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IFAC-PapersOnLine 49-31 (2016) 25–29

# Metrological Investigation of a Selective Laser Melting Additive Manufacturing System: A Case Study

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Abstract: Despite all the improvements that have occurred in the last three decades, surface finish and the cost of production are among the main barriers preventing the widespread application of metallic Additive Manufacturing (AM) process in the industry. This paper presents a metrological performance investigation study for a Selective Laser Melting (SLM) system. In order to do so, an experimental procedure is performed to evaluate the technical performances of the process in terms of repeatability, geometric and dimensional capabilities, and the effects of part removal. The results of the investigation show that SLM appears to be a very repeatable process requiring particular attention during part removal, and it could be considered a suitable candidate for high technology applications.



*Keywords:* Additive Manufacturing, Dimensional and Geometric Measurement, 3D Printing, Metrology

## 1. INTRODUCTION

Additive Manufacturing (AM), also referred to as 3D printing, is a relatively new technology that consists of building three-dimensional (3D) components by laying down materials in layers. The materials can be polymers, metals, ceramics and composites. The method is driven by a 3D Computer-Aided Design (CAD) model detailing the geometry of the part, most commonly saved in Stereolithography (STL) file format. There are mainly two direct techniques for metal AM. The first one is Powder Bed Fusion, which includes Selective Laser Melting (SLM) and Electron Beam Melting (EBM) processes. These are full-melt layer-based processes that apply a heat energy source to fuse selectively powder particles. The main difference between them is that SLM uses a high power laser beam as an energy source in a chamber filled with inert gas, whereas EBM uses an electron beam in a vacuum, instead. The second technique is the Directed Energy Deposition (DED), where metal powder or wire is deposited into a melt pool heated by a focused laser, electron beam or plasma arc as a high power energy source. More details about these processes can be found in (Gibson et al., 2010; Frazier, 2014 and Korner, 2016).

The metallic AM technology presents many advantages over conventional machining processes. Fixtures or tooling are not required, which may lead to shorter setup times, and therefore, lower setup costs. In addition, with minimum wasted material, AM has the ability to produce normally unachievable complex shapes and geometries, such as internal pathways, cavities and structures. Some detailed investigations of metallic AM technologies and materials have been carried out by (Mur et al., 2012; Vayre et al., 2012 and Tapia et al., 2014). In 2014, Tapia and Elwani described what had been achieved in the field of process monitoring and control of metal-based AM processes to enhance part quality and repeatability, and provided insight into what still needed to be achieved. In 2015, Sing et al. presented a review of EBM and SLM processes, materials and designs. They described a significant potential of both processes to become the preferred methods for producing orthopaedic implants. Another review on the additive manufacturing of metallic components by Selective Electron Beam Melting (SEBM) was presented by Körner in 2016. This work describes the relationship between the SEBM process characteristics, the material consolidation phenomena and the resulting component properties. In the same year, Ding and Kovacevic studied the feasibility of printing metallic structural materials with robotized laser-based metal additive manufacturing. Nevertheless, this technology still presents limitations in terms of surface finish and accuracy, process speed, production costs, component size, mass production of identical parts, material options, post-processing, standardisation, etc. It is obvious that these key areas need further investigation before metallic AM will be adopted by high technology industries, such as aerospace, automotive, etc.

In this study, a metrological performance investigation of a selected SLM AM systems is presented. The paper is organized as follows: Section 2 describes the experimental procedure carried out, followed by a comparative/statistical analysis of the results obtained and a general discussion (Section 3). Finally, a summary is provided and future works are described in Section 4.

## 2. EXPERIMENTAL PROTOCOL

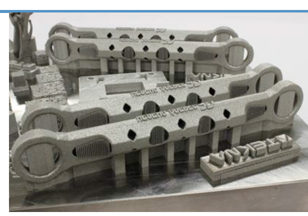
The goal of the experimental procedure is to evaluate the technical metrological capabilities of a selected SLM system currently used for 3D printing of metallic parts. To this end, a total of five (5) printed components were provided from two (2) different Canadian manufacturers for examination. The


10.1016/j.ifacol.2016.12.156

considered test component was built on a base plate using Ti-6Al-4V powder. The overall dimensions of the test component are: length of 188 mm, width of 29 mm and height of 19 mm. Table 1 summarizes the proposed experiment matrix. Part $A$ includes four (4) components that were produced using an EOS M290 system. Part B consists of one (1) component produced using an EOS M280 system. In both cases, the components' orientation, support and SLM parameters were identical (EOS Ti64 Performance setup with $30\,\mu m$ layer thickness). After fabrication, an EOS-recommended stress-relieving heat treatment (6 hours at $800°C$) was carried out on all the components. After heat treatment, only component $B$ was separated from the building platform using a band saw (see Table 1).

