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Evaluation of the influence of post-processing on the optical inspection accuracy of additively manufactured parts

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Abstract: Optical measurement systems are important techniques for rapid inspecting additively manufactured parts by techniques such as selective laser melting (SLM). Depending on their application, SLM parts require post-processes such as sandblasting or heat treatment, commonly applied in order to improve their surface finish or mechanical properties, respectively. These post-processes modify the parts surface characteristics, and therefore the suitability for optical inspection. This work evaluates the influence of these SLM post-processes on optical inspection. For this, a test part, manufactured in 17-4PH stainless steel using a 3DSystems ProX100 machine, was optically measured using a structured light scanner and compared to the values obtained from contact measurements (reference values). Both optical and contact measurements were performed under three conditions: as-built, post sandblasting, and post sandblasting and subsequent heat treatment. The analysis results show that applying the sandblasting post-processing provides a surface finish to the SLM parts suitable for optical inspection. This post-process allows precise inspection of this type of parts, reaching values close to those obtained by contact. Likewise, it is concluded that the used structured blue-light scanner is suitable for inspecting SLM parts.

Keywords: Accuracy, Additive manufacturing (AM), Non-contact inspection, Post-processes, Structured light scanner.

1. Introduction

Among other additive manufacturing (AM) techniques based on powder bed fusion (PBF), selective laser melting (SLM) stands out for its ability to create functional and high-complex metal parts of great interest to several sectors such as aerospace, medical or automotive, among others. In these sectors geometrical and dimensional accuracy is a critical factor.

Optical measurement systems play an important role in inspecting parts obtained by AM processes, as they allow the creation of dense point clouds in very short times, characterized as rapid inspection systems. In addition, the free form shapes and complex geometries typical of AM parts convert them into evident targets to verify using non-contact measurement systems. Nevertheless, for these inspection techniques to be extended, the accuracy that can be reached from the metrological point of view still needs to be determined. The evaluation of these non-contact inspection systems depends not only on the materials, surface finishes, lighting, etc. [1] but also on the technology used by the optical sensor [2].



During SLM manufacturing process, the part is subjected to a complex thermal cycle that produces residual stresses in it [3], negatively affecting its accuracy. Additively manufactured parts using SLM technology require post-processes. Some of them are mandatory, such as separating the part from the built-up plate or removing the support structures, and others are optional and applied in order to improve the parts properties. These post-processes are usually classified into mechanical and heat treatment (HT) procedures. In addition to separating the part from the built-up plate, mechanical post-procedures are usually applied to ensure the assembly of parts (machining or grinding) and to improve their surface finish (sandblasting, shot peening, dry mechanical-electrochemical polishing, abrasive processes, etc.) [4-7]. On the other hand, HT post-procedures are applied to relieve the thermal stresses generated during the SLM process, as well as to improve the mechanical properties and reduce the internal porosity of the parts [8-10]. These post-processing operations modify (to a greater or lesser extent) the surface finish (brightness, colour, texture, etc.) of the parts and thus their suitability to be captured by optical sensors.

In a previous study [11], the influence of different common post-processes on the geometrical and dimensional accuracy of SLM parts was analysed using a coordinate measuring machine (CMM). Now, the parts are measured at different states using a 3D scanner with the aim of evaluating the optical accuracy after different post-processing (sandblasting and HT), comparing the results obtained with the CMM measurements (reference). The optical measurement system used is a structured light scanner, which is one of the most suitable equipment for measuring such parts, as concluded in previous research [2].

2. Methodology

A test part consisting of 21 cubes homogeneously distributed on the built-up plate was manufactured from 17-4PH stainless steel (whose composition is shown in table 1) using SLM technology. The cubes are 10 mm length and separated in both X and Y directions by 10 mm. This type of geometry allows a quick dimensional and geometrical evaluation using both contact and optical equipment.

Table 1. 17-4PH stainless steel powder composition specifications.

