TECHNICAL REPORT

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Additive manufacturing — Non-destructive testing — Intentionally seeding flaws in metallic parts

Fabrication additive — Essais non destructifs — Implantation intentionnelle de défauts dans les pièces métalliques

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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 can 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 on 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 the following URL: www.iso.org/iso/foreword.html.

This document was prepared by 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, and 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

This document provides information for intentionally seeding flaws in additively manufactured parts and complements ISO/ASTM TR 52905[1].

The different AM building descriptions can be found readily in published standards (see ISO 17296-2) and scientific papers.

Jargon commonly used in the literature describing AM metal process defects includes “balling”, “fireworks”, “smoke” and often are not specific to the morphology of the defect and often result from widely differing mechanisms of formation.

When defining terms specific to AM metal flaws it may be useful to review some examples related to welding technology.

This document is for the creation of seeded replicas supports the user’s understanding not only for the characterization of actual flaws with respect to physical morphology but also for the materials and mechanisms of formation, location, and orientation. In addition, the fundamentals of the processes creating the replica (e.g. PBF or DED with regard to the heat sources electron beam (EB), laser beam (LB) or AP (arc processes) also need to be considered). The intentional seeding to produce flaw replicas can match the character of the actual flaw as closely as possible.

The reference photomicrographs or non-destructive testing images included in this document are in no way to be construed as specifications. These reference photomicrographs and non-destructive testing images are offered primarily to permit examples of “flaws” or replicate images thereof. They can be used for comparison of reports. Flaw seeding will be discussed without context to a specific part, location, or dimension. The material alloy will be provided as known. With some flaws the material alloy may not be as important, for example, a pore may reside in any number of alloys. It can be noted that there is currently no proven method for controlled and replicable seeding of intimate disbonds (sometimes known as “kissing bonds”) – where two surfaces are in intimate or close contact, but with compromised adhesion – in AM parts so this feature is, therefore, currently out of scope.

This document will not go into the fundamentals of each process but rather identify the parameters within each process that can lead to the intentional seeding of AM structures.

1) In preparation. Stage at the time of publication ISO/ASTM DTR 52905:2022.

Additive manufacturing — Non-destructive testing — Intentionally seeding flaws in metallic parts

1 Scope

This document is intended to serve as a best practice for the identification and "seeding" of nondestructively detectable flaw replicas of metal alloy PBF and DED processes. Three seeding categories are described:

a) process flaws through CAD design;

b) build parameter manipulation;

c) subtractive manufacturing.

These include flaws present within as-deposited materials, post heat-treated or HIP processed material, and those flaws made detectable because of post-processing operations. Geometrical aspects or measurement are not the subjects of this document.

WARNING — This document does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this document to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

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/ASTM 52900, *Standard Terminology for Additive Manufacturing — General Principles —Terminology*

ASTM B243, *Standard Terminology of Powder Metallurgy*

ASTM E7, *Standard Terminology Relating to Metallography*

ASTM E1316, *Standard Terminology for Nondestructive Examinations*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900, ASTM E7, ASTM B243, ASTM E1316 and the following apply.

NOTE Terms for AM metal technology flaws are logically divided between PBF and DED categories of processes.

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

— IEC Electropedia: available at https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
coupon
piece of material from which a specimen is prepared

3.2
flaw classification
classification approach that provides a high-level system based on a primary characteristic or a combination of characteristics

Note 1 to entry: Flaw classification may include similar flaw types that were created differently.

3.3
inclusion
foreign material held mechanically

Note 1 to entry: Inclusions are typically oxides, nitrides, hydrides, carbides, or combinations thereof being formed due to contamination of the chamber gas, or already be present in the metal powder.

3.4
keyhole
type of porosity characterised by a circular depression formed due to instability of the vapour cavity during processing

3.5
pore
inherent or induced cavity within a powder particle or within an object not connected to an exterior surface

3.6
porosity
presence of small voids in a part making it less than fully dense

3.7
replica
intentional manipulated condition (flaw) to serve as the "seed" in a *coupon* (3.1) representing a known flaw type

3.8
seeding
act of intentionally creating flaws, through CAD or manipulation of designated processing parameters, that results in the placement of the anticipated *replica* (3.7) or the act of intentionally creating a *replica* (3.7) through the insertion of a foreign object

3.9
sintering
process of heating a powder metal compact to increase density and/or improve mechanical properties via solid state diffusion

3.10
surface-connected flaw
flaw that is in the body of the material but its boundaries reach to the material's surface

3.11
unsintered
powder unaffected or affected but not fully consolidated during the additive manufacturing printing process

