

Vol. 19, No. 4

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Inspection of Additive Manufactured Parts Using Computed Tomography: Part 1

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Additive manufacturing (AM) offers new possibilities in manufacturing and designing products. The aerospace and automotive industries are main drivers because of the possibility of manufacturing lighter structures that reduce weight and save fuel. During the manufacturing process, different discontinuities or defects can occur, depending on the applied AM technology. To ensure constant manufacturing quality of the parts, regular sampling or 100% inspection using nondestructive testing (NDT) techniques is required. In particular, computed tomography (CT) allows a contactless investigation and includes different analysis techniques (such as nominal-actual comparison, porosity analysis, wall thickness analysis, and so on). As an advantage to other techniques, it can even evaluate parts with a very complex inner structure.

The following article gives an overview of the AM technology, particularly selective laser melting (SLM), and commonly occurring discontinuities and their possible causes. Furthermore, the functionality of a CT system and the reconstruction process will be explained. In Part 2, we will show a few examples of AM parts under different types of analysis. The limits of this NDT technique will be discussed as well.

Introduction

Additive manufacturing is defined as "the process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" (ASTM 2015). The first method of creating a 3D object using computer-aided design (CAD) was rapid prototyping, developed in the 1980s for creating models and prototype parts. Rapid prototyping is one of the earlier AM processes (Gustafson 2002). Compared to traditional subtractive manufacturing processes like milling, drilling, and turning, AM offers distinct

From *NDT Technician Newsletter*, Vol. 19, No. 4, pp: 1-5.

possibilities. Subtractive techniques start with a block of the base material, which is then subtracted from until the final desired product is reached, leaving much of the initial material as wasted scrap. In the AM process, the part is constructed by depositing material layer by layer in the Z direction until the final product is produced, leaving little to no waste (Wong and Hernandez 2012).

This offers a new freedom in the design of products. There are a variety of applications in the medical field that allow individual adaptation to the human body. Furthermore, there is an enormous interest in the automotive and aerospace sector, because it's possible to create complex structures in a one-piece design and integrate functionalities or redesign products to save weight without sacrificing stability. In addition, in many cases this process is more economical than traditional manufacturing methods, due to reduced tool and storage costs.

With the desire to use this technology, the first concerns arose. There are a lot of internal and regional standards and guidelines for casting and welding products. It is regulated which discontinuities can occur and with which inspection techniques these are to be checked. But what about the AM products? AM methods are diverse and differ greatly, as shown in Figure 1. Just as diverse are the types of discontinuities that can occur, such as pores, cracking, inclusions, delaminations, lack of fusion, undercuts, and trapped powder, to name a few. With advances in AM technology, there must be an increase in quality control of the AM parts to ensure their structural integrity (Hassen and Kirka 2018). This article discusses the applicability of the nondestructive CT technique to evaluate discontinuities in AM parts and which inspection techniques can be used, especially for parts manufactured with the SLM process for metals.

AM Technologies and Types of Discontinuities

The AM process starts with a CAD model that gets sliced into individual layers using software that generates instructions, known as G-code, which are sent to the AM machine (Hassen and Kirka 2018). Figure 1 shows an overview of the different AM processes.

These processes are classified into three major types: liquid based, solid based, and powder based. The shown processes are selective laser sintering/melting (SLS/SLM), electron beam melting (EBM), 3D printing (3DP), binder jet AM (BJAM), laminated object manufacturing (LOM), ultrasonic AM (UAM), adhesive-coated laminates, fused deposition melting (FDM), stereolithography (SL), and direct energy deposition. The liquid- and powder-based processes seem more promising than the solid-based processes, of which LOM is the predominant one used today. In 2004, EBM, BJAM, powder bed fusion, and direct energy deposition were nonexistent (Kruth 1991). In this article, we will focus on SLM, the selective laser melting process.