Element	Fe	Cr	Ni	Cu	Si	Mn	Nb
Weight (%)	Balance	15-17.5	3-5	3-5	<1.0	<1.0	0.15-0.45

In order to evaluate the influence of post-processing on the optical inspection accuracy of SLM parts, this test part was measured both by contact (reference) and optically (test) in the following three conditions:

- As-built condition (AB): A 3DSystems ProX 100 machine was used to manufacture the test part. This SLM machine is equipped with a fibre laser of 1,070 nm of wavelength. The setting process parameters were: laser power of 38W, scanning speed of 140 mm/s, layer thickness of 30 μm , hatch distance of 70 μm and hexagonal scanning strategy.
- Post sandblasting condition (SB): After the SLM process, the part was sandblasted using a Sablex S-2 machine. It works at a pressure of 7 bar by propelling abrasive powder of white aluminium oxide WFA F100 through a 4 mm diameter nozzle.
- Post sandblasting and subsequent stress relieving HT condition (SB-HT): After the sandblasting process, the test part was subjected to stress relieving HT. According to the manufacturer recommendations, for this material the stress relieving HT consists in heating the part to 650 $^{\circ}\text{C}$ for 2 h followed by air cooling.

A CMM DEA global image together with the computer-aided inspection software PC-DMIS 2015 were used for contact measurements. This CMM equipped with a contact scanning touch-probe Renishaw[®] SP25 and a 1mm diameter tip was used to measure 100 points (evenly distributed in a 10 x 10 grid) on each of the five accessible faces of the test part cubes.

For optical measurements, a structured blue-light scanner Breuckmann smartSCAN^{3D}-HE (currently AICON SmartScan) based on the fringe pattern projection technique was used. This 3D scanner, which works based on the miniaturized projection technique, consists of a projection unit (550 ANSI Lumen and 28 Mpx resolution) and an acquisition system with two-cameras (4 Mpx resolution per camera). It can work with different fields of view (FOVs) from 30 mm to 1500 mm. In order to obtain good measurement accuracy according to the evaluated part size, a 125 mm FOV was used for this study [12]. The main specifications of this equipment are shown in table 2. The used 3D scanning software was Optocat[®]. For the complete capture of the test part, after previous sensor calibration, 16 scans were performed in each condition (AB, SB, SB-HT).

Table 2. 125 mm FOV specifications.

FOV size (mm)	Measuring depth (mm)	X, Y resolution (μm)	Z resolution (μm)	Feature accuracy (μm)	Working distance (mm)	Triangulation angle (°)
95 x 95	60	50	5	9	370	32.5

Geomagic[®] Control XTM inspection software was used to geometrically and dimensionally analyse the test part scans. For this, the plane features of all cubes accessible faces of the test part and the base XY plane (top face of the built-up plate) were created using the “best-fit” adjustment method (least squares algorithm). To create these planes, all points captured by the structured light scanner were taken except those located less than 1.5 mm from the cubes edges (thus avoiding errors arising from the “edge effect”).

Figure 1 shows the experimental methodology followed in this work.