4 Abbreviated terms

AM	Additive Manufacturing
BM	Base Metal

CAD	Computer-Aided Design/Computer-Aided Drafting/Computer-Aided Drawing
CNC	Computer Numerical Control
DDC	Ductility-Dip Cracking
DED	Directed Energy Deposition
EB-DED	Electron Beam Directed Energy Deposition
DR	Digital Radiography (non-film)
EB-PBF	Electron Beam Powder Bed Fusion
EDM	Electrode Discharge Machining
GMA-DED	Gas Metal Arc Directed Energy Deposition
HAZ	Heat Affected Zone
HIP	Hot Isostatic Pressing
LC	Liquation Crack
L-DED	Laser Directed Energy Deposition
L-PBF	Laser Beam Powder Bed Fusion
MB	Metal Base
NDE	Non-destructive evaluation
NDT	Non-destructive Testing
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PSD	Particle Size Distribution
RT	Radiography Testing(film)
RQI	Representative Quality Indicator
SC	Solidification Crack
T_m	Temperature melting point
WM	Weld Metal
XCT	X-ray Computed Tomography

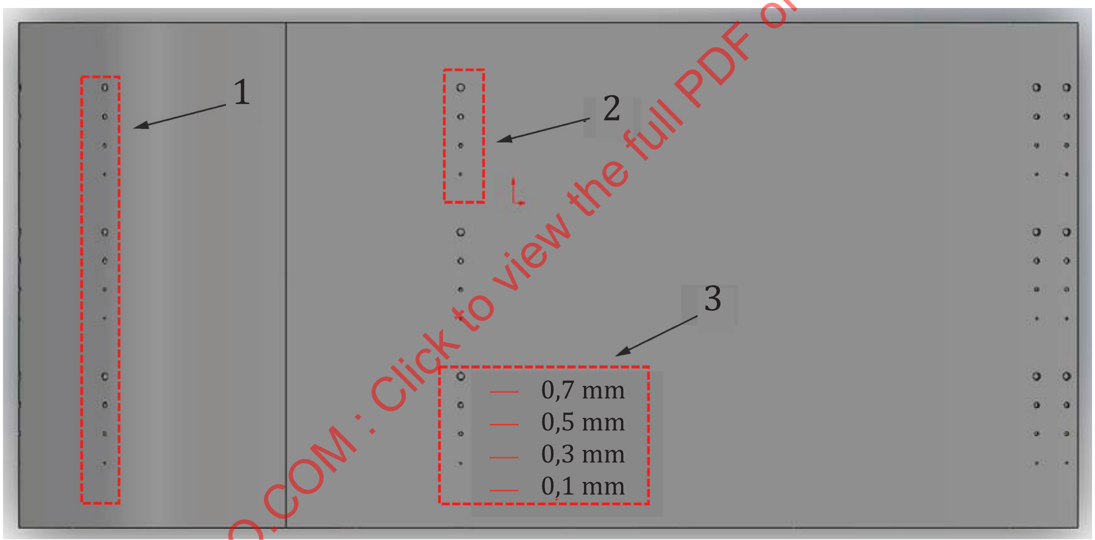
5 Typical AM flaws

Typically, additive manufacturing flaws in materials fabricated using optimised parameters have small spherical flaws. Builds with less developed parameters may have a keyhole or larger angular pores. However, high value components are often screened for flaws at a level determined by fracture analysis such as those described below. The ability to create replicas to support the NDT detection capability of complex structures is unique to additive manufacturing and can be considered when standard inspection techniques are not adequate to ensure inspection reliability.

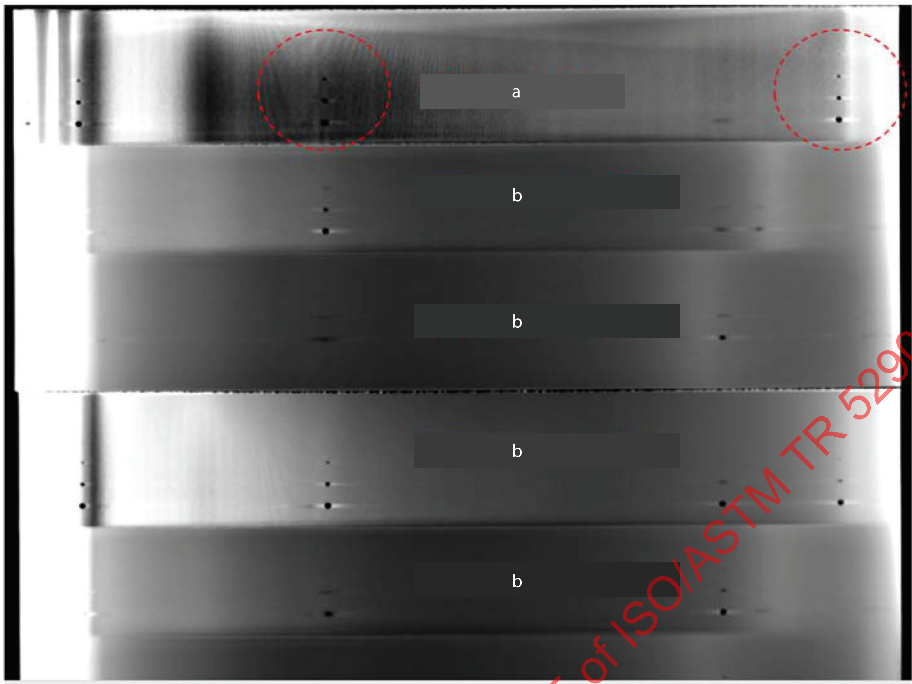
The occurrence of unintentional flaws during the additive manufacturing build is a possibility. The flaw classification has been laid out in ISO/ASTM TR 52905 both L-PBF and DED. These flaws are: layer-defects (horizontal lack of fusion), cross-layer (vertical lack of fusion), unconsolidated powder, trapped powder, inclusion, layer shift, porosity and void; moreover, incomplete fusion, hole and cracking. It is important to highlight that some DED defects are similar to those produced during the welding process, while for L-PBF some defects are unique.

