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Impact on mechanical properties following a process interruption during Additive Manufacturing

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Abstract

Over the past decade, additive manufacturing has made a tremendous progress; This technology gets a great interest to the development of mechanical parts with complex geometries and compositions. The freedom of conception allows using additive manufacturing process in order to integrate optical sensors during the printing process and opens the way to the production of instrumented components for SHM (Structural Health Monitoring). The latter required a particular process with adapted printing strategy and an interruption of the procedure in order to implement the sensor. The impact of this insertion needs to be investigated in order to assess its influence on the mechanical parts behaviors.
In this work, we perform several experiments on different 3D Printed parts with and without inserted sensors and identify the impact of the process interruption on the mechanical properties of manufactured parts.

Keywords: Laser powder bed fusion, optical fiber, mechanical properties, process interruption

1. Introduction

Additive manufacturing is mandatory in order to embed optical sensor inside metallic parts for critical components monitoring. In this work, the selected process is the Laser Powder Bed Fusion (L-PBF). L-PBF, also called Selective Laser Melting (SLM) is often used to produce complex metallic parts. These metallic parts can be manufactured with several types of metals such as stainless steels, nickel superalloys, titanium alloys, copper, aluminum alloys and many more. Regardless of the printer type, the process remains the same; a layer of powder (10-90 µm) is distributed on a build platform, afterwards a laser beam by interacting with the powder will melt ilts particles with a selective algorithm, then the molten metal will solidify. These operations will be repeated several times in order to build the full metallic part, layer by layer [1].

Currently, most studies associating optical sensor with additive manufacturing are focusing on the monitoring of metallic parts thanks to these sensors. For instance, Havermann *et al.* [2] and Maier *et al*. [3] described the process in order to embed such sensors. Only a few papers described the impact of integrating optical sensors into metallic parts on their mechanical properties [4, 5]. Globally optical sensor embedment requires a process interruption for L-PBF and this may have a significant impact on the mechanical properties; the aim of this paper is to study the impact of a process interruption on the mechanical properties of several parts printed in different configurations.

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Nomenclature

L-PBF	Laser Powder Bed Fusion
SLM	Selective Laser Melting
SS	Stainless Steel
Ec	Volumic energy
Plaser	Laser power (W)
Vscan	Laser speed
HD	Hatching Distance
t	Thickness
Rp0.2	Yield Strength
Rm	Ultimate Tensile Strength

2. Materials and methods

2.1. Material and process

The tested samples were produced using a TruPrint series 1000 L-PBF printer (TRUMPF GmbH).The material used for this study was a gas-atomized AISI SS 316L powder manufactured by SLM Solutions Europe GmbH with a particle size distribution of about 20 – 45 µm.

Table 1 shows the average chemical composition of the virgin stainless steel powder measured by inductively coupled plasma mass spectrometry (ICP-MS).

Specimens were manufactured with a 200 W continuous Yb-fiber laser (1064 nm) and a spot size of ~ 30 µm. Fabrication was performed under argon atmosphere with a residual oxygen concentration inside the build chamber below 200 ppm. The parts built was achieved with a layer thickness of ~ 30 µm and a 67° rotation between each layer laser scanning strategy. Laser parameters were optimized beforehand to achieve a high density of ~ 99.98% (determined by Archimede's principle). A volume energy density (Ec) of 76.2 J/mm^3 was used according to the formula (1), with Plaser the power of the laser in W, Vscan the laser speed, HD the hatching distance and t the layer thickness:

$$Ec = \frac{Plaser}{Vscan * HD * t} \tag{1}$$

2.2. Methodology

For the assessment of process interruption impact during L-PBF process, two different batches of tensile sample were built. Each one of them uses vertical building orientation as described in Fig. 1 with Z corresponding to the direction of construction. First samples A1 were manufactured without process interruption, in order to acquire reference data for future comparison. Samples A2 were realized in two times with a process interruption located 6mm under the middle plane of the tensile tester. The process interruption was performed with 3 hours interruption to ensure that the part and the powder bed are at room temperature. Furthermore, the process to embed optical fiber requires removing the part from the machine, the parts were in contact with ambient air during these 3 hours. Fig.1 shows how the tensile tester specimen was manufactured with the process interruption.

2.3. Methods

The mechanical properties acquired on a tensile tester MT-Criterion43 were determined according to DIN-EN-10002 (ISO-6892). Parts density were determined using Archimede's methods on cubic sample built in the same batch as the tensile tester specimens.