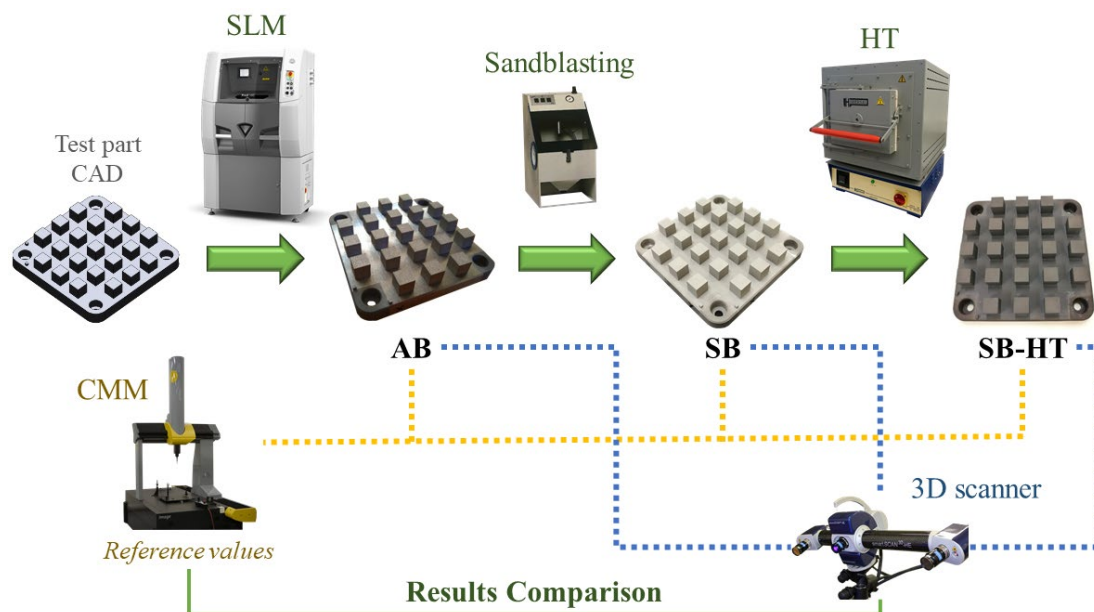


Figure 1. Experimental methodology.

3. Results and Discussion

All the results shown in this section are the deviations between the values obtained from the optical measurements with respect to the contact measurements values (taken as a reference). The smaller the resulting deviations, the closer the optical and contact measurements are.

Although similar values are sought in both inspection methods, it should not be forgotten that in this type of part, characterized by high roughness, contact measurements may not capture all the real points

on the surface, while the 3D scanner can more reliably capture this surface texture, except when the surface is shiny or has a colour difficult to scan (leading to spurious points).

3.1. Geometrical analysis

The flatness results are similar in all three states: AB (figure 2(a)), SB (figure 2(b)) and SB-HT (figure 2(c)). Figure 2 shows two views of each state thus allowing the complete visualization of the part. There is a slight difference depending on the direction of the analysed plane (XZ, YZ, XY), the XZ plane being the one with the lowest deviations (table 3). This may be related to the SLM manufacturing process, where the roller moves in the X direction (parallel to the XZ plane) corresponding to the surfaces of least geometric error. As shown in figure 2, flatness deviations vary between positive and negative values without a clear trend, being the ranges from -0.041 to 0.116 mm (157 μm range), -0.071 to 0.129 mm (200 μm range) and -0.075 to 0.114 mm (189 μm range) for the AB, SB and SB-HT condition respectively.

