APPLICABILITY OF NDT METHODS FOR THE DETECTION OF TYPICAL DEFECTS IN SELECTIVE LASER MELTING PARTS

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Abstract

Nondestructive testing is an important part of any production process that is required to ensure the quality of materials and parts. The development of reliable nondestructive testing (NDT) methods applicable to novel materials and manufacturing processes such as additive manufacturing is a challenging task because of the complex geometry and anisotropic material properties. The majority of review publications related to the NDT methods in the additive manufacturing process are focused on only one aspect: either the defect classification or NDT methods and quality control systems. In this study, various NDT methods such as X-ray testing, acoustic emission, IR thermography, etc. were analyzed from the point of view of an application for selective laser melting (SLM, one of the most common additive manufacturing processes of metal parts). Typical defects appearing in SLM parts were classified and matched with NDT methods able to detect them. Recommendations on the use of different methods for in-situ process monitoring and printed parts inspection are given.

Keywords: Selective laser melting, nondestructive testing, defects, additive manufacturing

1. INTRODUCTION

Additive manufacturing (AM) is a process that creates objects from 3D model data, layer by layer, using various materials such as polymers, metals, ceramics, and composites. Unlike subtractive manufacturing, it allows for more complex geometries [1]. Selective laser melting (SLM) is a common AM process for metal parts, with various materials being successfully commercialized [2]. Quality control and nondestructive testing (NDT) are crucial for industries such as aerospace and medicine, and there are numerous studies on these topics. However, there is still much to learn about defect generation, causes, and consequences, as well as suitable NDT methods. This study aims to classify different defect types in SLM metal parts and match them with appropriate NDT methods, covering in-situ and ex-situ techniques, their detectability, advantages, and limitations.

2. DEFECTS IN SLM METALLIC PARTS

The SLM process involves creating a 3D model, slicing it into 2D images, and distributing metal powder on a substrate. Laser energy selectively melts and solidifies the powder according to the 2D slice, and this process is repeated layer-by-layer. The process is affected by 50 different process parameters, but only 12 are controllable during printing. Defects, residual stresses, and anisotropy can affect the mechanical and thermal properties of SLM parts. Maintaining energy density within certain limits is crucial for achieving the best quality of printed parts.

Different studies describe varying numbers of main defect types in additive manufacturing. For example, some consider only two defect types: pores and micro-cracks, while others include lack of fusion, porosity, hot cracking, anisotropy, and surface quality. Defect classification in SLM parts is lacking standards [3], but it can be considered as a starting point by referring to the ISO 6520–1 standard for welding, which identifies six main groups of imperfections: cracks, cavities, solid inclusions, lack of fusion and penetration, imperfect shape and dimension, and miscellaneous imperfections.

Porosity is a common defect found in parts produced using SLM technology. Pores are small gas cavities that can be single or distributed uniformly or localized (clustered). Porosity can be categorized as microporosity or macroporosity, with the latter being more detrimental to material strength. Porosity can occur due to metallurgical reasons such as gas absorption or evaporation of alloying elements or due to process faults. The most critical factor affecting porosity in SLM is the input energy density and laser power, while other factors that can impact porosity levels include laser irradiation conditions, gas flow, powder humidity, and oxygen. Optimizing these parameters and ensuring stable process conditions can help reduce porosity and enhance part quality [4].

Lack-of-fusion (LOF) is a defect that occurs when metal powder fails to melt sufficiently to connect with neighboring layers or scan tracks during the SLM process. There are two types of LOF defects: poor bonding resulting from deficient molten metal and defects with unmelted metal powders inside. Poor interlayer bonding is usually caused by the low penetration depth of the molten pool, while defects with unmelted powders occur when the width of the scan track is not enough. LOF defects reduce the strength of parts, initiate cracks formation, and have a higher influence on fatigue life than other defects. The main reason for LOF defects is the lack of energy input during the SLM process, and oxide films on the surface of the layer can also cause LOF defects [5].