Selective Laser Melting

SLM is based on manufacturing components using metal powders (with a range of 10 to 45 μm) that are melted through, selectively exposing a desired area to a focused laser beam. The laser beam is moved over the build area through mirrors affixed to a galvanometer, as schematically shown in Figure 2 (ASTM 2011). In recent years, machine manufacturers have introduced systems that incorporate two to four laser sources, each with its own independent mirror galvanometer set to enhance the build speeds. The addition of powder for the next layer occurs through a recoater mechanism that traverses the build area and has a piston gravity feed. SLM processes occur within an inert environment, such as argon or a buffer gas, to prevent reactivity of the alloying elements in the liquid state with environmental impurities. Additionally, SLM processes have the capability of building components in a heated powder bed, with the temperatures reaching several hundred degrees celsius. Heated powder

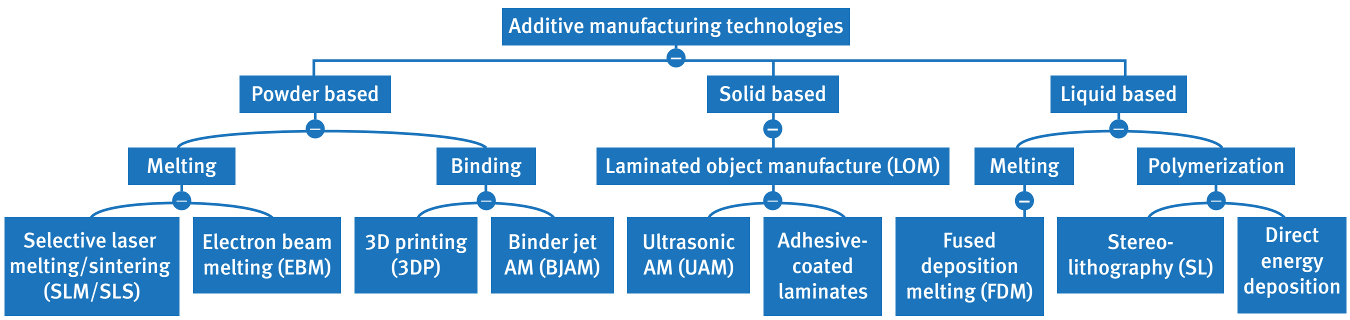

Figure 1. An overview of the different additive manufacturing processes.

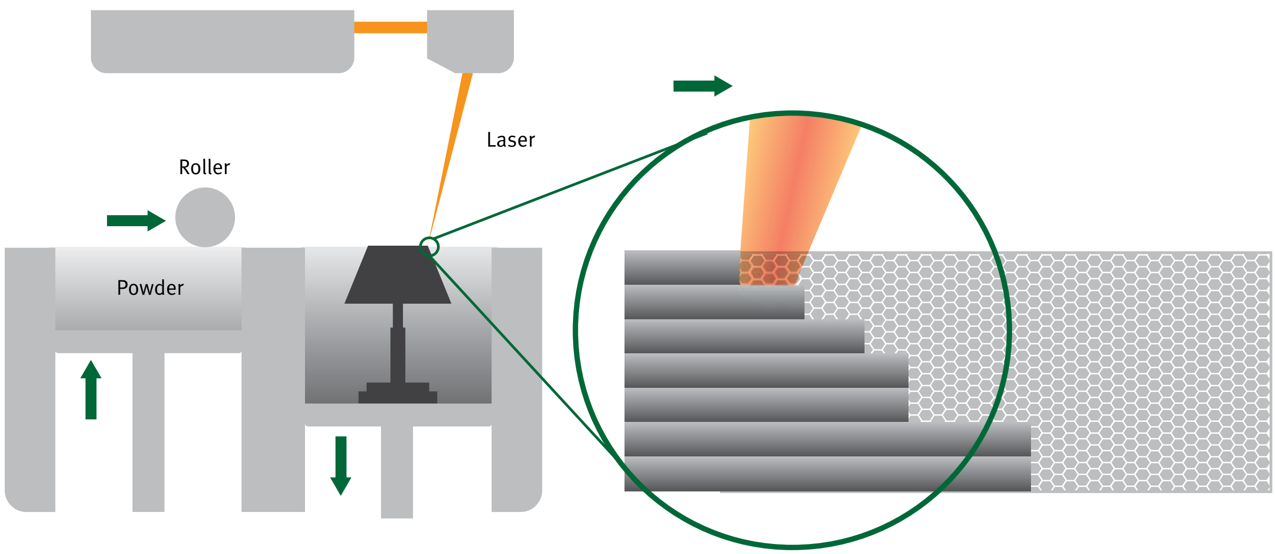

Figure 2. How the selective laser sintering process works.

beds are favorable for reducing the buildup of residual stresses during the fabrication of a component; however, at the current temperatures, this is applicable only to alloys with a lower melting point (Hassen and Kirka 2018).

