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LASER POLISHING OF ADDITIVE LASER MANUFACTURING SURFACES

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Abstract

The Additive Laser Manufacturing (ALM) technique is an additive manufacturing process which enables the rapid manufacturing of complex metallic parts and the creation of thin parts so as, for example, to decrease parts weight for biomechanical or aeronautic applications. Furthermore, compared with Selective Laser Sintering (SLS) technology, the ALM process allows creating more huge parts and material gradient. However, for aesthetic or tribological functions, the ALM surfaces need an additional finishing operation, such as the polishing operation. Polishing processes are usually based on abrasive or chemical techniques. These conventional processes are composed by many drawbacks such as, accessibility of complex shape, environmental impact, high time consumption and cost, health risks for operators etc... In order to solve these problems and to improve surface quality, the laser polishing (LP) process is investigated. Based on melting material by laser, laser polishing process enables the smoothing of initial topography. However, the ALM process and the laser polishing processes are based on laser technology. In this context, the laser ALM process is used directly on the same machine for the polishing operation. Moreover, an alternation between both processes can be established during the manufacturing operation in order to treat non accessible surfaces. Currently, few studies focus on laser polishing of Additive Laser Manufacturing surfaces, and it tends to limit the industrial use of additive manufacturing technology.

The proposed study describes an experimental investigation of laser polishing surfaces obtained by Additive Laser Manufacturing process. The investigation results in the improvement of complete final surface quality, according to laser polishing parameters. This experimental study introduces the laser polishing of thin section parts, in order to develop laser polishing applications.

According to a manufacturing chain context, the final objective is to create a multi-process mastery in order to optimize the final topography and productivity time.

1. Introduction

Based on laser melting of powders projection, the Additive Laser Manufacturing (ALM) technique is an additive manufacturing process which enables the direct manufacturing of complex metallic parts. Compared with SLS technology, the ALM process enables the creation of bigger parts and material gradient [1]. ALM process also enables the creation of thin parts so as, for example, to decrease parts weight for biomechanical or aeronautic applications. Integrated on a 5 axis milling machine or on an anthropomorphic robot, the laser melts the powder in order to create the desired part, layer by layer or in a continue deposition (Fig.1). Based on CNC machine, it is possible to use hybrid manufacturing technology such as ALM, laser polishing and milling operations.

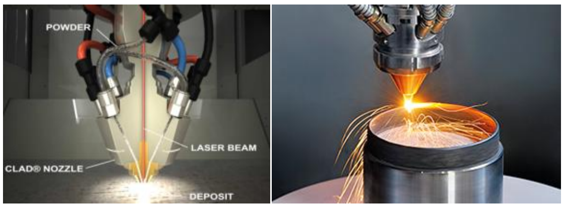

Fig.1: principle of ALM process

However, the final quality of ALM manufactured surfaces is a real problematic [2,3], that tends to limit the industrial application of the process. For aesthetic or tribological function, the manufactured surface needs a finishing operation, such as a polishing operation. Based on abrasive or electrochemical technics, these conventional polishing operations hold many drawbacks. For automated abrasive process, the drawbacks relate to the accessibility of complex surfaces caused by the diameter of the abrasive tool. Actually, the polishing operation is effectuated manually and it remains a slowly task. The efforts applied to the surface are not mastered, and can create nonfunctional parts. Finally, the repetitivity of task and the presence of residual powder of metal can cause a health risk for operators. Regarding the electrochemical polishing process, it holds an environmental drawback, due to the use of a chemical flow and because it requires an identic cathode part to polish the surface. In order to solve these problems, and to improve ALM surface quality, the laser polishing process is investigated. Used a few years ago to polish diamonds [4,5] or optical lenses [6], the laser polishing technique is now chosen more frequently, especially to polish metals. Thereby decreasing processing time and reaching 10 to 200 s/cm² according to the initial topography. The energy of the laser beam is applied to the surface and the topography peaks are melted. With the surfaces tensions, the molten material flow is reallocated into cavities in order to smooth the initial topography (Fig.2). The final topography depends on the operating parameters of the laser on the material, and is also linked to the initial topography and the strategy of laser polishing [7].

2. Problematic

Some studies focus on SLS polished surfaces optimization [8-10] and less are concentrated on ALM laser polished surfaces [11]. Laser polishing optimizations [12; 13] of surfaces of thick section parts are proposed and it tends to limit aeronautic and biomechanical applications of laser polishing process.