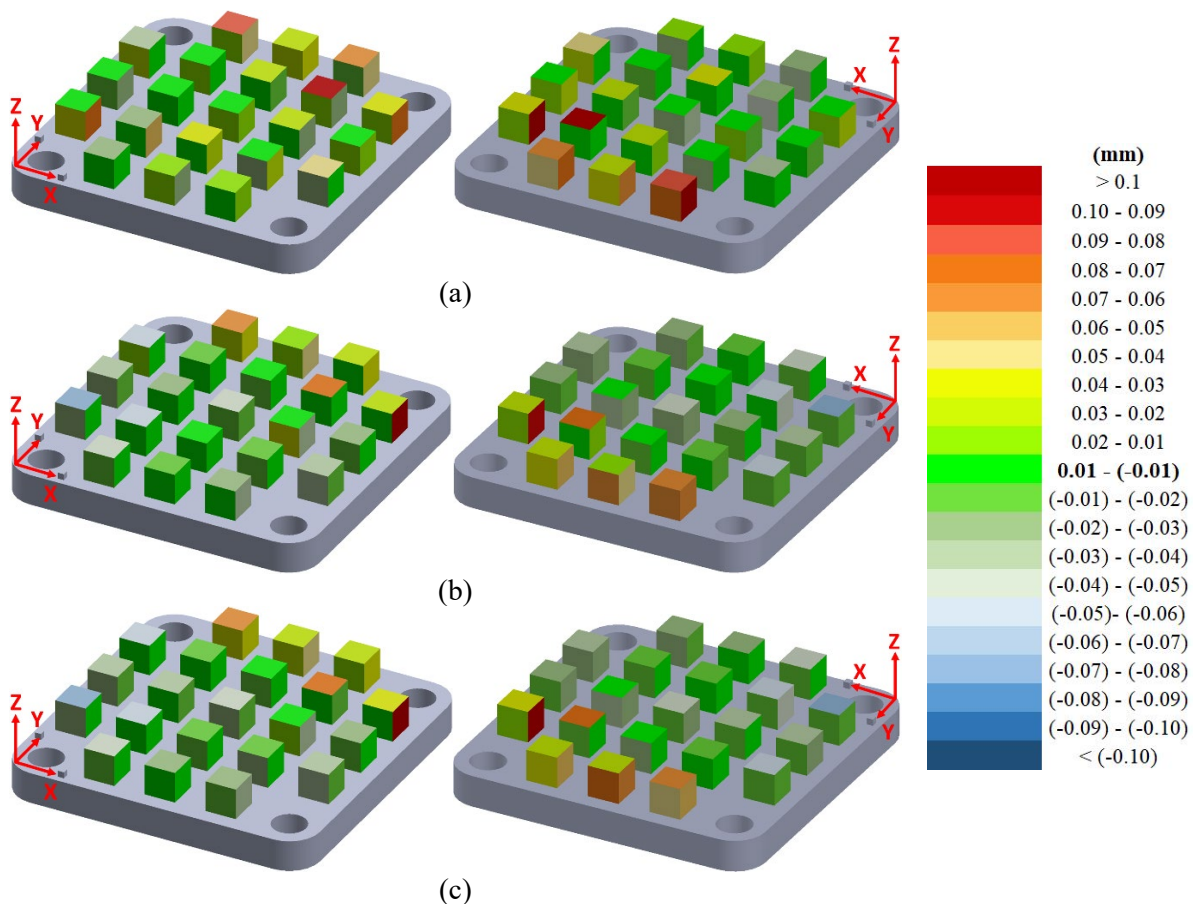


Figure 2. Flatness deviations of the cubes accessible faces of the test part for the condition: **(a)** AB, **(b)** SB and **(c)** SB-HT.

Table 3. Average absolute values of flatness deviations of the cubes accessible faces of the test part for the three conditions.

Condition	XZ (mm)	YZ (mm)	XY (mm)	Average (mm)
AB	0.0170	0.0267	0.0279	0.0231
SB	0.0174	0.0217	0.0330	0.0222
SB-HT	0.0183	0.0229	0.0349	0.0235

As shown in table 3, the average geometric deviations are about $18\ \mu\text{m}$, $24\ \mu\text{m}$ and $32\ \mu\text{m}$ according to the XZ, XY and XY planes of the test part cubes, respectively. Therefore, regarding flatness measurements, the two different post-processes applied to SLM parts do not show a noticeable influence.

For the parallelism error, measured in the cubes XY planes with respect to the base XY plane, an average deviation of $50\ \mu\text{m}$ was obtained for the AB condition, $24\ \mu\text{m}$ for SB condition and $27\ \mu\text{m}$ for SB-HT condition. All parallelism deviation values were positive regardless of the cube and condition (figure 3). Values that have a notable difference between the initial state (AB condition) and the post-processing conditions (SB and SB-HT). The most unfavorable results are in the AB condition (figure 3). This may be mainly due to the brighter appearance of the part, since in the AB condition it is riddled with small bright facets scattered across its surface, with their normals oriented in multiple directions.