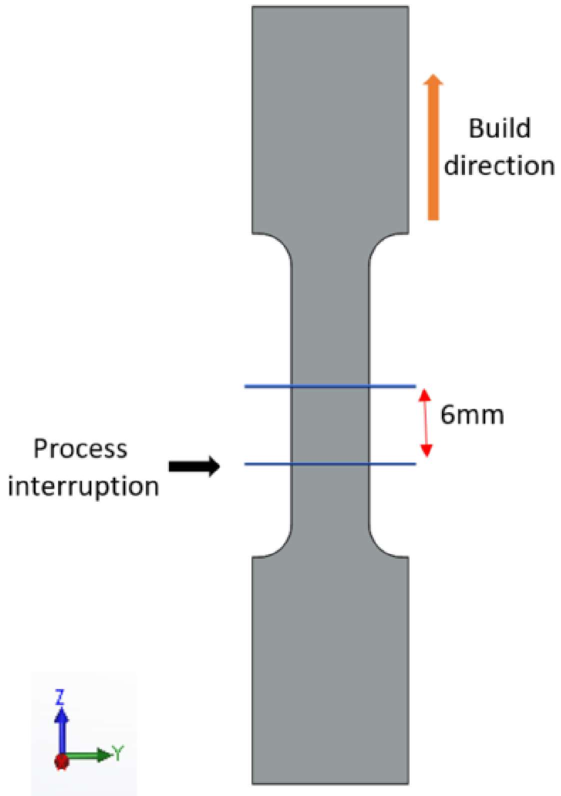

Fig. 1. Tensile tester specimen construction and process interruption

Furthermore, the process interruption has been located 6 mm under the middle plane of the tensile tester specimens in order to demonstrate two points. First, that a process interruption for a vertical build direction does not decrease the mechanical properties, a key aspect for the foreign body embedment inside metallic structures thanks to additive manufacturing. The second point is to ensure that a process interruption whenever it is located in the sample, does not create a local area of weakness. The process interruption was located 6 mm under the middle plane with the aim to be in the effective section for local plasticity.

Table 1. Chemical composition of the virgin SS316L powder, in wt.%

Element	Fe	Cr	Ni	Mn	Mo	Si	N	C	P	S
Weight %	Bal.	17.5	12.6	1.5	2.4	0.04	0.07	0.02	0.002	0.001

3. Results and discussion

3.1. Mechanical properties

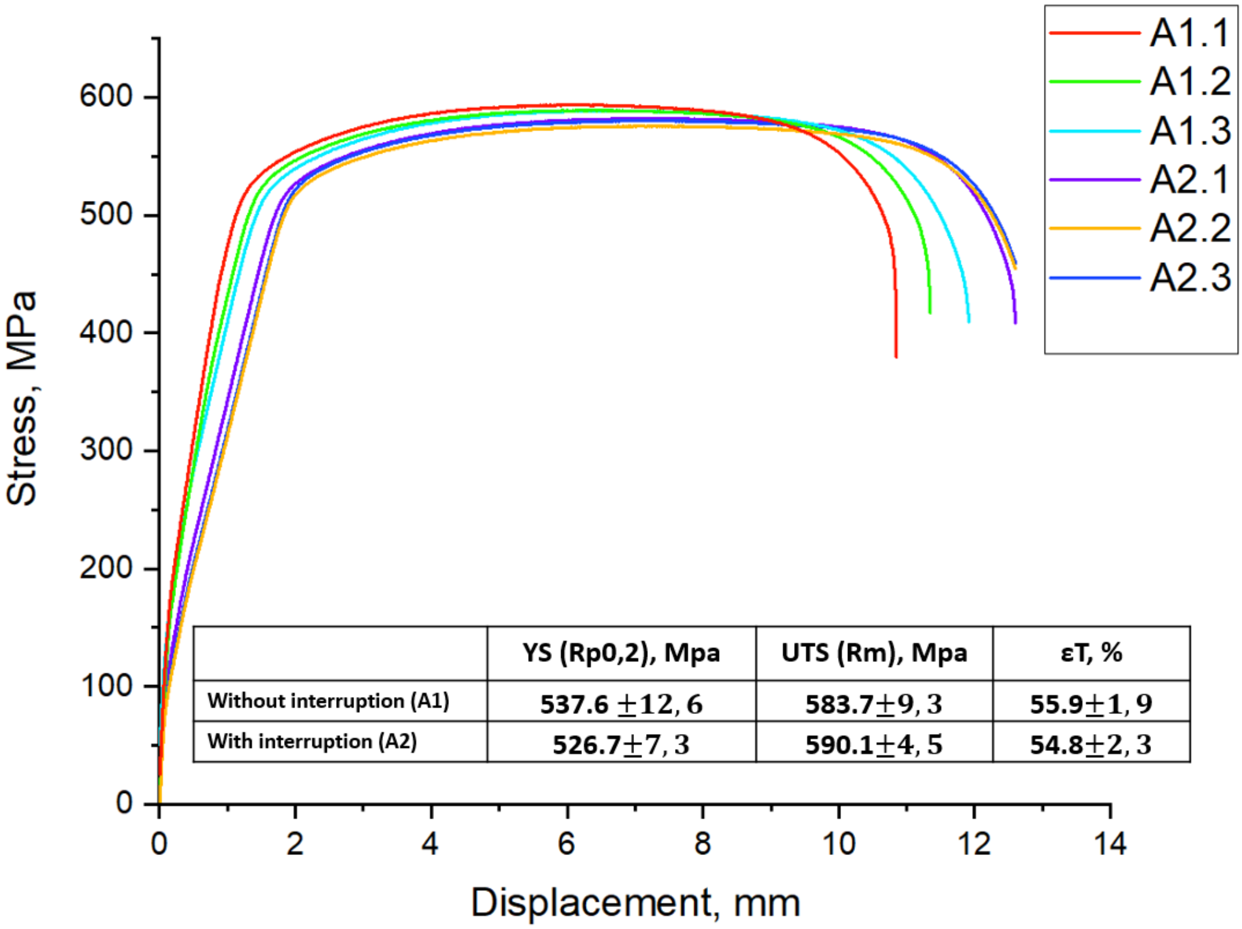

Fig. 2. Tensile Stress/Displacement curve of the L-PBF SS316L specimens built with and without interruption with the mean value and standard deviation

