The present Non Destructive Examination techniques for Metal Additive Manufacturing (AM) parts and components and their future

Peter AMIN  
MSIS, Lloyd's Register Asia,  
63-64, Kalpataru Square, 6th floor, Kondivita Lane, Off Andheri - Kurla Road, Andheri (East), Mumbai 400 059, India.  
Phone: +91 43 250 250, email: peter.amin@lr.org

Abstract  
One of the key challenges of AM components is non-destructive examination. While NDE techniques are well-developed, their application for inspection of AM components has not been fully established. This paper includes a brief introduction to AM technology and its different processes, followed by a discussion on the possible discontinuities and/or defects commonly observed in the final product and the suitability of the traditional NDE techniques for proper detection and evaluation of defects. In the final topics, a case study of the first certified additively manufactured part for the Oil and Gas industry is given to get a clear perspective on the topic at hand. Also discussed herein, are the shortcomings of the present technology and standards to address the requirements of AM and the future steps that can be taken in order to address them in a proper way.

Keywords: Additive Manufacturing, NDE for AM, 3D Printing, Metal AM, Freedom manufacturing

1. Introduction to AM

Additive manufacturing (AM) is the process of joining materials to make objects from Computer Aided Design (CAD) model data, usually layer upon layer, as opposed to subtractive manufacturing methods. These new techniques, while still evolving, are projected to exert a profound impact on manufacturing. There are a wide range of materials that can be adopted by AM including but not limited to various metal, carbon fibers, ceramics, plastics and some biological materials.  
Herein, we briefly look at a few of the most widely adopted methods for manufacturing metal AM components for industrial use,

- Powder Bed Fusion (PBF),  
- Direct Energy Deposition (DED),  
- Wire Arc Additive Manufacturing (WAAM),  

![Figure 1. Laser Powder Bed Fusion (PBF)](http://www.ndt.net/?id=24347)
Powder Bed Fusion (PBF) is an additive manufacturing process that produces parts from the bottom up by depositing a layer of powder, levelling that powder layer by means of a roller or recoater blade, melting then solidifying powder in a cross-sectional manner based on position from the CAD model and using a laser or electron beam as the energy source. The build platform is then lowered, a subsequent layer of powder is deposited and the process is repeated until the full CAD geometry has been manufactured. This process is performed in an inert atmosphere in order to avoid oxidation and entrapment of the atmospheric gases, as shown in the figure above (Figure 1).

Direct Energy Deposition (DED) also known as ‘Powder fed’, ‘Powder blown’ or ‘Laser Deposition Technology’ is a process in which metal powder is fused, as it is deposited by a focused laser or electron beam under tightly controlled atmospheric conditions. The focused beam melts the surface of the target material and generates a small molten pool of base material. The delivered powder is absorbed into the melt pool, thus generating a deposit.

In the Wire + Arc Additive Manufacturing (WAAM) process, wire is the feedstock material deposited. The wire melts by an arc plasma and deposits layer by layer.

We can see today that AM technology is becoming more sophisticated, reliable and commercially viable. That is because after much development, the adoption of AM technology is increasing across a wider range of industries. There are still some economic challenges but AM has the potential to revolutionize parts of the manufacturing industry as well as the design philosophy currently applied.

However, when it comes to adoption of this ground-breaking technology across the industry, manufacturers still face numerous challenges for the inspection, testing and certification of AM components. As of today, all the international certification codes and standards are based on the traditional subtractive manufacturing terms. Therefore a need arises for a certification scheme for AM parts, which address different aspects of the process, inspection and testing on terms broad enough to include multiple AM processes and at the same time establishes the assurance needed for the part to be used for its intended purpose.
2. Different types of discontinuities related to AM

As with any manufacturing and fabrication technology, AM parts are also prone to some process specific and some general discontinuities. Discussed below are some major discontinuities / defects observed in AM process, mainly focusing on metal AM processes.

2.1. Volumetric Discontinuities: Porosity and Lack of Fusion

Porosity and lack of fusion are two types of volumetric defects that may be observed more frequently in metal AM processes. Porosity is generally described as being closer to spherical shape while lack of fusion can be irregular shaped and may contain un-melted powder particles. The main probable reason for formation of these types of defects may be the incorrect set energy level or other parameters. Also, contamination of the input raw materials may contribute to entrapment of inert gases in the fast solidifying metal. Mostly, the shape and size of these types of volumetric defects may not impact the short-term mechanical properties of certain components.

2.2. Planar Defects: Cracking and Delamination

Planar defects have significantly more negative effect on the properties and life of the component as compared to any other. The main reason for development of these type of defects may be a large thermal gradient through a part, which is created due to application of a high intensity (focused) beam and the fast cooling rate in additive manufacturing. The presence of thermal stress can result in delamination of a part from the substrate or cracking of the part especially in large components with higher levels of developed stresses.

