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MEMO

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Verification of Additive Manufacturing processes

1 INTRODUCTION

Additive Manufacturing (AM) technologies are considered enabling by the European Space Industry, whose stakeholders are willing to introduce parts produced by AM into ESA missions. The frequency at which parts are introduced has been increasing rapidly over the last years.

In order to avoid a potential vacuum between the introduction of parts into ESA missions and the formal issuing of the new ECSS standard on AM (expected to be released by 2020), it is necessary to put in place some intermediate measures. In this document, the basic Product Assurance Requirements are detailed such that they can either be inserted directly into future PARDs or can be referred to as a separate document.

Powder bed fusion (PBF) based Additive Manufacturing processes are the most widely applied ones, for which reason, this memo is mainly considering technical aspects of these. However, the principles can also be applied to other processes, e.g. ones based on robots with a laser as energy source and powder as feedstock, beside others.

As Additive Manufacturing is considered a critical process, a RFA shall be issued for each application or part.

2 GENERAL

2.1 Classification of AM criticality levels

2.1.1 Overview

Additively manufactured parts for space applications are classified into three classes according to their function and requirements using safety categories and sensitivity levels. In agreement with the customer, the supplier shall identify a safety class for the intended product.

2.1.2 Safety Class 1

Class 1 parts are considered critical. Failure of a Class 1 part results in a loss of spacecraft, major components, loss of life, or loss of control of the spacecraft.

2.1.3 Safety Class 2

Class 2 parts are non-critical but structural and are considered as their failure can reduce the efficiency of the system but not cause the loss of the spacecraft.

2.1.4 Safety Class 3

Class 3 parts are non-critical and non-structural and are contained so that failure does not affect other flight elements. These parts require minimal integrity verification, the controls are mainly visual.

2.2 AM acceptance criteria

2.2.1 Powder properties

The supplier shall specify acceptable ranges for at least: the chemical composition including contaminants and moisture, the particle size distribution, and the flowability. Every new powder batch shall be delivered with a Certificate of Conformance (CoC), which shall be in compliance with the previously defined ranges.

2.2.2 Inner defects

The supplier shall define and justify maximum acceptable sizes for inner features. Types of inner features shall include as a minimum: inclusions, pores, areas of lack of fusion, and cracks. Acceptability of defects can depend on their location and aspect ratio. Suppliers may define locations of lower concern.

3 REQUIREMENTS FOR VERIFYING ADDITIVE MANUFACTURING PROCESSES

This memorandum specifies the necessary requirements to perform metallic Powder Bed Fusion for space applications. Firstly, it is comprised of four development phases, as they typically occur during the development of additively produced space hardware:

1. Within the **AM definition phase**, all influencing factors on the final product are defined, allowing for an early assessment of the feasibility of the envisaged AM project.
2. The aim of the **AM pre-verification phase** is to establish the preliminary Additive Manufacturing Procedure Specification (pAMPS). In this specification, the acceptable powder characteristics, AM machine operation parameters, AM machine processing window, post processing parameters (e.g. pressure and working distance for jet blasting), and NDI techniques are defined. These parameters are then verified through rather low-cost tests (e.g. density cubes and tensile tests). Once the result of these are acceptable, the pAMPS is defined.
3. The pAMPS, i.e. the AM end to end process is then verified through a dedicated test campaign within the **verification phase**, which is done on specimen as well as on part or "critical feature" level. After successful verification, the preliminary AMPS becomes an AMPS.
4. The aim of the **hardware production phase** is to produce the intended hardware according to the previously defined AMPS, and to validate it through non-destructive, mechanical, or functional tests, as well as through witness specimens.

Additive Manufacturing processes are considered critical and many factors are known to have a substantial influence on the properties of the final product. Therefore, after the four development phases (AM definition phase to hardware production phase), three clauses address the suitability of operating and supervision personnel, the applied equipment and facilities and define quality assurance requirements.

4 AM DEFINITION PHASE

The supplier shall define:

1. Functional and technical requirements,
2. AM design constraints,
3. Risks associated to the AM process,
4. Post processing techniques, and
5. NDI techniques, suitable for the final parts.

