Quality assurance and Quality control in metal AM: Metrology & Maintenance

Key words: Metrology, Destructive Testing, Non-destructive testing, 3D scanning, standards, maintenance

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**Introduction**

Metrology is defined by the International Bureau of Weights and Measures (BIPM) as "the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology."[1]

For each specific application and production process there are various elements which are important to determine the quality of the end product. In chapter ‘Applications’ the main elements are specified, namely;

- Dimensional Tolerances
- Porosity
- Microstructures
- Residual Stress
- Surface Roughness
- Finished parts/mechanical performance (i.e. tensile strength)
- Chemical composition analysis.

In this chapter metrology and maintenance aspects related to AM manufactured end product are discussed. Section 2 described testing methods. Section 3 described methods to measure dimensional tolerances. Section 4 describes standards related to metrology. Finally Section 5 discussed AM specific maintenance issues. Additionally, In situ process monitoring is discussed in chapter ‘process’, while material metrology aspects are discussed in chapter ‘materials’.
(Non-) Destructive Testing

In order to validate the part quality the application and process specific requirements need to be measured. ISO 17269-3 provides an initial guideline to classify which quality aspects need to be checked.

In general the two main groups of testing include;

- **Destructive Testing;** Methods which limit or remove part functionality
- **Non Destructive Testing;** Method which do not interfere with part functionality

The testing methods used for Additive Manufacturing are largely similar to conventional production technologies. However, two main differences between testing methods for conventional technologies and AM may be identified. Firstly, the complex geometries produced with AM technologies may be difficult to inspect. Complex geometries may include internal features, which are difficult to detect with conventional testing methods. Secondly, the main quality elements (as described in the introduction) are specifically associated with AM technologies. Considering the two main differences, suitable testing methods may be identified for AM technologies.

Additive Manufacturing enable to cost-effective production of complex geometries in low-volume. Therefore non-destructive testing methods are favourable for testing of the actual part. However, destructive testing methods which use a surrogate part in order to validate the compliance of a part to the application and process specific requirements are also used. Such a surrogate part - frequently called a witness or traveller specimen - is produced together with the part. A number of witness specimens are produced in various build orientations to provide insights in the performance of the part and the production process.

Additional non-destructive testing methods which are suitable for AM include;

- **X Ray Computed Tomography,** measure internal porosity, dimensional tolerances.
- **Scanning Electron Microscopy (SEM),** measure microstructures, surface roughness and surface porosity.
- **Neutron/X Ray Diffraction,** measure residual stresses.
3D Scanning and Inspection

3D scanning and inspection is the final step of the post processing activities. For fulfilling QA/QC requirements, it is important to check if the component has been built accurately within the acceptable limit. By using 3D scanning techniques, components can be scanned as an STL file and then compared against its original CAD data. The results can be analysed in the inspection software for point to point deviation or exact shape measure.

The most recent and advanced scanning technique used for inspection is blue light scanning technology. It is very fast process, where very powerful LED and innovative projection system used to capture the scanned data faster (http://www.steinbichler.com/products/3d-scanning).
Quality control of the final part
The system operator must control several parameters of the final part, especially those regarding to dimensions and finishing of the part.

After post processing of the part, the system operator will be the responsible of control the following aspects:

- Visual control of the final part
- Accurate dimensions control
- Quality Surface control
- Non-destructive tests
- Destructive tests

For this purpose, a check list will be available near the expeditions table, to be completed by the system operator. See the checklist below:

<table>
<thead>
<tr>
<th>Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Build plate reference</td>
<td></td>
</tr>
<tr>
<td>Operator machine</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters to control</th>
<th>OK</th>
<th>NO OK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder removal control</td>
<td></td>
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<tr>
<td>Visual control of the final part</td>
<td></td>
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<tr>
<td>Roughly dimensions control</td>
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<tr>
<td>Comments</td>
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</table>
Standards
From the SASAM project (SASAM deliverable D3.3) we learned that the test methods under consideration for AM comprise test methods to characterise materials and machines dedicated to AM and final products regarding their physical, mechanical and other properties. We will extend the existing standards (rather than inventing new ones) in order to cover additively manufactured final products.

Two main groups already exist: mechanical test methods and geometrical conformity test methods:

1. Standard characterization tests and methods used at present
   - Geometrical conformity to the model (dimensions, details resolution, etc.)