These residual thermal stresses can influence the dimensional accuracy of a part especially with a smaller cross-section or a part with insufficient support structure. In addition, the tensile residual stress formed on the surface of a part can reduce the effective structural load that can be applied on the part.

2.3. Geometrical accuracy and surface roughness

For many conventionally manufactured parts, geometrical accuracy and surface roughness may not be considered as a defect or even a discontinuity but, still needs to be accounted for during setting build parameters for AM Processes. A stair-stepping effect may be observed in AM components if the thickness of deposited powder layer is coarse to decrease build time, but it will increase the amount of post processing and NDE (Figure 4 (b)). Also, AM can be utilised for parts with complex internal cavities and channels, sometimes a finer surface finish is required to maintain the survivability of those internal openings. The easiest way to achieve a finer surface is to decrease the thickness of powder layer, which in turn, lowers the stair-stepping effect but increases the build time and requires different build parameters (Figure a (c)).
2.4. Microstructural Issues

Microstructure and granular anisotropy can present significant amount of noise when applying different non-destructive examinations. Large grain size and anisotropy may result in increased attenuation and skewing of the acoustic beam when performing an ultrasonic examination. Due to the layer-by-layer manufacture of a component, accompanied by the establishment of a unidirectional heat transfer along the build direction, grain growth during solidification preferably occurs in the opposite direction of heat transfer. The formation of elongated grains along the build direction is common, especially in metal AM.

3. Case Study a 3D printed titanium gateway manifold

Global technology company Lloyd’s Register has announced the certification of a 3D printed titanium gateway manifold for pipelines (Figure 5). The part is reportedly the first additively manufactured part to be certified by the company for the oil and gas industry. The part itself was designed by Safer Plug Company (SPC), and was produced by 3T RPD. The part was manufactured from titanium using a powder bed fusion 3D printing process, and was certified using the Lloyd’s Register’s own qualification framework [2] after they were approached by SPC over a year ago for the project.

The part features complex internal channels and structures, which would be impossible to achieve using another manufacturing process (Figure 6). The 3D printed part was inspected at
various stages of manufacturing using its innovative certification framework—which was developed in partnership with The Welding Institute (TWI). LR is now working with SPC and 3T RPD to certify 10 more titanium manifolds, and provide a “Type Approval” which will enable 3T RPD to 3D print the manifolds and other pipeline tools on demand. LR, which is currently working on various 3D printing projects within a range of industries (including construction, marine, and nuclear), is hoping the landmark certification will encourage the oil and gas industry to further adopt 3D printing technologies.

Figure 8. Assembly of Manifold

4. Existing Industrial NDE Techniques and their applicability.

NDE methods are needed to interrogate features that are unique to AM parts, such as fine scale porosity, complex part geometry, and intricate or inaccessible internal features. The overall goal will be to understand the types of commonly occurring flaws produced by the AM process, what their effects are, and what NDE techniques are best suited for their detection.

The ability of each technique to detect different types of flaws such as inclusions, porosity, lack of fusion, and cracks, as well as locate these flaws in the interior or exterior surface of a conventionally manufactured metallic component, is discussed below

4.1. Visual Testing (VT)

Visual testing (VT) is the most widely used inspection technique. It is the first step in any quality assurance NDE process. Visual inspection can be much effective by naked eye, or it can be enhanced by using various tools, like magnifying glasses, or a boroscopic camera. Computerized remote visual systems are now commercially available to conduct high resolution visual inspection, data acquisition, digital storage and evaluation. Lighting requirements are a major factor affecting the visual testing.
4.2. **Liquid Penetrant Testing (LPT)**

One of the prominent features of AM parts is higher levels of porosity compared to conventional wrought, cast or moulded parts. The irregular or rough surfaces present in as-built parts make traditional NDE methods for the detection of surface defects difficult and unsuitable. LPT may not be a realistic method for inspection of porous or rough AM parts without post-process machining and polishing. Also, it requires strict adherence to quality procedures and processes to ensure a high detection rate for critical components and parts. The technique is capable of detecting surface breaking discontinuities. It will image the discontinuity length but will not provide information regarding the discontinuity depth.

4.3. **Eddy Current Testing (ET)**

An eddy current (ET) is induced in a conductive material when an alternating magnetic field is brought into close proximity with the material. The alternating magnetic field is usually created by a coil connected to a source of sinusoidal current. The magnetic field of induced eddy currents interacts with the coil magnetic field causing the coil impedance to change. The change of coil impedance is monitored with the ET instrument and depends on material electrical conductivity, magnetic permeability, distance between the coil and material or lift off. Although direct contact between the coil and the material is not required to conduct the test, the ET sensitivity to surface and subsurface discontinuities and conditions is the highest when the distance between the two (lift off) is as small as practically possible.