To conclude the AM definition phase, a Preliminary Manufacturing Concept Review (PMCR) shall be held together with the customer. During this review, the supplier shall present the selected end to end process, including the definition of the AM machine (specifying the serial number), the raw material, the post processing equipment, and the process parameters.

5 AM PRE-VERIFICATION PHASE

The supplier shall:

1. Validate the feedstock as per clause 2.2.1,
2. Define all relevant AM machine operation parameters,
3. Establish processing windows for the AM machine,
4. Define parameters for post processing operations,
5. Establish the build direction showing the lowest strength values through tensile testing, the specimens shall be tested after being subjected to post processing heat treatment, if applicable, and
6. Select NDI techniques.

This shall be compiled in a preliminary Additive Manufacturing Procedure Specification (pAMPS), as per the template in clause 10.1.

6 AM VERIFICATION PHASE

The AM verification phase shall be split into two phases:

1. The AM verification of the metallurgical and mechanical process on specimen coupons, see clause 6.1.1, and
2. The AM verification process on prototypes: see clause 6.1.2.

The build job set-up typically refers to the location and orientation of the part(s), and witness specimens in the build volume.
The build job set-up shall be frozen for class 1 parts (including nesting). The build job set-up may be altered for class 2 and class 3 parts upon approval of the customer.
A-base or B-base values shall be calculated from the obtained test data in this phase.

6.1 Additive Manufacturing Verification Test Plan (AMVTP)

The supplier shall define an Additive Manufacturing Verification Test Plan (AMVTP), which allows establishing design allowables for all design driving loads. The AMVTP shall include as a minimum the tests specified subsequently, acceptance criteria in 2.2, and shall be agreed with the customer. Relevant information for creating the test plan is provided in clause 10.2 and 10.4.
Powder capture samples according to clause 10.2 shall be included for class 1 and class 2 parts.

6.1.1 AM verification of the metallurgical and mechanical process on specimen coupons

6.1.1.1 Safety classes 1 and 2

Table 1 Test methods for class 1 and 2 parts

Test definition	Test object
Visual inspection	On all produced specimens
Metallography	At least 3 vertical bars on representative locations in the build volume, covering the full build height of the particular build job.
Tensile testing	At least 2 build jobs with 7 specimens each, evenly distributed in the build volume
Fatigue testing	At least two build jobs with 10 specimens each, to create 2 Woehler curves until the fatigue limit. If a fatigue critical hardware is built, a Woehler curve with 24 specimens (at least 4 load levels with 6 specimens each) shall be generated.
X-Ray CT	On fatigue specimens, grip section can be excluded
Fracture toughness	At least 3 specimens, crack plane parallel to build plate, loading in z direction
Customised tests	Details to be specified in AMVTP

Fatigue testing and X-Ray CT may be waived if it can be demonstrated that the intended part is not subjected to cyclic loading.

6.1.1.2 Safety class 3

A bar in vertical (z) orientation with a diameter of at least 10 mm shall be built, covering the full height of the build job. From this bars, 3 samples for micro sectioning shall be extracted and subjected to visual inspection, metallography, or specific application tests defined by the customer.

6.1.2 AM verification process on prototypes

All prototypes, demonstrators, or test specimens shall be produced according to the pAMPS, including all manufacturing steps and post build operations.

6.1.2.1 Safety classes 1 and 2

A prototype shall be built and tested for every new part design. Prototypes or demonstrators and witness samples shall be tested as specified in Table 2 below. Relevant information for creating the test plan is provided in clause 10.2 and 10.4.

Table 2 Test methods for prototypes, demonstrators, and witness samples for safety classes 1 and 2

Test definition	Test object
Dimensional control	All prototypes, demonstrators, and witness specimens
Visual inspection	100 % on all prototypes, demonstrators, and witness specimens
Tensile witness specimens	5 specimens (see 10.4.3.1 a)
X-Ray CT	On all prototypes and demonstrators
Dye penetrant inspection	On all prototypes and demonstrators
Density testing	2 cubes with 10x10x10 mm
Customised tests	Details to be specified in AMVTP

6.1.2.2 Safety class 3

Tests shall be done according to Table 3.