The proposed study focuses on the laser polishing of ALM topographies obtained according to a complex and thin part context. Both processes are based on the laser technology. The investigation enables to apply ALM process and laser polishing process on the same 5 axis CNC machine, and it helps to improve productivity. Furthermore, the laser polishing operation can be applied between each ALM deposition layer. Based on experimental investigation regarding laser parameters and scan strategy, the proposed study analyzes final topography optimization according surface roughness and surface integrity. Finally, this study takes into account the final surface roughness and, in a first approach, the geometrical deviation of a real complex geometry, in order to define the process parameters.

3. Experimentations

3.1. ALM Process

The initial topography is obtained according to a complex parts' manufacturing context. Indeed, many strategies are workable in order to create functional parts. The ALM strategy can be based on vertical or flat strategy. The initial topography is function of the primary process strategy. According to a complex part manufacturing context, the vertical strategy is used (Fig.3) to create 316L thin section sample. The argon gas is used during both processes in order to protect the oxidation of surfaces. The gas is projected through the powder projection nozzle of the additive manufacturing machine. The operating parameters used for the manufacturing sample are laser power (P) [W], feed rate (V_f) [mm/min], powder flow rate (Q_m) [g/s] and superposition step (h) [mm]. The 316L powder diameters used for experiments are situated within the range of 45-90 µm and the composition is conform to the standard ISO (Table 1).

Table 1: composition of 316L powder used for manufacturing ALM surfaces

Component	Si	C	Mo	Ni	Mn	Cr
%	0.8	0.02	2.5	12.2	1.4	17.3

3.2. Laser Polishing Process

LP and ALM processes are based on the same 5 axis machine, and use the same laser fiber. The maximum laser power is 800 watts, for an 1070 nm wavelength and a 0,8 mm top-hat spot diameter at offset (O_f) equal to 0 mm. Each ALM sample is divided into several 7 mm x 30 mm laser polished areas. The laser polishing path is perpendicular to the initial ALM topography. The tested laser polishing parameters are:

- Laser power (P) [W]
- Feed rate (V_f) [mm/min]
- Overlap (O_v) [%] which means the distance a line overlaps with the last one
- Strategy of laser polishing

The initial and final topographies are characterized by surface roughness (S_a) [µm] (Eq.1) [14] and calculated according to the standard ISO 4288. The topography optimization is characterized by the surface roughness reduction [%] (Eq.2).

$$S_a[\mu m] = \frac{1}{A}\iint_A |z\,(x,y)|dx\,dy \quad (1)$$

$$S_{a_{reduction}}[\%] = \frac{S_{a_{initial}} - S_{a_{polished}}}{S_{a_{initial}}} * 100 \quad (2)$$

3.3. Material Measurement

The measurements were carried-out thanks to a focal variation microscope ALICONA Infinite focus. This equipment enables to obtain a three dimensional topography of polished surfaces. The roughness parameters were extracted after a 3D-reconstruction, established with the software used.