Cracks in SLM parts occur due to the high residual stress and temperature gradient generated during the rapid melting and solidification of metal powder. The key factors influencing the generation of cracks are the material properties, part geometry, laser scanning strategy, and heating and cooling conditions. Ways to prevent crack generation include modifying the alloy composition, optimizing laser scanning parameters, substrate heating, and post-heat treatment. Cracks are critical defects that significantly reduce tensile strength and can lead to material destruction under fatigue loadings [6].

Delaminations are the separation of two consecutive layers of the material. This is a typical defect for composite materials and AM parts. It is caused by residual stress at the interface of the layers [7]. Delaminations are critical defects that usually make the part inapplicable. Residual stress in SLM can cause delaminations, typically at part boundaries and sometimes hidden due to complex geometry.

Anisotropy. SLM parts can have varying mechanical properties in different directions due to structural inhomogeneity and anisotropy, which depend on building direction and scanning strategy. Properties can be manipulated through parameter variation and post-treatment. Anisotropy can be used to achieve desired properties, but may be considered as a defect if it deviates from expected or required values [8].

Surface roughness is an important characteristic of metal components, and while the SLM process may not always meet industry requirements, surface properties can be improved through laser scanning parameter manipulation. Insufficient overlap between scan tracks, caused by high scanning speeds, can lead to pits and crests on the surface. Laser beam power, spot size, scanning speed, hatching distance, layer thickness, and scan strategy are all parameters that can influence surface quality [9].

Other defects. Microstructural defects can impact the mechanical properties of parts produced by the SLM process. Non-equilibrium microstructure caused by microstructural features with different mechanical characteristics can affect the strength and fatigue performance of the parts. Internal residual stresses can accumulate and concentrate during rapid heating and cooling, affecting the mechanical properties and generating deformations and other defects. "Balling" is a common microstructural defect caused by the thermal processes in the melting pool, affecting the fatigue performance of the parts and disrupting interlayer bonding, surface quality, and porosity. Fish-scale defects are perpendicular to the heat flow and caused by solute concentrations during layer-by-layer solidification of powders, leading to layer delamination.

3. NDT METHODS FOR SLM PARTS INSPECTION

NDT is well-established in industries such as metallurgy and welding, but additive manufacturing (AM) has specific requirements for NDT methods due the layered structure, complex geometry, and specific defect types in AM parts. Existing NDT standards and reference samples are insufficient for AM and SLM industries, which require development of defect indication and characterization methods, as well as development of standards and acceptance criteria. ISO 9712 specifies NDT methods, but some of them are hardly applicable for NDT of SLM parts due to complex geometry and surface conditions. NDT in the SLM process can be divided into powder properties measurement, in-situ process measurement, and NDT of printed parts. NDT of printed parts is a traditional nondestructive testing, aimed at estimating of the quality of printed parts and finding internal defects, with challenges due to complex geometry and surface conditions. Typical NDT methods used for SLM parts inspection are listed below, advantages and limitations of the methods are then summarized in **Table 1**.

Visual inspection is the oldest method. It is based on the detection of defects on the surface of the components by the naked eye or with the assistance of some optical tools. Since it does not require special equipment and is relatively fast, it is the first inspection method used in the production phase. However, it does not detect internal defects and requires experienced inspectors to identify certain types of defects.

Surface testing methods allow detection of small defects at the material's surface that are not visible to the naked eye**. Penetrant testing** detects surface and through surface defects using indicator liquids that penetrate cavities and discontinuities in the material. **Magnetic flaw detection** detects defects in ferromagnetic metals using stray magnetic fields and magnetic particle method is the most common. **Eddy current testing** analyzes the electromagnetic field of eddy currents induced in the test object to detect surface and subsurface discontinuities and measure various properties of the material [10].