In addition to flaws created to replicate naturally occurring anomalies, replicas may be generated to serve as targets that can be used to understand x-ray, ultrasonic or other NDT capabilities (see Figure 1). It is important that the fabricator of such replicas understands the physics of the NDT's method for which the flaws will be used. Capabilities demonstrations include detection in a specific complex geometry such as a Representative Quality Indicator (RQI) according to ASTM E1817[5], or detection at a specific orientation relating to the radiation beam. This replica is “seeded” intentionally around the needs of the demonstrations. Ultrasonic sensing may find applicability through the technical approach of ASTM E127[3]. Additionally, some of these seeding methods are implemented and detection capabilities of seven NDT methods are assessed in ISO/ASTM TR 52905.

It has been found that replica size, orientation, and location can be designed into the build model to create shapes (spheres, cubes, and rectangular prisms), sizes (lengths and diameters), and depths. An example is shown in Figure 1 where embedded defects were designed into the step wedge with CAD software, and since they are embedded with no powder removal vent, they are filled with unmelted powder (unconsolidated powder/trapped powder).



a) CAD model showing the set of clusters and dimensions of the holes in the airfoil



b) XCT scan displaying the visibility of the replicas seeded at different locations and those that are not visible

Key

1 sets of holes containing 3 cluster

2 number of holes per cluster

3 holes dimensions per cluster

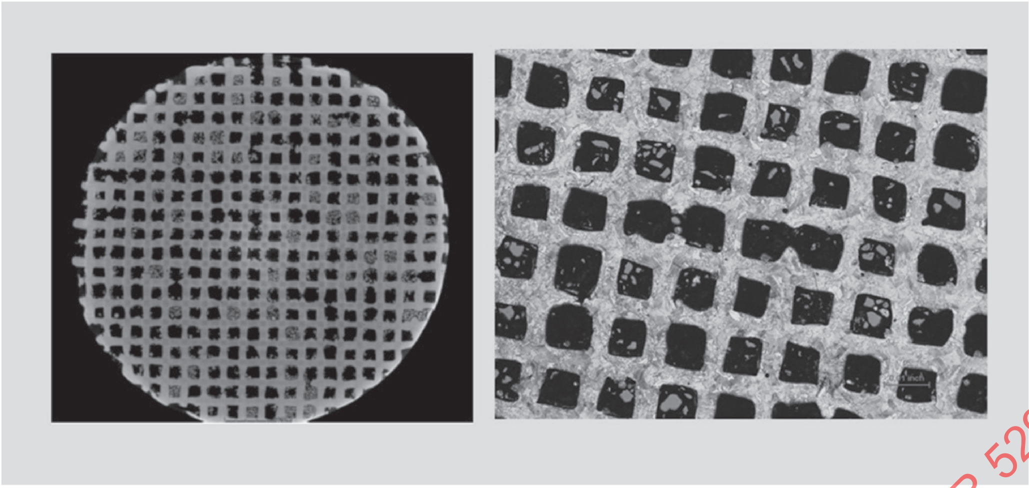
a All 4 are visible.

b ⌀ 0,1 mm not visible.