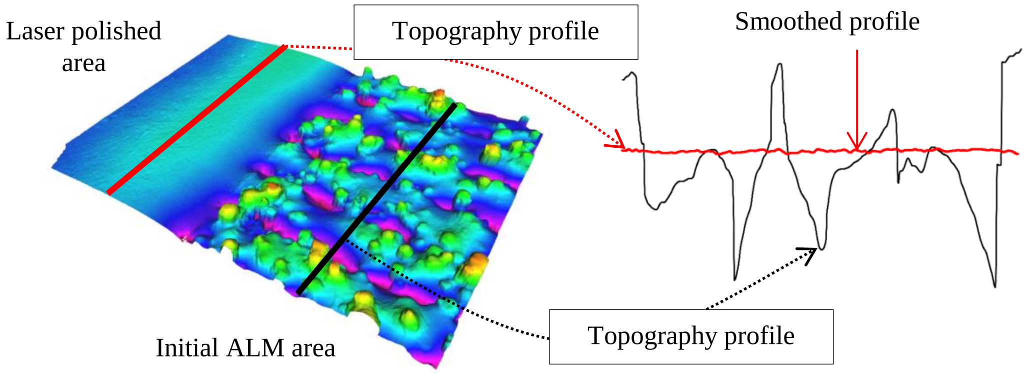

Fig.2: principle of laser polishing process

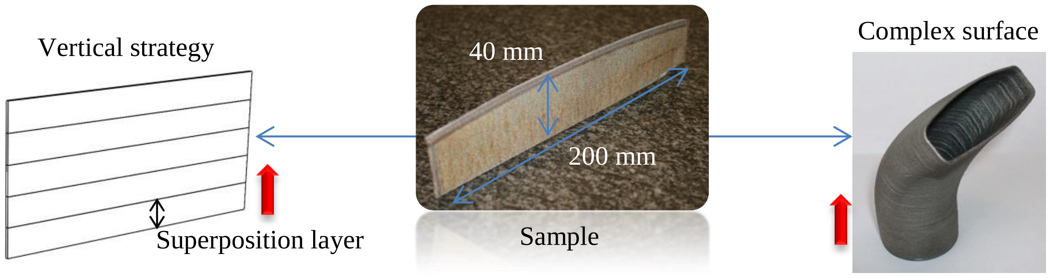

Fig.3: manufacturing strategy of complex ALM surface context

In order to control the surface integrity, a Scanning Electron Microscopy was used. This measure device enables to characterize micro-cracks and helps to measure the composition of the material.

4. Results

4.1. Initial Topography Analysis

The final surface topography depends on laser polishing parameters, strategy, material and initial topography. Unlike milled surfaces, which can be considered as an homogeneous laser polished topography [15], ALM surface is more chaotic, heterogeneous and composed of two different textures (Fig.4) correlated with the process principle. The first one is directional and caused by the layer-by-layer deposition direction. The second one is chaotic and caused by the partially melted powder. The analysis of the initial topography shows an oxidation of the surface. This phenomenon is highlighted by the color of the surface. According to the vertical manufacturing strategy, the argon protection is not sufficient. In other words, the efficacy of protection gas is depending on the argon flow direction.

4.2. Feasibility Study

The first step of the experimental campaign considered the feasibility of laser polishing process according to two objective functions. These objective functions are the final topography smoothing and the form of the polished surface. In this study, the form analysis focuses on the collapse of the surface. Finally, the best determined parameters are a laser energy density E = 525 J/cm² obtained with P = 210 W, V_f = 3000 mm/min, O_f = 0 mm and an overlap (O_v) of 60 %.

After laser polishing, the surface is not collapsed and the topography is smoothed. However, the final topography is not perfectly smoothed and not optimized (Fig.5). The final topography still includes some defects such as material drops and micro-cracks. These material drops tend to increase the surface roughness and impact on the tribological behavior. The micro-cracks reduce the fatigue resistance of the functional surface. Moreover, laser polishing creates a form distortion, caused by the heat transfer onto the thin surface.

4.3. Metallography Analysis Of Material Drops Defect

In order to perceive the composition of surface defect, the scanning electron microscopy device was used. The analysis showed a concentration of silicon oxide into the material drops (Fig.6). The silicon component comes from the AISI 316L powder and becomes a silicon oxide drop during laser polishing process. The oxide component is linked to the ALM surface environment, which is composed of a non-mastered protection gas flow.