Types of Discontinuities Found in Metal AM Parts

Common discontinuities observed in materials fabricated through metal AM include lack of fusion (delamination), shrinkage porosity, gas entrapped porosity, cracking, thermal distortion, warpage, and swelling. Lack of fusion discontinuities arise when a newly deposited layer of powder is not adequately heated and, in turn, melted. This prevents the fusion of the new layer to the underlying solid layer (Hassen and Kirka 2018). Shrinkage porosity is a discontinuity that occurs when the liquid metal available during solidification is not able to compensate for shrinkage/density changes as the material undergoes the liquid-to-solid phase transformation (Dantzig and Rappaz 2017). The identifiable characteristics of shrinkage porosity include an elongated void containing secondary dendrite arms within the void. In the powder-bed processes, entrapped gas porosity is spherical in shape. It is the result of trapped gas within the powder feedstock that cannot escape the melt pool because of the rapid solidification conditions that occur in metal AM builds (Gaytan et al. 2008). In the SLM process, part warpage occurs due to a buildup of residual stresses within the part. This causes distortion in the part geometry because the stress relaxes when the part is removed from the build plate. Cracking in metals fabricated through SLM processes may occur due to the sensitivity of the material to strain age cracking. This is attributed to the precipitation of secondary phases or solidification cracking at the high solidification rates observed in AM processes (Carter et al. 2014).

CT Systems

In relation to performance, a CT system can be considered to be made up of four main components: the X-ray source, the detector, sample manipulation stages (the latter including any mechanical structure that influences image stability), and the reconstruction/visualization system (ASTM 2011).

In the majority of cases, the source and detector will be fixed while the sample rotates in the beam to acquire the necessary set of projections. Most industrial CT systems will use an electrically generated X-ray source, which can be subdivided into nano-, mirco-, or minifocus tubes, depending on the focal spot size, or into open tubes, closed tubes, or linear accelerators, depending on the technology. The energy range value in the industrial sector extends from double-digit kilovoltage to lower megavoltage values.

A radiation detector is used to measure the transmission of X-rays through the object along the different ray paths. The purpose of the detector is to convert the incident X-ray flux into an electrical signal that can be handled by conventional electronic processing techniques (ASTM 2011). For example, a high-resolution CT system (small X-ray focal spot size) may have a considerably lower flux output at more modest resolution settings than one designed to operate at such resolution. Furthermore, a high-performance rotation stage for a high-resolution scanner will have a much smaller load limit. Similarly, a system designed for high-energy imaging will require a thicker phosphor screen, giving a poorer resolution compared to a thinner screen, which is adequate at lower energies (ASTM 2011).