Table 3 Test methods for prototypes, demonstrators, and witness specimens for safety class 3

Test definition	Test object
Dimensional control	All prototypes, demonstrators, and witness specimens
Visual inspection	100 %, on all prototypes, demonstrators, and witness specimens
Density testing	2 cubes with 10x10x10 mm
Customised tests	Details to be specified in AMVTP

6.1.3 Additive Manufacturing Procedure Specification (AMPS) and test report

If all performed tests satisfy the previously defined acceptance criteria, the pAMPS shall become the AMPS.

6.1.4 Manufacturing Readiness Review (MRR)

The MRR shall be performed as per ECSS-Q-ST-20C and it shall be checked that the design is frozen through a configured drawing. Further, the results of the verification testing shall be presented, and the AMPS shall be signed by all parties.

6.1.5 Process interruption

No unplanned process interruption shall be accepted during the verification phase.

6.1.6 Documentation

The verification test plan shall be documented and incorporated in the RFA.

7 HARDWARE PRODUCTION

Prior to starting the manufacture of flight hardware, the powder procurement specification, the AMPS, design data, and evidence of MRR approval shall be made available to the customer.

7.1 Requirements for flight hardware production

Hardware production shall be done in compliance with the AMPS.

7.1.1 Process interruption

If an unplanned process interruption occurs during the hardware production phase, a major non-conformance shall be produced, but the manufacturer is authorized to continue the manufacturing.

7.1.2 Manufacture of hardware and witness specimens

An overview of witness specimens to be produced with hardware is given in Table 4.

7.1.2.1 Standard Tensile Test Specimens

Samples to provide validation of material shall be built as test piece blanks, undergo all post-build thermal treatments, and be machined to tensile test pieces.
The shape, orientation, and location in the build volume shall be agreed with the customer. It is good practice to locate the specimens such that the full extension of the build volume in all directions is encompassed.
Machines with multiple laser systems may require locating specimens in overlap areas.

7.1.2.2 Full height blanks

Two Full height test blanks shall be produced with each build for class 1 and 2 parts. The first full height blank shall be kept in the as-built condition. The second full height test blank shall undergo the full production sequence, in order that a tensile test can be carried out. The full height test blanks shall extend beyond the full height of the FM.
Metallography shall be performed and the chemical composition be assessed for class 1 parts on the full height blanks.

A Powder capture sample containing more than 60 g shall be built for class 1 parts. The shape shall be agreed with the customer.

Table 4 Minimum number of witness specimens to be successfully tested per build job

Test object	Safety Class 1	Safety Class 2	Safety Class 3
Tensile test samples	3	3	3
Full height blanks	2	2	-
Powder Capture Sample	1	1	-

7.2 Testing of witness specimens

Tensile testing shall be done according to ECSS-Q-ST-70-45C.
The density of the full height blanks shall be determined through the Archimedean method or X-Ray Computed Tomography.
The properties of the powder of the capture sample shall be in conformance with the ones specified in clause 2.2.1.

7.3 Inspection of hardware

7.3.1 Non-destructive techniques

Non-destructive techniques investigated in the AM Pre-verification phase and verified in the AM Verification Phase shall be implemented as defined in the AMPS to the pass/fail criteria described therein.
Any non-destructive inspection shall be performed after the last post-processing step.

Table 5 Overview of non-destructive tests for AM hardware

Test definition	Safety Class 1	Safety Class 2	Safety Class 3
X-Ray CT	100 %	-	-
Dye penetrant inspection	100 % on machined areas	100 % on machined areas	-
Visual inspection	100 %, or as far as possible as permitted by the geometrical complexity of the part	100 %, or as far as possible as permitted by the geometrical complexity of the part	100 %, or as far as possible as permitted by the geometrical complexity of the part
Dimensional control	100 %	100 %	100 %
Functional test	If no X-Ray technique is technically feasible	-	-

7.3.2 Destructive testing

If applicable, destructive tests shall be agreed with the customer.