Figure 1 — Example of RQI generic airfoil built on Ti-6Al-4V

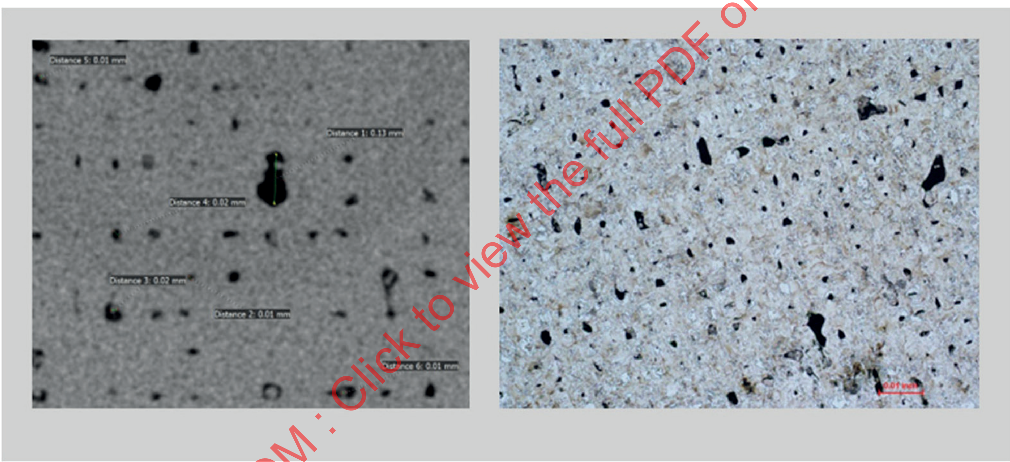
With adjustments to the optimum build parameters, replicas can provide a desired off-nominal build parameter. The shape of the replica can be planar, elliptical, rounded or another modelled configuration. Two such off-nominal build parameters for seeding replicas are lowering laser power and increasing the trace width to that which is greater than optimal.

Both of these types of replicas can be used to show the various NDT methods detection potentials. For example, the computed tomography scans of the seeding replicas resulted in different yet detectable material density changes created by each build parameter adjustment. The level of detail and different views possible through computed tomography is shown in Figure 2 and Figure 3. The images in both figures are not comparatives as those only illustrate differences in the detail when different magnifications and methods are used.



a) Computed tomography (XCT) slice image b) Microscopy image at 50×: large hatch spacing

Figure 2 — Example of the difference in image when different magnification



a) Computed tomography (XCT) slice image b) Microscopy image at 50×

Figure 3 — Example of the difference in image when different method

Replicas that are open to the surface are producible through the predetermined width dimension in the model. Figure 4 shows a model used to determine the width capability of the L-PBF machine. These are linear-type replicas which can have the powder removed. Figure 5 shows the surface in the as-built and polished conditions.

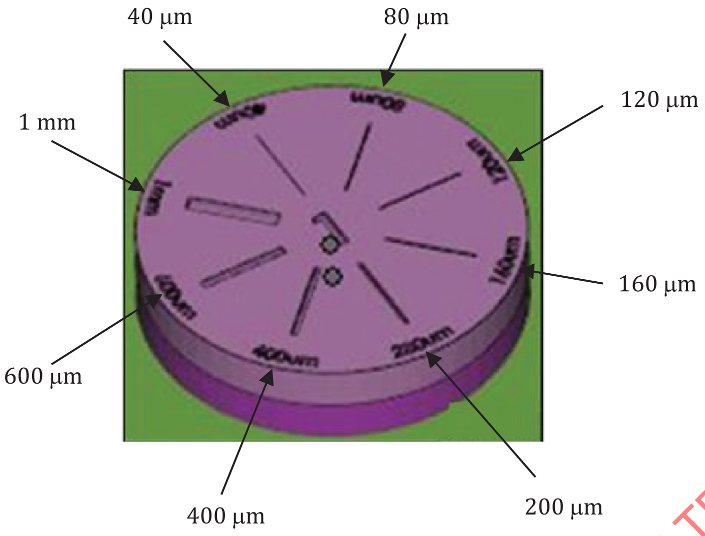


Figure 4 — Open to the surface replica at different width dimensions

Figure 5 — As-built (left) and polished (right) coupon of the model in Figure 4

6 Procedure to produce replicas

The introduction of the AM process replicas can be accomplished through the changing of machine parameters, feedstock conditions or mechanical procedures. The most representative methods are:

— seeding methods;

— AM process manipulation;

— mechanical procedures.

7 Seeding approaches

7.1 General

The following subsections provide seeding approaches for flaw replication using CAD insertion, manipulation of off-nominal processing and mechanical machining.