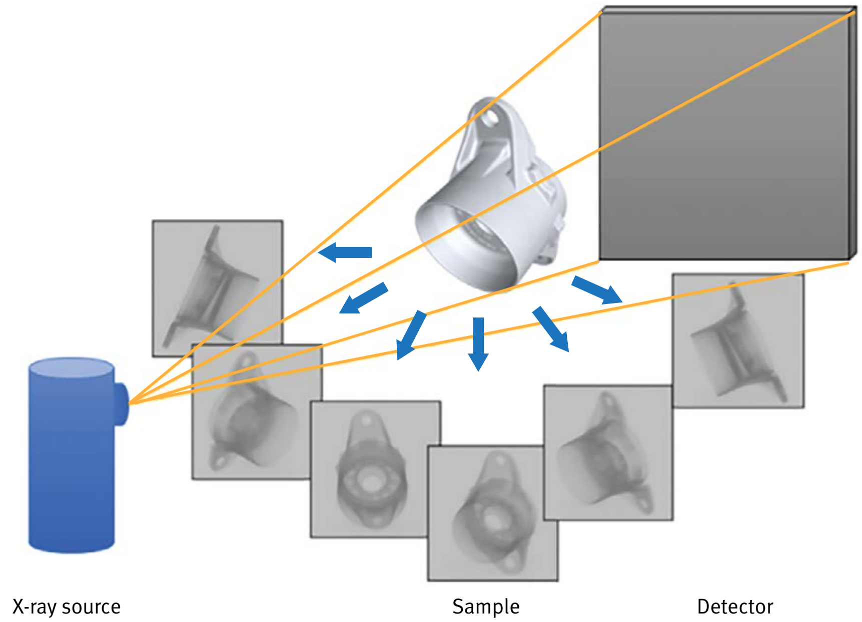

Figure 3. Scheme of the CT scan process.

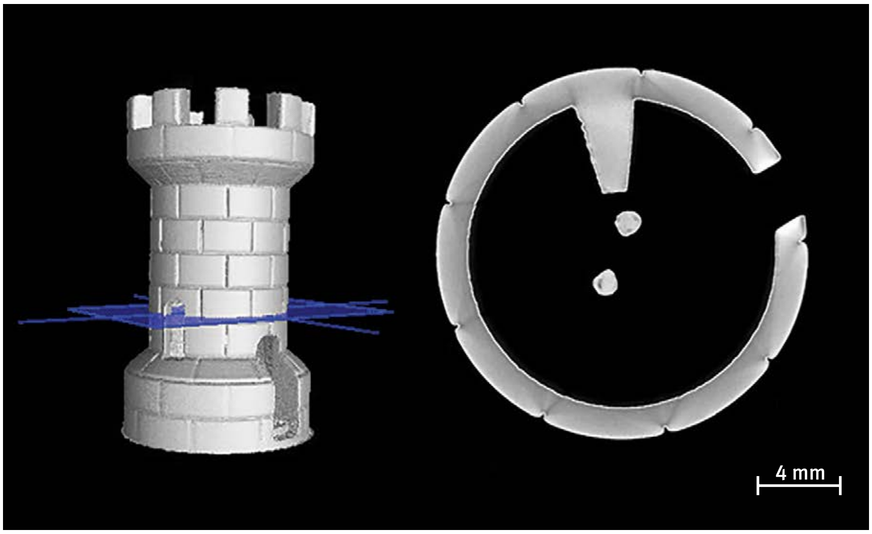

Figure 4. Sample 3D volume and top view of a cross-sectional plane.

CT Process

During a CT scan, multiple projections are taken in a systematic way: the images are acquired from a number of different viewing angles (Figure 3). Feature recognition depends, among other factors, on the number of angles from which the individual projections are taken. The CT image quality can be improved if the number of projections of a scan is increased (ASTM 2011).

The main step is the reconstruction process of these images, which distinguishes this examination technique from other radiographic methods. A computer reconstructs the volume of that stack of projections and an image of a cross-sectional plane (slice) through an object (Figure 4). The resulting cross-sectional image is a quantitative map of the linear X-ray attenuation coefficient, μ, at each point in the plane. The linear attenuation coefficient characterizes the local instantaneous rate at which X-rays are removed during the scan, by scatter or absorption, from the incident radiation as it propagates through the object (Rapid Prototyping Services Canada 2018).

This radiographic technique can be an excellent choice whenever the primary goal is to locate and quantify volumetric details in three dimensions. In addition, since the technique is X-ray based, it can be used on metallic and nonmetallic samples, solid and fibrous materials, and smooth and irregular-surface objects. Furthermore, this kind of inspection allows an acquisition without contact, access to internal and external dimensional information, and, depending on the reconstruction software, a wide range of different analysis methods (ASTM 2011).

Part 2 of this article will provide examples of CT inspection, along with evaluation criteria and a description of the types of discontinuities that are found in AM parts. A case study will be presented as well.

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