A 3D dimensional inspection of the components was carried out using a Metris LC50 laser scan mounted on a Mitutoyo Coordinate Measuring Machine (CMM) (accuracy $\approx 20\,\mu m$ @ 95% level) and a Nikon XT H 225 Micro-Computed Tomography (μ-CT) system (accuracy ≈ 50 $\mu m$ @ 95% level) as shown in Figure 1. The units were provided by the École de Technologie Superieure (ÉTS) laboratories in Montreal, Canada. The following are the results of the metrological investigation.

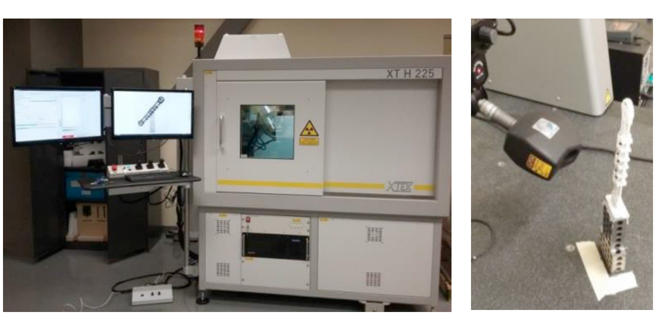
**Table 1. Proposed experiment matrix**



**Overall dimensions ≈ $188 \times 29 \times 19\ mm$**

| Part | Process | Number of components | Printing direction | Post-Treatment |
|---|---|---|---|---|
| $A*$ | SLM | 4 | H | HT |
| $B$ | | 1 | H | HT+PR |

H: Horizontal; HT: Heat Treatment; PR: Part Removal;
*A=[A1, A2, A3, A4]




(a) (b)

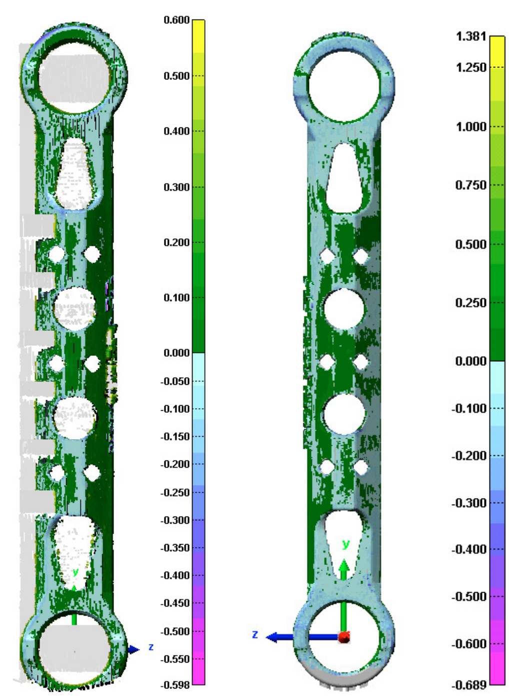
Fig. 1. 3D scanners used to digitize the part at ÉTS: (a) Nikon μ-CT, and (b) Metris laser on CMM

## 3. RESULTS

The results of the dimensional and geometric analysis based on ASME Y14.5 (2009) of the printed parts are presented in this section. Five (5) types of analysis were performed (dimensions are in mm):

(1) Overall 3D profile deviation analysis;
(2) Repeatability study (same process, same setup);
(3) Effect of part removal;
(4) Statistical analysis: Similarity comparison using the Kolmogorov-Smirnov (KS) and the Mann–Whitney (U) statistical tests;
(5) Geometric and Dimensioning Tolerancing (GD&T) analysis.

The first analysis was performed using the IMInspect module of PolyWorks® V.12. It consisted in measuring the profile tolerance deviations (without frame of reference) between the digitized parts (SCAN) and the nominal part (CAD). Color deviation maps are presented in Figure 2. The different colors in the deviation map represent the amplitude of the deviations of the profile (normal vector to the nominal surface). Figure 3 shows the frequency-density histogram of deviations and a Gaussian distribution fit. Table 2a summarizes some descriptive statistical outputs.




(a) (b)

Fig. 2. Color deviation map of (a) A1 and (b) $B$ (dimensions in mm)