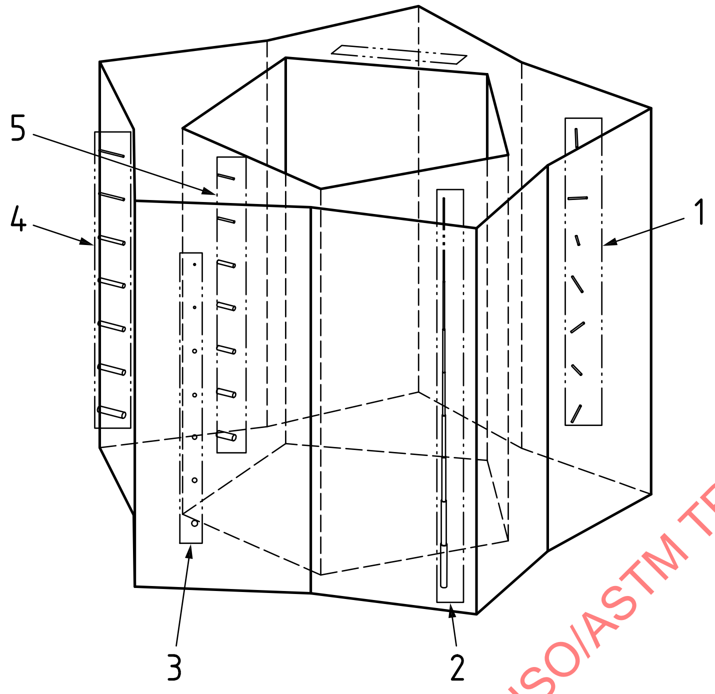
7.2 CAD seeding

This is the simplest, most direct, and most accurate method to seed defects on AM parts. Defects of specific geometries (cylinders, spheres, etc.) are added in the CAD design at specific locations. Some defects are open to the surface allowing the powder to be released and some are closed geometries which will have trapped powder. This method is used in ISO/ASTM TR 52905 where artefacts were built with such seeded defects and then tested with several NDT methods.

The typical AM only flaws were intentionally seeded in the following manner: horizontal cylinders open to the surface for layer-defects (horizontal lack of fusion), vertical cylinders open to the surface for cross-layer defects (vertical lack of fusion), spheres and cylinders not connected to the surface for unconsolidated powder or trapped powder. Inclusions are represented by inserting foreign material into the surface open seeded defects. Table 1 shows more detail of how this is achieved, while Figure 6 and Figure 7 show examples of a design S1 and the corresponding build in Inconel.

Table 1 — General AM Seeding by CAD design

Defect Classification	CAD seed into geometry
Layer defects (horizontal lack of fusion)	Add horizontally oriented geometrical features to the part geometry at desired locations in the part. Geometries can include but not limited to: cylinders, cuboids, etc. Ideally open to the surface to allow the powder to be released.
Cross Layer (vertical lack of fusion)	Add vertically oriented geometrical features to the part geometry at desired locations in the part. Geometries can include but not limited to: cylinders, cuboids, etc. Ideally open to the surface to allow the powder to be released.
Trapped powder or unconsolidated powder	Add geometrical features to the part geometry at desired locations in the part. Geometries can include but not limited to: spheres, short cylinders, etc.
Layer shift	Add such deviations to the CAD design of the part.
Inclusions	Using any of the layer and/or cross layer defects insert a determined material in such cavity.



Key

	Region	Description	Diameter mm	Length mm
1	Region 1	Cylinders in various orientations (Unconsolidated/trapped powder). Orientation offsets of 45° and 90° relative to the first instance	0,3	2,0
2	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
3	Region 3	Spheres (Voids/porosity, unconsolidated/ trapped powder)	0,1, 0,2, 0,3, 0,4, 0,5, 0,6 and 0,70	-
4	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
5	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

Figure 6 — Example design for S1 version of seeded defects

Figure 7 — An example of an S1 design build on Inconel

7.3 AM process manipulation replicas

7.3.1 General

This seeding is perhaps the more common approach when discussing the seeding of replicas (flaws) and represents as closely as possible the potential naturally occurring flaws. Table 2 provides a list of parameter adjustments that can be used for replica creation. It can be understood that the severity of the replica may or may not match the target flaw. For example, the lack of fusion-type flaw can vary considerably based on the cause and length of processing time. To compensate for severity, multiple replicas using a range of the primary process manipulations provide a broader approach to understanding demonstrable detection.

Many studies have been conducted through the manipulation of off-nominal processing parameters such as defects – holes or slots, delays – laser on and/or off delays, trace width increase or decrease, and laser power decrease or increase. Associated with these manipulations is the reference power or optimal build parameters. Based on the outcome and end-use of the replica, the producer can seed needed coupons. Table 2 presents the build parameter adjustments to create replica/flaw during the additive manufacturing process.