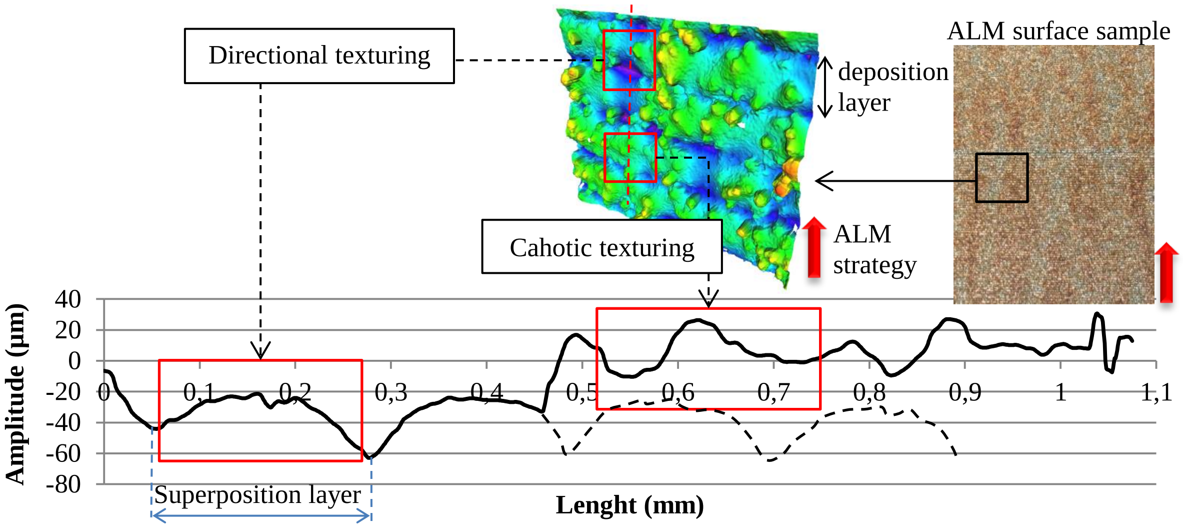

Fig.4: topography of ALM surface

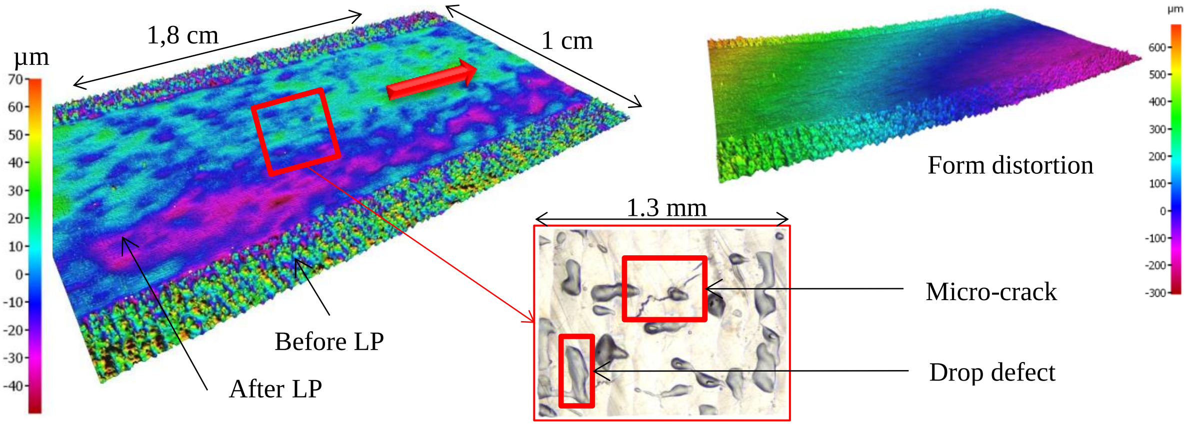

Fig.5: surface topography before and after L.P. and surface defects

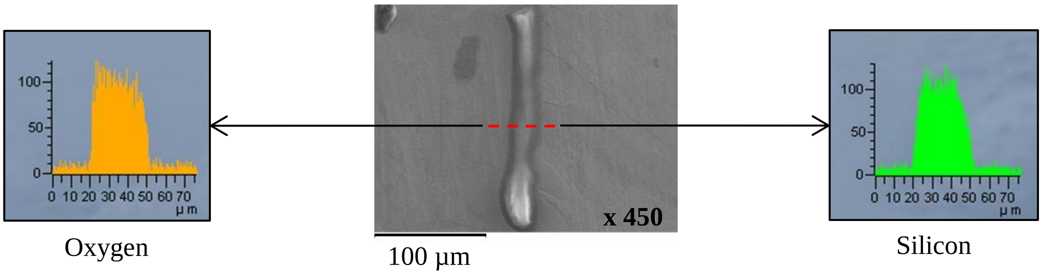

Fig.6: material composition of drops defects

5. Optimization

5.1. Laser polishing strategy

In order to improve the surface smoothing, a multi-pass strategy was chosen. The multi-scan strategy consists in applying N times the same laser parameters on the same surface, according to the same laser path. Keeping the same laser parameters operated for each pass, this strategy simplifies the mastering of laser polishing process. The number of passes varied from 1 up to 5 according to the same laser parameters. As a result, increasing the number of passes improves the topography smoothing (Fig.7). After five laser polishing scans, the initial topography is greatly smoothed (Fig.8). This laser polishing strategy enables to obtain a final surface roughness of 0.79 µm for an initial S_a of 21 µm, and a surface roughness reduction of 96 %. The cut-off filter used for the polished topography is 800 µm and 2500 µm for the initial topography, according to ISO 4288.