8 AM OPERATING AND SUPERVISION PERSONNEL

A suitably qualified AM supervisor shall be appointed. Personnel for operating AM equipment shall be trained and certified e.g. according to DIN 35225.
Personnel performing non-destructive inspection shall be trained and certified according to ECSS-Q-ST-70-15C.

9 EQUIPMENT AND FACILITIES

AM equipment shall be maintained and calibrated according to Original Equipment Manufacturer's recommendation.
A powder management plan, describing safe handling, procurement, storage, loading, recycling, sieving, blending and disposal of powder shall be produced.
For safety class 1 and 2, only alloys of the same family shall be processed in the same machine due to the risk of cross-contamination.

10 ANNEX

10.1 AMPS

a. The Additive Manufacturing Procedure Specification shall include as a minimum:

1. A flow chart, detailing all performed operations in the final sequence, indicating the responsible stakeholder(s), shall be established
2. General information
   - (a) the date, issue and revision number.
   - (b) AM process,
   - (c) Powder quality level (CoC)
   - (d) Design tool
   - (e) Safety Class: 1, 2 or 3,
3. Manufacturer and supplier
   - (a) Identification of the manufacturer and supplier who performs the design
   - (b) Identification of the manufacturer and supplier who performs the process
   - (c) Reference to applicable documents.
4. Equipment and facilities
   - (a) identification of the equipment, model and serial number, used to perform the process
   - (b) software
   - (c) Pre-process cleaning procedure
   - (d) Tools calibration
5. Reference to powder management plan
6. Powder procurement specification
7. Shielding gas
   - (a) The composition,
   - (b) Shield gas type,
   - (c) Shield gas flow rate,
   - (d) Duration of the shield gas.
8. Tooling and fixtures
   - (a) Tooling and fixtures
   - (b) The part position in the chamber
9. Pre-heating and post-process heat treatment

(a) In case of pre-heating is applied, the temperature, and the time at temperature,

(b) In case a post heat treatment is applied, the temperature and the time at temperature.

10. Part build file including layer thickness, manufacturing file including supporting strategy, etc.,
11. Alloy type of base plate
12. Thickness of base plate, a change of more than 5 mm is not permitted
13. Type of recoater blade
14. Level of vacuum
15. Level of oxygen during the build
16. Base plate temperature
17. Post processes operations
    (a) All post process operations, tools, procedures
18. Non-destructive inspection
19. Test results
    (a) All the mechanical tests results
    (b) All the controls results
20. Measurements
    (a) All the dimensional measurement results
21. Personal
    (a) Certifications and training of the personnel
22. Traceability
    (a) Powder traceability
    (b) Tools traceability
    (c) Samples used and position in the chamber
    (d) Post process mechanical or thermal treatment
    (e) Process anomalies
    (f) All data recorded during process
    (g) People involved during the process

Additional content for Electron Beam based processes:

a. In addition to the requirements specified, the AMPS for Electron Beam based Powder Bed Fusion processes shall contain as a minimum, the following information

   1. Equipment:
      (a) Model and make,

(b) Electron gun type

2. Manufacturer's or measured values for the beam quality parameters:

b. In addition to the requirements specified, the AMPS for Laser based Powder Bed Fusion processes shall contain as a minimum, the following information:

1. Equipment:

   (a) Type of source, model and make,

   (b) Nominal power,

   (c) Number of lasers combined.

2. Manufacturer's or measured values for the beam quality parameters:

10.2 Testing of powders

a. Testing of powders shall include as a minimum:

1. Elemental composition, including carbon, hydrogen, oxygen, and nitrogen,
2. Particle size distribution
3. Powder porosity
4. Density in both apparent and tapped conditions
5. Flow rate

Particle size distribution can be done as per ASTM B214, or by laser diffraction in compliance with ASTM B822. Porosity can be performed by helium pycnometry in compliance with ASTM B923, or through X-Ray CT scanning. Flow properties can be determined through the Hall Flowmeter test in compliance with ASTM B212 or DIN EN ISO 4490 and tap density as per ASTM B527.
It is good practice to determine morphology and satellite build-up with a SEM as complementary information.