Table 2 — Build parameter modifications and powder conditions for flaw formation in the AM process

Defect Classification	Off-nominal build condition
Pore	Hatch speed/hatch spacing
	Vary/measure powder moisture content (or modify bake-out)
	Vary powder or chamber atmosphere purity
	Remelt voids into larger or irregular pores
	Choose parameter to ensure keyhole formation and collapse

Table 2 *(continued)*

Defect Classification	Off-nominal build condition
Void	Spread powder layer with a damaged blade, rake, or roller Choose parameters to create ejecta (“fireworks”), “balling” or “smoke” related defects Induce intentional process interruption/restart Beam power spike
Crack	Vary constraint or support geometry to increase stress state upon solidification and cooling Choose an alloy with a decreased level of weldability Contaminate the built environment or alloy with a trace alloy to mock improper chamber cleaning conditions
Layer defects (horizontal lack of fusion) (unconsolidated]	Beam power, W Energy density, J/mm^2 Beam focal offset, spot size, µm Hatching spacing (line offset), µm Scan speed, m/s Scan strategy Temporary reduction of or turn off the heat source Halt process, introduce thin layer tracer film, restart process Induce disturbance typical to process, e.g. leak air into the process gas Induce disturbance typical to process, e.g. switch process gas Ar to N_2
Trapped powder in Part Geometry	Due to part geometry design, the unmelted powder is trapped within part cavities
Cross-Layer (vertical lack of fusion)	Similar cause as in layer defects but consistently occurring in the same area of the build and connected or semi-connected through consecutive layers.
Layer shift	Start-Stop-Start Halt process, introduce thin layer tracer film, restart process Magnetic interference in EBM

7.3.2 Entrapped unsintered powder

This flaw can be replicated through the use of a weak power source or the entrapment of powder in channels or passageways that can be void of powder.

NOTE This condition can be affected by post-thermal processing. Thermal processing can sinter loose powder.

7.3.3 Manual insertion of high-density inclusions

This seeding is perhaps the more difficult one as it requires the introduction of foreign material into the build chamber. A common occurrence of the flaw can happen when different alloys are unintentionally mixed in the build feedstock. No consistent method has yet been defined for this seeding.

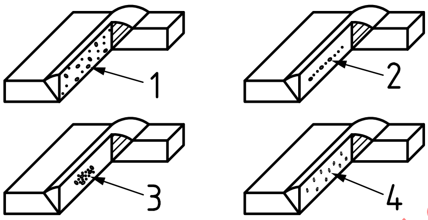
7.4 Post-production mechanical introduction of replicas

This is used as an alternative approach to seeding flaws and it is commonly used in the subtractive machining processes to standardize or assess an NDT inspection method. While the use of process anomalies and/or unsintered powder may be preferred to create more realistic replicas arising from plausible build scenarios, the resultant replicas may not always possess the needed geometry and positioning of interest for a particular NDT investigation. If higher fidelity is required for the flaw geometry and location post-production, mechanical introduction of flaws can be a helpful tool.

7.5 Significance and use for homogeneity

Additive manufacturing of metals, although in development for many years, has only relatively recently emerged from university, national and corporate research laboratories due to the rapid increase of original equipment manufacturers' direct metal AM machine production numbers. As a result, much of the flaw terminology developed over the past decades was locally derived and non-standardized.

Some AM metal flaws are most similar to those could have come from a welding engineering using high-energy beams (EBW, LBW) and conventional arc welding (see Figure 8 and Figure 9). Unlike welding, 3D model-based deposition has a critical difference in creating the potential for flaws to occur at any location within the part volume not primarily along with the weld joint configuration. Other important differences for AM PBF-LB processes relate to the rapid traverse speed of the laser or EB heat source and the presence of a powder bed layer, each putting at risk consistent energy coupling, steady-state melting conditions and stable metallurgical phase formation. The small scale of AM PBF-LB defects can challenge the detection limits of many NDT techniques commonly used to evaluate castings and weldments.



Key

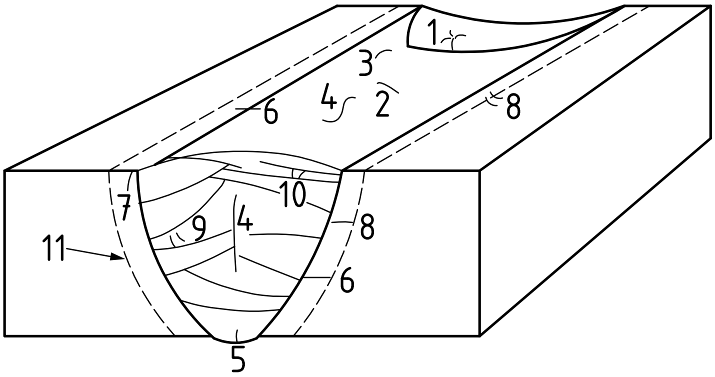
1 uniformly distributed porosity

2 linear porosity (layer defects)

3 clustered porosity

4 worm-hole porosity (cross-layer defects)