Ultrasonic testing (UT) is a widely used nondestructive testing method based on the transmission of high-frequency sound waves to detect defects. UT achieves high resolution depending on the selected frequency, allowing for the determination of the length, location, and type of defect. However, calibration with standard samples can be time-consuming, and the test surface must be smooth with the use of couplants. UT works well for metals and can detect most types of defects, but it is not suitable for localizing micro-pores common in SLM parts. High-frequency UT or acoustic microscopy allows high resolution but at the cost of reduced penetration. Advanced techniques such as testing inside immersive tanks or using smart flexible transducers can be used for complex geometry parts [11].

Acoustic emission (AE) is a nondestructive method that detects elastic vibrations generated during various processes in an object. AE can detect and classify developing defects by their danger level, and has high sensitivity to small defects. AE can be used for NDT of SLM parts and in-process monitoring. However, separating useful signals from noise can be difficult, and processing of signals is required for closed feedback-loop control systems. Machine learning techniques can aid in AE data processing for process monitoring systems [12].

Radiography is an NDT method that uses X or gamma-rays to detect surface and subsurface defects in a material. The radiation passes through the material, and areas of thinner material or lower density transmit more and absorb less radiation, forming a shadow image on film or detector. However, radiography has limitations, including radiation hazard, bulky and heavy equipment, time-consuming and expensive testing, and the need for experienced personnel to interpret the results. Radiography also has difficulty detecting thin delaminations and cracks in parts of complex geometric configurations Radiography can also be used as an in-process monitoring technique, with synchrotron X-ray imaging suggested for real-time monitoring of the SLM process [13].

X-ray computed tomography (CT) is a method used to reconstruct layer-by-layer images of object cross-sections (tomograms) by measuring and processing the difference in X-ray attenuation at different orientation angles. CT allows for advanced metrological analysis of the object and can provide more accurate sizing and positioning of defects than single X-ray images. Challenges can arise when detecting cracks and defects with weak differential attenuation. CT is established as one of the best NDT methods for inspecting AM parts and is effective for 3D visualization of complex geometry parts and porosity measurement [14].

Infrared thermography analyzes temperature fields at the surface of an object using infrared cameras. Infrared thermography can detect temperature anomalies that indicate defects inside the material. Infrared thermography is useful for detecting air voids, delaminations, cracks, corrosion, inclusions, and entrapped water in metals and composite materials. Its advantages are high speed, non-contact testing, and relatively inexpensive equipment. Disadvantages include limited penetration capability and limitations in detectable defect size. IR thermography can detect large defects but may struggle with smaller ones, and the minimum detectable defect size depends on the defect depth. In SLM, active and passive thermal testing are used for printed parts and process monitoring, respectively. IR thermography can be used to monitor the SLM process by observing the temperature evolution of the molten pool, hatch distance, powder layer thickness, melting strategy, and solidification rate [15].

Optical methods use light as an information signal to detect defects or irregularities in materials. CCD cameras or optical radiometers capture an image of transmitted or reflected light to detect defects, which cause a change in the intensity of light. Optical inspection is limited to surface defects or transparent materials, but interferometry and holography can detect internal defects by applying optical or mechanical loads to the object and measuring displacements. Optical testing is widely used for SLM process monitoring, such as melting pool monitoring, by using photodiodes and optical cameras. Optical cameras can also be used for 3D tomography mapping and analyzing melting pool characteristics. Low-coherence interferometry can be implemented to monitor melting pool dynamics and detect defects. The holographic method was used to measure distortion during laser melting [16].

Table 1 summarizes the advantages and limitations of NDT methods for SLM parts inspection, including detectable defect types and approximate minimum defect sizes.