2. Physical / Mechanical / Other properties
   - Physical properties: exact composition, density, microstructure, CTE (ISO 22674:2006), etc.
   - Mechanical properties (density, porosity, hardness, surface roughness, etc.)
   - Sensorial aspects (visual, surface texture and roughness, etc.)

SASAM indicated that the criterion for selecting the most relevant standards is based on the information provided by suppliers of equipment and materials to their customers. Key standards have been selected according with the most common and usual standards shown in the material data sheets of manufacturers.

Table 1 shown below focuses on metals because of the available information. The second column of both tables explains those standards that are currently used by companies (based on conventional standards). The third column indicates recently approved standards by international committees (ISO, ASTM) and it is expected that these new standards replace the old ones in each particular test. The fourth column shows standards being in the process of being edited and approved. It should be noted that not all existing standards related to one particular test resolves the full problem because some of them are partially applied.
**Table 1** Actual standards for metals (Source SASAM D3.3)

<table>
<thead>
<tr>
<th>TESTS</th>
<th>Nowadays Applied Standards</th>
<th>New existing AM standards</th>
<th>New ongoing AM standards</th>
<th>Identification of needs relevant for AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Properties</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Tensile Strength, Yield</td>
<td>ISO 8892-1:2009</td>
<td>ASTM WK30107</td>
<td>ISO YYY-1</td>
<td>Operational parameters and build direction necessary in specimen geometry definition</td>
</tr>
<tr>
<td>DIN 50125</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tensile Strength, Ultimate</td>
<td>ISO 8892-1:2009</td>
<td>ASTM WK30107</td>
<td>ISO YYY-1</td>
<td>Operational parameters and build direction necessary in specimen geometry definition</td>
</tr>
<tr>
<td>DIN 50125</td>
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<tr>
<td>Elongation at Break</td>
<td>ISO 8892-1:2009</td>
<td>ASTM WK30107</td>
<td>ISO YYY-1</td>
<td>Operational parameters and build direction necessary in specimen geometry definition</td>
</tr>
<tr>
<td>DIN 50125</td>
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<td></td>
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</tr>
<tr>
<td>Modulus of elasticity</td>
<td>ISO 8892-1:2009</td>
<td>ASTM WK30107</td>
<td>ISO YYY-1</td>
<td>Operational parameters and build direction necessary in specimen geometry definition</td>
</tr>
<tr>
<td>DIN 50125</td>
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</tr>
<tr>
<td>Hardness</td>
<td>ISO 8508.1</td>
<td></td>
<td>Existing standard could be applied</td>
<td></td>
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<tr>
<td>ISO 8507.1</td>
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<tr>
<td>Fatigue strength</td>
<td>ASTM E486:1006</td>
<td></td>
<td>Operational parameters and build direction necessary in specimen geometry definition</td>
<td></td>
</tr>
<tr>
<td>Thermal Properties</td>
<td></td>
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</tr>
<tr>
<td>Coefficient of Thermal</td>
<td>ISO 22874:2006</td>
<td></td>
<td>Existing standard could be applied</td>
<td></td>
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<tr>
<td>Expansion</td>
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</table>

It is important to mention the Additive Manufacturing Standards Development plan between ISO/TC 261 and ASTM F42 for development of additive manufacturing (AM) standards.

The objectives of the joint planning sessions and this resulting Standards Development Plan include the following:

- Bring AM industry experts together from ISO/TC 261 and ASTM F42
- Identify specific standards needs common to the AM industry
- Align standards roadmaps, resulting in a joint roadmap common to ISO/TC 261 and ASTM F42 interests
- Determine how the two groups can best work together
- Determine the priorities for specific AM standards
Committee F42 on Additive Manufacturing Technologies from ASTM. In particular Subcommittee F4.2.01 on Test Methods is working developing particular standards for additive manufacturing testing methods. Currently there are three active standards:


Some additional standards are in the status “working progress” to be proposed as new standards. Please see the current state of them in this webpage (http://www.astm.org/COMMIT/SUBCOMMIT/F4201.htm)

Moreover, there are some standards developed for particular materials. These standards define all properties that shall be tested to obtain a quality part made by a particular additive manufacturing technology. For example these are the active standards developed by the subcommittee F42.05 on Materials and Processes:

- F3001-14 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
- F3049-14 Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
- F3056-14e1 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion

Some additional standards are in the status “working progress” to be proposed as new standards. Please see the current state of them in this webpage (http://www.astm.org/COMMIT/SUBCOMMIT/F4205.htm)

ISO/CD 17296-3 is a general standard which covers the principal requirements applied to testing of parts manufactured by additive manufacturing processes. This standard gives the list of characteristics and corresponding recommended test standards. These standards do not suit perfectly additive manufacturing because they were written prior to the development of additive manufacturing technologies. The broad variety of standards for metals in mechanical properties is due to the different materials where they are applied. CoCr Alloy, Ti6Al4V Titanium Alloy, etc.

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ISO/ASTM NP 52902 is in development for developing standard test artefacts.

ASTM F2971 – 13 is a Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing.


SASAM deliverable report D3.3 provides several conclusions and recommendations for future standardization for tensile testing, flexural testing, fatigue resistance, geometric tolerance, geometric requirements (technical drawings in AM).
Maintenance

Maintenance concerns the tasks related to maintaining the functionality of a part. This includes the status of the part, as well as potential replacement or repair of the part. While maintenance for AM parts is largely similar to conventional production technologies, there a number of quality aspects which need to be considered. The specific quality aspects related to maintenance of AM parts are due to specific AM characteristics, namely:

- New technology with limited standards
- Design freedom leading to complex shapes

Part aspects → unknowns (lack of standards)

Design freedom -> complexity (shapes and part consolidation) -> difficult to inspect

A solution to monitor the status of a part is a novel technology active structural health monitoring. Here, passive or active system are integrated into the part design to monitor the structural health of the part. Refer to:

Sources & further reading

- NIST 2008 – Measurement Science Roadmap for Metal-Based Additive Manufacturing

A list applicable material testing standards for AM materials has been published by NISTIR in 2008: ‘Applicability of Existing Materials Testing Standards for Additive Manufacturing Materials’. This publication provides the measurement science for the additive manufacturing (AM) industry to measure material properties of additive manufacturing materials in a standardized way.


- Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing (Everton, 2016)

Scientific article discussing the following:

  o An overview of state-of-the-art methods for assessing the quality of additive manufacturing processes is presented.
  o The need for new sensors and monitoring methods for emergent additive manufacturing processes is introduced.
  o Material discontinuities resulting from well understood processes are explored and the case for in-situ monitoring is made.
  o The industrial opportunities and potential benefits of using these advanced methods are explored.


- Non-destructive testing of Additively Manufactured components: challenges ahead (insidemetaladditivemanufacturing.com, 2015)

Many of the existing non-destructive evaluation (NDE) standard procedures applied to conventionally wrought, forged, and moulded metal components are generally applicable to parts made by AM. However, specific challenges must be addressed by newer AM-specific standardized NDE procedures. In addition, there is a recognized need to develop in-process monitoring techniques to inspect parts during the build process.

http://www.insidemetaladditivemanufacturing.com/blog/non-destructive-testing-of-additively-manufactured-components-challenges-ahead

- X-ray detection limits in Hastelloy X components made with Selective Laser Melting

The most promising non-destructive technique (NDT) for complex geometry parts made by additive manufacturing appears to be x-ray radiography and computer tomography (CT). Both techniques are very well established NDT methods. But little is known about the defect detection limits in dense component manufactured by Selective Laser Melting. Here we present preliminary results to help understand the X-ray defect detection limits in Hastelloy X parts manufactured by SLM.

• Nottingham University working group on end product metrology


• Metrology Needs for Additive Manufacturing - Lawrence Livermore National Laboratory (Kurfess & Taylor)

http://www.aspe.net/publications/Short%20Abstracts%2014SP/3994.pdf

• CT scanning for AM parts at the University of Leuven


• NIST metrology portal

Overview of NIST metrology projects


• ASTM International. ASTM International is a globally recognized leader in the development and delivery of voluntary consensus standards. Today, over 12,000 ASTM standards are used around the world to improve product quality, enhance health and safety, strengthen market access and trade, and build consumer confidence.

http://www.astm.org/

In particular for Additive Manufacturing technologies, Committee F42 on Additive Manufacturing Technologies (http://www.astm.org/COMMITTEE/F42.htm).