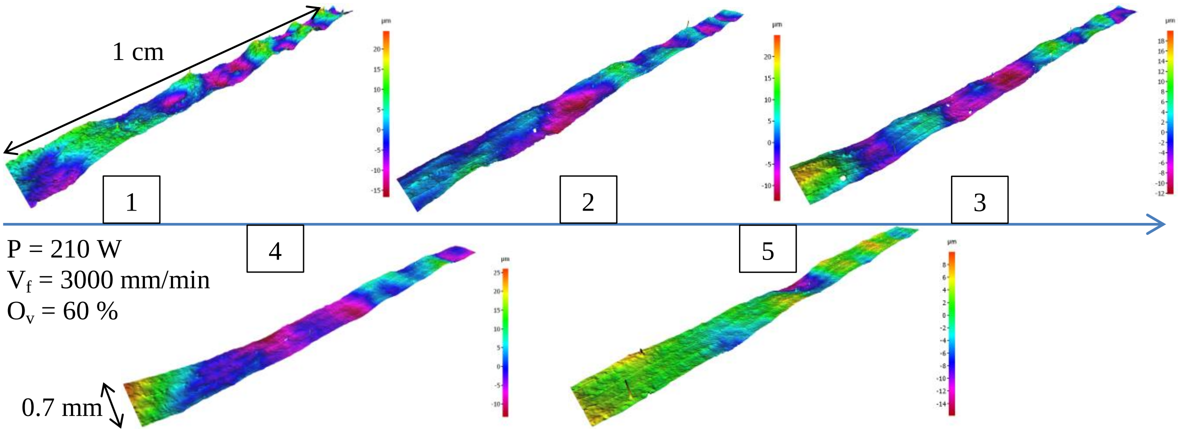

Fig.7: evolution of topography according to the number of passes

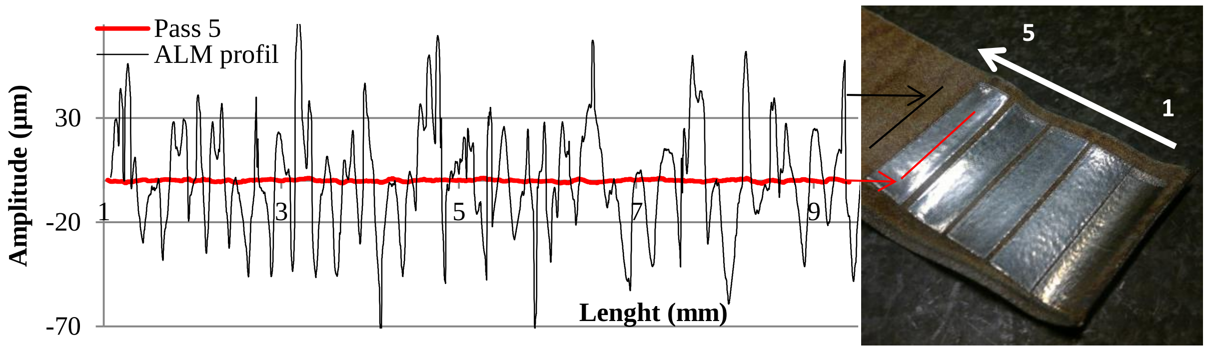

Fig.8: profiles roughness before and after laser polishing according to a 5 passes strategy

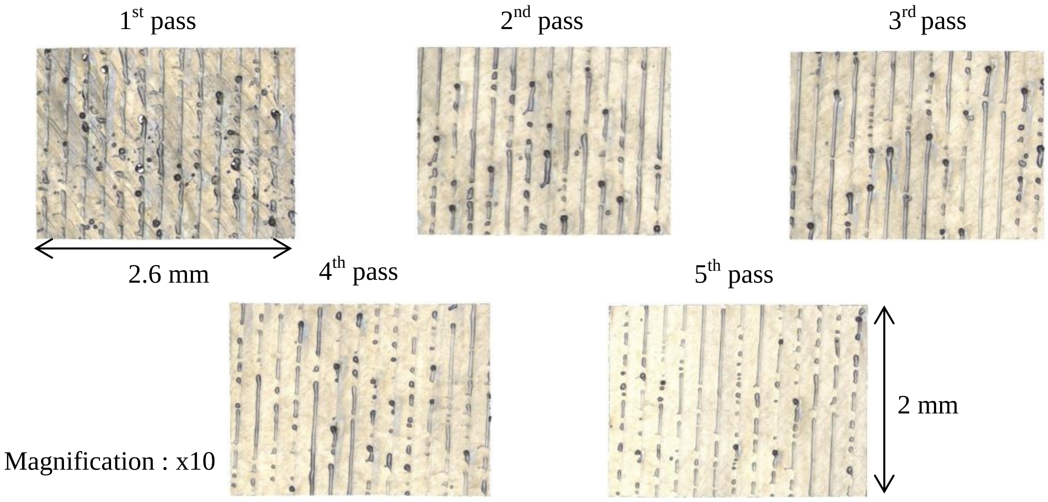

Fig.9: evolution of silicon oxide phenomenon according to the increase of passes number

Additionally, increasing the number of passes tends to limit the silicon oxide drops on the surface (Fig.9). The increase of passes number creates a directional texturing of silicon oxide phenomenon, following the laser direction. After five passes, the silicon oxide phenomenon decreased.