Method	**Advantages**	**Limitations**	**Detectable defects**	**Application for SLM parts**
Visual testing	- Simple and fast; - no special equipment is required	- Only visible defects; - subjective; - low reliability.	Visible defects on the surface	The first check
Penetrant testing	- Simple; - The location, size, shape and orientation of surface defects.	- the absence of mechanization; - high consumption of flaw detection materials; - surface preparation requirements; - long duration; - contact method.	Surface open pores, LOF, cracks and delamination with opening width from 1 μm and depth from 0.1 mm.	Printed parts with processed surface
Magnetic flow detection	- Simple; - cheap; - low requirements to the surface quality.	- Only surface and shallow defects in ferromagnetic materials; - non-uniform magnetic properties and defect orientation affect the result; - contact method	Surface and shallow pores, LOF, cracks and delaminations (up to 1-2 mm deep) defects. Opening width from 2 μm, penetration depth from 0.1 mm.	Printed parts. Ferromagnetic materials.
Eddy current testing	- High speed; - non-contact; - applicable to painted and coated parts.	- Only for conductive materials; - only surface and shallow defects; - electromagnetic properties of the tested object should be uniform	Surface and shallow pores, LOF, cracks. Surface cracks with opening width from 0.01 mm, depth from 0.1 mm and length from 2 mm.	Printed parts.

Ultrasonic testing	- High sensitivity and accuracy; - high penetration power (deep defects can be detected).	- Surface preparation requirement; - use of couplant; - contact; - testing of complex geometry parts is challenging; -thin parts and shallow defects detection is challenging.	All defect types. Shallow defects from 10 μm. Resolution decrease with penetration depth. Increased porosity regions can be localized.	Printed parts
Acoustic emission testing	- High sensitivity; - all volume is inspected; - any positions and orientations of defects.	- Difficult signal processing, interpretation of results, and defect localization. - contact sensors.	Growing cracks from 1e-6 mm^2, delaminations, residual stresses, pores, LOF, developing microstructural defects.	Printed parts, process monitoring.
Radiographic testing	- Non-contact; - high penetration depth; - high speed.	- Radiation hazard; - bulk and expensive equipment; - challenges with crack detection and defects that weakly change attenuation of X-rays	Individual pores and LOF from 0.2 mm. Pore clusters. Melting pool parameters.	Printed parts, process monitoring
X-ray computed tomography	- Non-contact; - 3D visualization; - high resolution; - good for complex geometry parts.	- Radiation hazard; - bulk and expensive equipment; - challenges with crack detection and defects that weakly change attenuation of X-rays; - long duration of testing and reconstruction.	Individual pores and LOF from 15 μm, pore clusters. Evaluation of porosity volume. Dimension metrology.	Printed parts
Active thermal testing	- Non-contact; - high speed; - low price.	- low penetration capability; - limited detectability of small defects	Pores, LOF, delaminations, and cracks with lateral size greater than depth. Regions of higher porosity.	Printed parts
Passive thermal testing	- Non-contact; - low price; - layer-by-layer inspection of printing sample allows 3D reconstruction of the object	- Big amounts of data; - complicated calibration due to high temperatures; - resolution and sensitivity are lower than CT.	Pores, LOF, cracks, and delaminations above 50 μm. Material properties prediction by melting pool analysis.	Process monitoring
Optical testing	- Non-contact; - low price; - In-situ inspection; - high framerate and resolution.	- Big amounts of data; - difficult interpretation of results; - IR gives more clear information about the thermal process.	Pores, LOF, cracks, and delaminations above 50 μm. Material properties prediction.	Process monitoring

Defect detection methods for SLM parts vary in their capabilities and limitations. Surface testing methods are sensitive but cannot detect internal defects, while eddy-current testing has no surface preparation requirements but is limited to conductive materials. Ultrasound testing is sensitive but requires surface preparation. X-ray computed tomography provides complex visualization but can be expensive and time-consuming, and may not detect certain defects. Acoustic emission is useful for detecting of growing defects and process anomalies during printing. In-situ process monitoring methods can detect growing defects and process anomalies. Combining several methods and using machine learning can increase testing reliability.

4. CONCLUSION

NDT methods were evaluated for their suitability in detecting defects in SLM parts. Typical defect types appearing in SLM parts were classified and matched with NDT methods able to detect them. X-ray computed tomography and acoustic emission methods were found to be effective in detecting various types of defects. The use of a combination of IR thermography, optical cameras, and acoustic sensors shows great promise for in-situ process monitoring and control. This would enable the detection of defects at early stages and the implementation of closed feedback-loop control systems.

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