It may seem that ET is the most suitable method, detecting surface and subsurface defects for metal AM parts; however, the process parameters are difficult to set, considering the complexity of the part under examination. Also the anisotropy of the material may cause some noise in the final scan.

4.4. **Ultrasonic Techniques for Discontinuity and Microstructure Detection and Imaging**

A variety of ultrasonic techniques have been established to examine raw materials and critical components in the oil and gas, energy, heavy and light manufacturing, and aerospace industries, to inspect for discontinuities. Detection is primarily accomplished by monitoring sound energy reflected from a discontinuity. A significant improvement in ultrasonic capabilities and expansion of applications came with the development and deployment of phased array technology which may seem like the perfect solution to all NDE problems.

As already discussed, AM components will have strong directional anisotropy, and possibly, larger grains, than conventional wrought products. This will cause more attenuation, and possibly, beam skewing which in turn might lead to deterioration of detection and sizing capabilities for small discontinuities. The formation of a microstructure with high anisotropy may result in the attenuation of the ultrasonic wave and generation of noise during the non-destructive ultrasonic inspection. Beam attenuation may mask defects, resulting in lower inspection accuracy and reliability. Also, UT is mostly a contact type NDE and placing the probe on the surface of the part to cover the entire volume of part may not be always possible.
4.5. **Conventional Radiography Testing (RT)**

Conventional Radiography Testing (RT), using either film or digital imaging media, produces two dimensional imaging of components. As the component cross-section becomes more complex however, abrupt thickness changes will lessen the effectiveness of this method due to difficulty in imaging thick and thin areas simultaneously. While techniques such as multiple exposures, use of different speed films, and digital enhancement can help, complete useful coverage of complex geometries is not possible with conventional RT.

4.6. **X-Ray Compute Tomography**

Industrial compute tomography (CT) scanning technology was introduced in 1972. The objective of CT is to obtain information regarding the nature of material occupying exact positions inside a body or an object. X-ray CT is the most common form of computerised tomography. The primary components of industrial X-ray CT are a radiation source, a rotational stage, an X-ray detector, and a data processing/image reconstruction centre. The X-ray line beam is translated across the part and data is collected by the detector. The data is then reconstructed to create either a multiple 2D images or a 3D volume rendering of the part.

There are certain valuable advantages of CT over the other NDE methods such as detect deep or embedded defects, interrogate inaccessible features, confirm the effectiveness of post-process treatments often required to make usable AM parts, and to characterize and qualify as-manufactured AM parts (without post processing) (Figure 7). The limitations of CT include inability to reliably detect cracks since cracks oriented perpendicular to the x-ray beam.

4.7. **Leak Testing (LT)**

Leak testing (LT) evaluates the capability of a part or component to prevent the escape or entry of gases or liquids from or into the component and strength of the component, in some cases. The leak test is conducted to detect a leak and/or measure the leakage rate where some leakage is acceptable. However, LT is applicable in very few cases, as it requires a closed of volume which can be pressurised/vacuumed for leak measurement.

5. **Conclusion**

It is clear that there is a need for optimizing and adapting NDE during and after processing. Thermography is a key capability for in-situ process monitoring. CT is a key technique for characterizing finished parts with complex geometries and the challenge of implementation of this technique is the availability of affordable high power and high resolution systems.

Also, there were a limited number of studies found in the open literature investigating NDE techniques for post process inspection of AM components, so what is lacking is a knowledge base of NDE part inspections, which is needed to understand relevant defect types and detectability. Due to the limited number and scope of available studies, performance of NDE techniques, cannot be reliably evaluated or anticipated when testing metal AM components. The challenge presented by the most complex AM parts has not been adequately addressed. The following issues represent three significant technical gaps:

- Limited number of NDE studies for AM;
- Limited scope of NDE studies for AM; and,
• Lack of Standards for NDE of additive manufacturing for Qualification and Certification.

5.1. Methodology to Address Technical Gaps

Regardless of what NDE technique is selected to inspect an AM component, it must be qualified and/or quantified. The qualification or quantification process is a systematic assessment of the NDE equipment, procedure and/or operators’ capabilities to detect, characterize, and size certain defects and conditions.

Results of NDE quantification / qualification will provide information about the ability of NDE equipment, procedure, or operator to meet the AM component inspection objectives. The information might contain sizing accuracy statistics and other quantifiers for some or all of the three quantification components ─ equipment, procedures, and operators. All contracting parties along with NDE vendors or providers are involved to determine the scope and performance level of the quantification process needed to meet the applicable inspection requirements or objectives. It is important to identify the NDE performance level early in the planning process so that adequate time and resources can be allotted. This process can take several months and good coordination between the different entities involved is essential.

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