10.3 Powder capture sample

Powder capture samples provide a useful historic reference to a powder used in a build. They can also provide an indication of any powder contamination issue occurring before or during the build. 50 g powder is needed to perform a hall flowmeter test. It is strongly advised to capture more than this amount, e.g. 60 g to be able to perform also this test.
A powder capture sample can be an mPBF (metal PBF) container built during the mPBF which intrinsically contains powder as-supplied to the build chamber and any contaminants generated during the build.
Equally, it can be a powder sampling tool, which is inserted into the bed, collects a sample and then withdrawn.

10.4 Testing for AM

10.4.1 NDI for AM

a. The selection of NDI techniques shall be performed in the AM definition phase.

b. visual inspection shall be performed with a magnification of at least 10x.

c. Dye penetrant inspection shall be carried out with sensitivity level 2 according to AMS 2644, unless otherwise specified by the customer.

d. Dye penetrant inspection shall only be performed on machined surfaces, unless otherwise specified by the customer.

e. The dye of the selected method shall be cleanable in full.

NOTE AM parts are expected to have relatively high surface roughness, which makes dye penetrant inspection very difficult. Jet/vapour/bead blasting can close surface-cracks and is therefore clearly not recommended without subsequent chemical etching as a preparation technique before dye penetrant inspection.

f. Unless otherwise specified in the AMVTP, the part shall be free of porosity, discoloration, contamination, cracks, lack of fusion, or inclusions.

g. X-Ray CT shall be applied to detect internal defects.

NOTE Typical internal defects for mPBF processes are pores, lack of fusion, cracks, or inclusions. X-Ray CT can also provide the porosity level, the defect’s size, shape, and location.

10.4.2 Metallography

a. The as-built microstructure shall be demonstrated free of detrimental defects when evaluated with metallurgical cross-sections at a minimum magnification of 100x and an area of evaluation ≥ 1cm^2.

b. In case of utilising more than one beam, it shall be demonstrated that this results in consistent mechanical properties throughout the build area, including the regions where beams overlap.

NOTE “beam” includes laser and electron beams.

c. For titanium alloys, no alpha case shall be accepted.

d. The absence of any alpha case shall be demonstrated in accordance with EN2003/009.

e. Unless otherwise stipulated in the AMVTP the microstructure shall be free of cracks, lack of fusion, inclusions.

f. Grain size and texture shall be assessed.

g. The assessment shall include top layer melt pool blanks and layers from the bottom of the build.

NOTE Top layer melt pool blanks are useful for the inspection of the geometry and macrostructure of melt tracks. Therefore a top (surface) layer from the bottom of the build may be compared with a top (surface) layer at the top of the build in to order confirm laser and optics performance at the beginning and end of the build, and to validate against material produced during the AM pre-verification and verification phases. It should be noted that some mPBF equipment will apply a cosmetic pass on top surfaces.

10.4.3 Destructive testing

10.4.3.1 Tensile testing

a. The direction showing the lowest strength values, determined within the pre-verification phase, if not done previously, shall be tested.

NOTE The direction showing the lowest strength values is very often z (vertical).

b. The tests shall be performed according to ECSS-Q-ST-70-45C.

c. The acceptance criteria shall be specified in agreement with the customer.

d. The type and size of the tensile samples shall be defined in the AMVTP.

10.4.3.2 Fatigue testing

a. The tests shall be performed according to ECSS-Q-ST-70-45C. The exact test sample surface conditions shall be agreed with the customer.

NOTE The samples can be tested in the condition “as built” without having received any surface treatment, after surface treatment or after machining.

NOTE Surface treatments include jet blasting, electro polishing, plasma polishing or similar processes.

b. The stress ratio (R) shall be -1.

10.4.3.3 Fracture toughness testing

a. The tests shall be performed according to ECSS-Q-ST-70-45

10.4.4 Density testing

a. If the density specimens are produced together with a part, these shall not be positioned farther away from the actual part than 10 mm in x or y direction.

b. In the case of machines utilising a gas-flow over the powder bed, one samples shall be placed at the side where the gas enters the build chamber, the other one where the gas is extracted from the build chamber.

NOTE Techniques for density measurement include Archimedes (ISO 3369), X-ray CT, and quantitative metallography.