Figure 8 — Weld defects that could also be found in DED AM processes

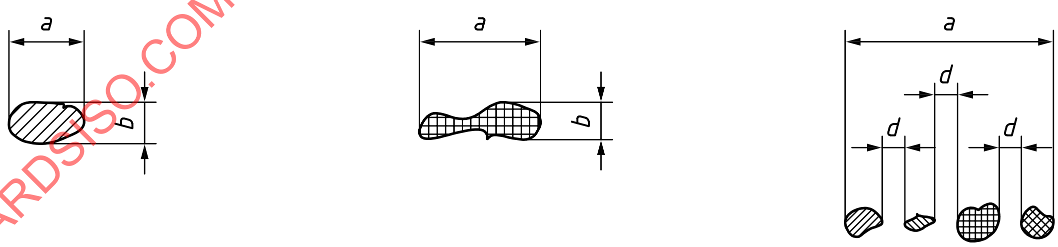


Key

1	crater crack (SC)	type 1A
2	transverse crack (SC)	type 1A
3	longitudinal crack (SC)	type 1A
4	centre crack (SC) in the longitudinal and transverse section	type 1A
5	root crack (SC)	type 1A
6	transverse crack (LC)	type 1B
7	edge crack (LC)	type 1B
8	DDC in HAZ	type 2A
9	DDC in HAZ (multi-run weld)	type 2B
10	DDC in HAZ (single-run weld)	type 2C
11	HAZ metal base (MB)	—

Figure 9 — Types of cracks on welds

The significance in seeding a replica is that it provides an opportunity to establish an understanding of the AM feature, the off-nominal condition(s), and an initial NDT detection level based on the flaw's signature in the material (see Figure 10). This knowledge can be used in the design of NDT inspection tools such as representative quality indicators (RQI) of complex shapes during x-ray examinations (XCT, DR, and/or RT) or internal reflectors for ultrasonic standards.



$(a/b) < 3$ — **a) Rounded indication**

$(a/b) \geq 3$ — **b) Linear indication**

$0 < d \leq 2$ mm — **c) Aligned indication**

Key

a dimension

b dimension

d dimension

Figure 10 — Indications

8 AM process manipulation for L-PBF and L-DED

8.1 General

The introduction of the AM process replicas can be accomplished through the changing of machine parameters and feedstock conditions. AM L-PBF processes rely on both sintering and melting by directing and rapidly traversing a heat source across a powder bed to consolidate the powder feedstock into successive layers.

Compared to DED, beam intensities are higher, traverse speeds much higher and fusion zones much smaller. As a result, the character and morphology of L-PBF flaws can deviate from those seen in DED as deposited. As-deposited material of the L-PBF process, aside from flaws, consists of rapidly cooled and fused material much of which has experienced multiple thermal cycles and some level of the heat-affected zone. Enlarging the hatch spacing from the ideal results in a replica resembling a mesh screen.

Table 3 summarises those conditions for L-PBF and L-DED, while other methods such as EB-PBF, and EB-DED and Arc – DED are not addressed here.

8.2 AM machine parameter manipulation

Additive manufactured EB-PBF material has undergone an extended high-temperature thermal cycle maintaining the powder bed at 0,8 T_m (alloy melting point), resulting in a stress-relieved and annealed structure and/or transformed structure.

Post-processing such as heat treatment and especially HIP may also affect seeded replica survival. Accordingly, the insertion of differently sized and shaped replicas in a single part is often an efficient way of learning which approach works best for a given material, AM system and set of nominal process conditions. Subsequent NDT (x-ray) in coordination with destructive inspection (metallography) can help confirm the results for a set of input conditions.

Table 3 — Parameters and feedstock conditions for flaw creation for L-PBF and L- DED process

No	L-PBF	L-DED
1	Beam power, W	Beam power, W
2	Energy density, J/mm^2	Energy density, J/mm^2
3	Beam focal offset, spot size, µm	Beam focal offset, spot size, µm
4	Hatch spacing (line offset), µm	Hatch spacing (line offset), µm
5	Scan speed, m/s	Travel speed, cm/s
6	Scan strategy	Powder flow rate
7	Powder, PSD, morphology	Powder, PSD, morphology
8	Powder layer thickness, µm	Powder layer thickness, µm
9	Powder moisture level	Powder moisture level
10	Deposit layer, Z step, µm	Deposit layer, Z step, µm
11	Build plate preheat, °C	Laser, powder delivery and chamber inert gas
12	Powder bed preheat, °C	Arc DED/EB-DED
13	Chamber gas, ppm O_2, H_2O	Voltage, current, wire feed rate
14	EB-PBF	Travel speed, etc., bead offset,
15	Chamber vacuum	Layer height
16	Sinter pass parameters	NA

NOTE When attempting to seed replicas, particular care is needed to ensure any "auto-correct" feature of the software programs used to convert the three-dimensional model into the file used by the AM machine is turned off. Otherwise, there is a strong likelihood that intended flaws will be removed from the build file. Also, creating replicas may take more than one build iteration due to flaw design and the effects of hatch spacing, layer height and heat energy.