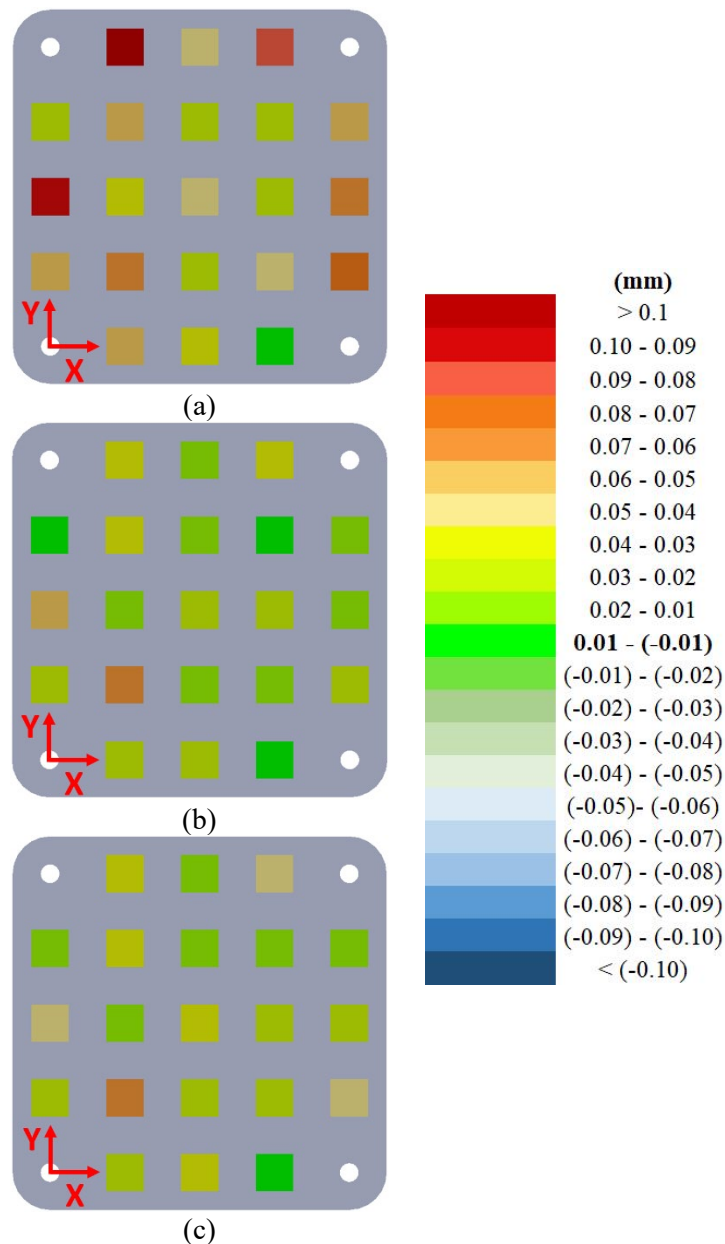


Figure 3. Parallelism deviations of the cubes XY planes of the test part with respect to the base XY plane for the condition: (a) AB, (b) SB and (c) SB-HT.

3.2. Dimensional analysis

Figure 4 shows visually the deviations (optical measurements with respect to contact ones) of the cubes dimensions of the test part in all three states: AB (figure 4(a)), SB (figure 4(b)) and SB-HT (figure 4(c)). Regarding dimensional errors, there is an improvement in the cubes dimensions measurement after the sandblasting post-process (table 4). This improvement is more remarkable on the cubes lateral faces (X and Y dimension) than on the top face (Z dimension). As a result of the sandblasting post-process, the dimensional error decreases by about 8 μm according to the Z direction, while in the X and Y directions it decreases by about 44 μm and 32 μm respectively (table 4). Dimensional deviations for AB and SB-HT conditions, as well as for X and Y dimensions of the SB condition, are negative, which is due to the filtering that is inevitably applied when using a probe tip in contact measurement. However, the Z dimension of the SB condition is positive because, in this case, the sandblasting process eliminates small imperfections from the parts outer surface, allowing the contact probe to touch a surface closer to the actual one. This effect is most noticeable on the cubes XY face since it is the roughest. For AB, SB and SB-HT conditions the range of the dimension deviation values is as follows: -0.057 to -0.024 mm (33 μm range), -0.033 to 0.017 mm (50 μm range) and -0.037 to -0.001 mm (36 μm range) respectively.