Tensile tester curves are displayed for both A1 and A2 samples in the Fig.2. For both conditions, three tensile tests were performed to prove repeatability. In an obvious way, under tensile loading the interrupted and not-interrupted tensile tester specimens have similar behavior. All error margin are given using standard deviation. The samples yield strength (Rp0.2) is the same for both processes, respectively 537.6 MPa ± 12.6 MPa for the non-interrupted process, and 526.7 MPa ±7.3MPa for the interrupted process. The ultimate tensile strength (Rm) is 583.7 MPa ± 9.3MPa for the classic process and 590.1 MPa ± 4.5MPa for the interrupted one.

It appears that for vertical samples yield strength and ultimate tensile strength do not decrease with a process interruption located under the middle plane. That means that the static mechanical properties remain the same. The obtained values for the yield strength and the ultimate tensile strength agree with those previously reported by Hitzler et al. [6], Spierings *et al*. [7] and Delacroix *et al*. [8].

This means that the values fit well into the range of static mechanical properties reported in scientific literature and outperform the conventional SS 316L process.

Conventional process reported with Rp0.2 = 200MPa, Rm = 500-700 MPa.

Elongation at break values are 55.9 % ± 1.9% for samples without interruption and 54.8 % ± 2.3% for tensile tester specimens with process interruption. These values are comparable, which also confirm the previous point saying that the static mechanical properties remain unchanged even by interrupting the process. The values for the elongation are the same than reported in literature: Hitzler *et al*. [6] and Spierings *et al.* [7]. They are also far superior to the conventional SS 316L process. This behavior is the result of a vertical construction and of the thin microstructure, which allow such high elongation. However, these properties can change according to the laser scan orientation as reported in [7].

3.2. Observation and discussion

Finally, it can be observed in Fig. 3 that the location where the interruption was made is directly visible. It is characterized by a gray straight line on the samples, which is mainly due to a superficial difference in oxidation between the two constructions. Fig.3 b) gives answer about the mechanical behavior of a sample with a process interruption. It is obvious that the process interruption was not involved in the failure mechanism of this specimen.

These tests acknowledge that an interruption not located on the middle plane do not decrease the mechanical properties for a sample built with a vertical orientation, similar result were found by Colosimo *et al.* [9].

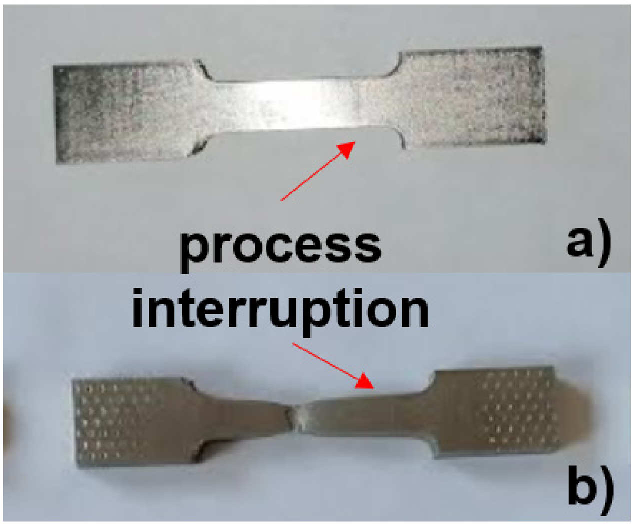

Fig. 3. a) Tensile tester specimen with process interruption; b) Tensile tester specimen with process interruption after testing

4. Conclusion

In this study, gas-atomized SS 316L was used to produce tensile tester samples with L-PBF process. These specimens were produced with and without process interruption.

The latter was located 6 mm under the middle plane of the samples in order to determine if the interruption has an effect on the static mechanical properties and if it creates a local area of weakness. The following conclusions can be drawn from this work:

- Yield strength (Rp0.2) and Ultimate tensile strength (Rm) do not decrease for a sample manufactured vertically with a process interruption located outside the middle plane,
- Elongation at break remains the same with and without process interruption for a sample manufactured vertically with a process interruption outside the middle plane,
- The process interruption does not create a local area of weakness, which means the sample will break at a different location during tensile test, it will not be at the interruption interface,
- This result demonstrates that embedding optical sensor into a vertically build part does not decrease their mechanical properties.

This study is a first step in order to characterize mechanical properties for the embedment of sensor. Even if the mechanical properties remain unchanged with a process interruption, study need to be conducted for the impact of a sensor embedment combined with a process interruption.

Acknowledgements

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