8.3 Applicable flaw-seeding approaches as a function of desired flaw type

8.3.1 General

This may depend on the degree of control and some parameters that the OEM vendors allow the users to control. Another more targeted approach, irrespective of whether the parameters are under machine control, would require knowledge of the process disturbances and mechanisms of flaw formation to then induce these disturbances into the process.

8.3.2 Porosity or voids (increased power density)

8.3.2.1 Overview

The increase of power density through decreased heat source travel speed can result in vaporization in powder-based systems, keyholing in wire-based systems or voids in either system.

8.3.2.2 Porosity

— vary/measure powder moisture content (or modify bake-out);

— vary powder or chamber atmosphere purity;

— remelt voids into larger or irregular pores;

— choose parameters to ensure keyhole formation and collapse.

8.3.2.3 Voids

— spread powder layer with damaged blade, rake, or roller;

— choose parameters to create ejecta (“fireworks”), “balling” or “smoke” related defects;

— induce intentional process interruption/restart.

8.3.3 Surface-connected flaws

8.3.3.1 Overview

Surface-connected flaws can be simulated using a method similar to that used to create unsintered, embedded powder flaws, such as regions of unsintered/unconsolidated powder, adjacent to AM part surfaces. Under most circumstances, the powder can be removed. Powder removal can be accomplished prior to any post-production heat treatment process to minimize unintended powder consolidation during heat treatment. A common approach for selecting a representative replica is to use the same length and depth but vary the replica width. Figure 4 shows a simple and effective manner to produce different replica widths. This surface-connected replica build allows for the powder to be removed from the width and to be observed. The build parameters can then be known for future use. The sketch in Figure 11 shows a layer defect known as lack of fusion.

8.3.3.2 Cracking

— vary constraint or support geometry to increase stress state upon solidification and cooling;

— choose an alloy with a decreased level of weldability (e.g. 6061 or 2024 Al);

— contaminate the built environment or alloy with a trace alloy to mock improper chamber cleaning conditions.

8.3.3.3 Layer defects (Lack of fusion)

— beam power, W;

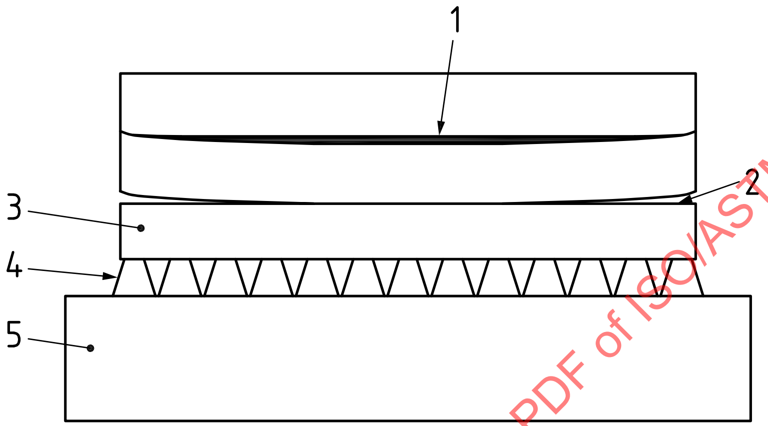
— energy density, J/mm^2;

— beam focal offset, spot size, µm;

— hatch spacing (line offset), µm;

— scan speed, m/s;

— scan strategy.



Key

1 layer defects (lack of fusion)
2 delamination
3 deposit layer
4 build support
5 base plate

Figure 11 — Lack of fusion illustration

8.4 Applicable flaw-seeding approach as a function of AM process

Unsintered, unconsolidated or loose powder

— The temporary reduction of the heat source can be used to generate embedded or surface-connected replicas. The build layer height also is a parameter that can be considered to use to prevent complete powder sintering during subsequent layer building. If the flaw is too small in the vertical build direction, subsequent passes of the power may alter the replica geometry or consume it completely.

— It is also possible to turn the heat source off completely in prescribed regions to generate regions of embedded replicas. Researchers have found the height (number of build layers over which the flaws are constructed) and overall geometry (e.g. spherical vs. cylindrical or another shape) of the flaw plays a role in the survivability of that flaw after subsequent heat source passes as well as post-processing thermal exposure.

  — Halt process, introduce thin layer tracer film, restart the process.

  — In process introduction of contaminant.

  — Induce disturbance typical to process, e.g. leak air into process gas.

  — Induce disturbance atypical to process, e.g. switch process gas Ar (Argon) to N_2 (Nitrogen).

