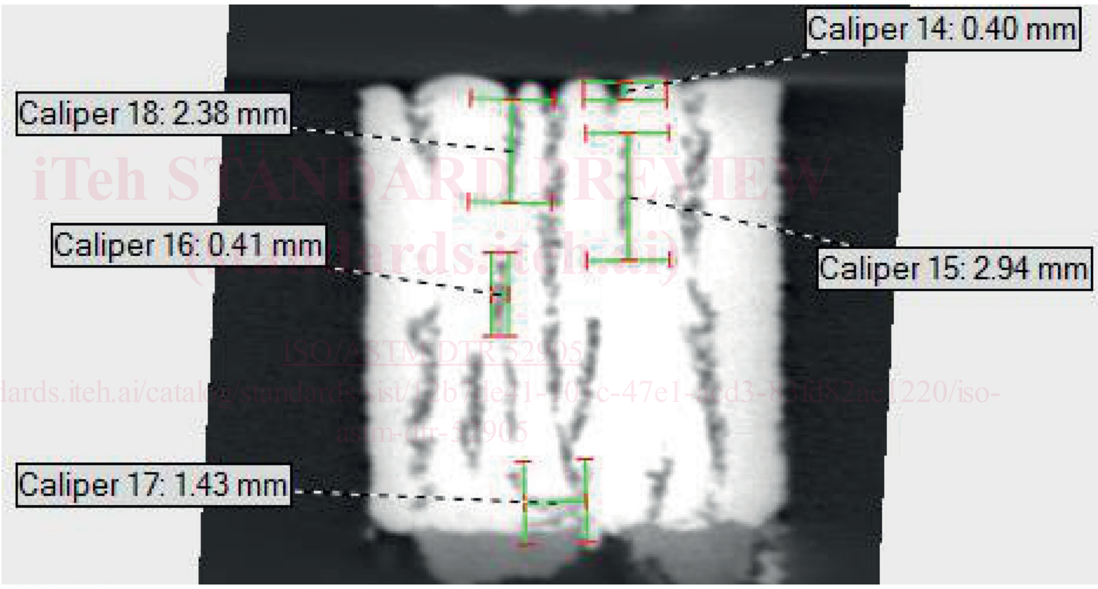
Flaw type	Description
Unconsolidated powder	Unconsolidated powder leading to porosity or voids. The morphology is different to gas generated pores, but the geometry and size are not dissimilar. The image below is an example taken from RASCAL project. 
Trapped powder	Unmelted powder that is not intended for the part is trapped within part cavities. 
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.