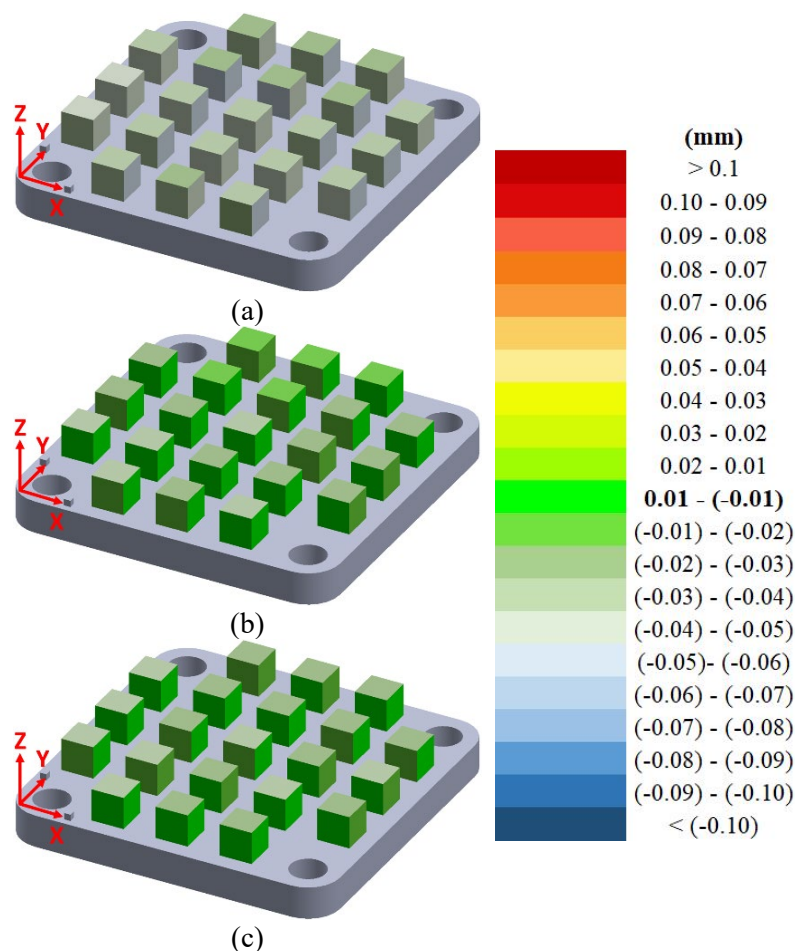


Figure 4. Dimensions deviations of the test part cubes according to the X, Y and Z axes for the condition: (a) AB, (b) SB and (c) SB-HT.

Table 4. Average absolute values of dimensions deviations of the test part cubes according to the X, Y and Z axes for the three conditions.

Condition	X (mm)	Y (mm)	Z (mm)	Average (mm)
AB	0.0499	0.0401	0.0330	0.0410
SB	0.0062	0.0085	0.0253	0.0133
SB-HT	0.0091	0.0074	0.0293	0.0152

The HT application after the sandblasting process does not produce significant variations in the results of dimensional measurements of the cubes. This may be because the change in colour or texture of the part after HT is not as significant as the matte finish provided by sandblasting post-processing.

4. Conclusions

In this work, the influence of two post-processes of the SLM manufacturing process in the optical measurement was analysed. These two post-processes, sandblasting and stress relieving HT, are commonly applied to parts after additively manufacturing using the SLM technology. To achieve this, a test part consisting of a grid of equally spaced cubes distributed upon the built-up plate was SLM manufactured and measured in three different conditions: as-built (AB), after sandblasting (SB), and after sandblasting and subsequent stress relieving HT (SB-HT). The material used was 17-4PH stainless steel. Optical measurements were performed using a structured light scanner and were compared to the reference values obtained from contact measurements (CMM).

- Regarding geometric error, optical measurements show a very similar tendency regardless of the part condition (AB, SB or SB-HT). In absolute value, the flatness average deviation of the structured light sensor measurements with respect to the CMM is about 23 μm . The surfaces with the smaller geometric deviations are the XZ planes of the test part, with an average value of about 18 μm .
- The parallelism measurements of the cubes XY planes show a greater deviation for AB condition (average value of 50 μm). While the deviations from SB and SB-HT conditions are 24 μm and 27 μm respectively.
- The results of the dimensional analysis show a considerable improvement in optical measurements (compared to those of contact) after the mechanical post-process. The optical measurements deviations after sandblasting post-process are about 6 μm , 9 μm and 25 μm according to the X, Y and Z directions, respectively. This means that sandblasting of SLM parts allows for accuracy optical measurements, close to those obtained with contact systems.
- On the other hand, regarding dimensional error, the application of the HT post-process does not significantly affect optical measurements. To check the HT effect regardless of sandblasting, it would be interesting to optically inspect the parts resulting from the application of this post-process without prior sandblasting. In this way, it would be verified whether the results obtained in this work are influenced by the previous sandblasting process or whether they correspond to the surface finish resulting from HT.

Finally, it can be concluded that the sandblasting post-process provides the SLM parts with finishing characteristics more suitable for measurement with optical systems. This post-process smooths and removes brightness from the surface, factors that can lead to spurious points in optical measurements. The structured light scanner evaluated in this work is suitable for the inspection of SLM parts, since the values are closed to the contact (CMM) measurements. Likewise, the deviations obtained between the optical and contact inspection of the SLM parts are negligible after applying the sandblasting post-process.

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