With a one-pass strategy, some micro-cracks are perceptible after laser polishing. After a multi-pass strategy, the micro-cracks are eliminated. A step structure phenomenon is visible after multi-scan strategy (Fig.10) and there are no micro-cracks.

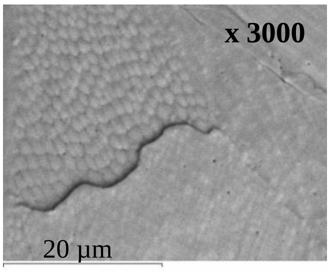

Fig.10: step structure phenomenon after a multi-pass strategy

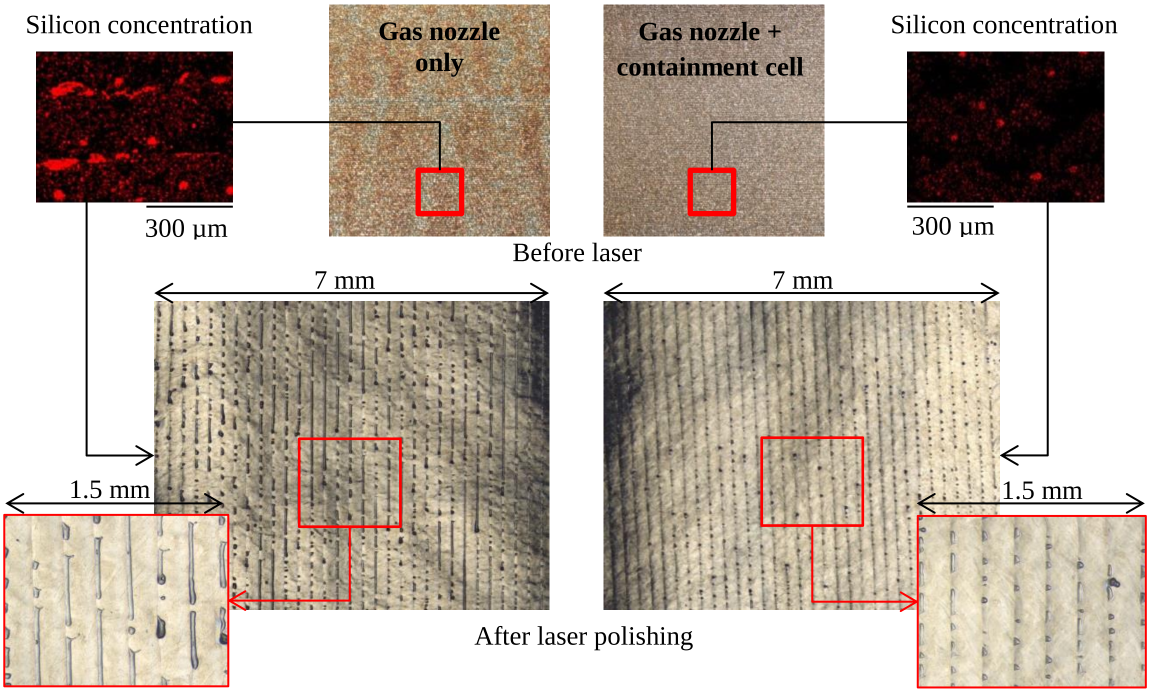

Fig.11: impact of ALM argon gas protection on laser polished topography

5.2. Decrease Of Silicon Oxide Drops

In order to eliminate silicon oxide defect from laser polished surfaces, a containment cell was used during ALM and LP processes. Mastering the environment enables to create a homogenous gas flow around the melt pool of ALM process and limits the oxidation (Fig.11). Indeed, the silicon concentration decreased with the mastery of the argon flow. As a result, the decrease of silicon concentration on ALM surface reduces the silicon oxide drops phenomenon on laser polished surfaces.

6. Laser Polishing Of Real ALM Complex And Thin Part

Conforming to an industrial application, a real thin and complex ALM part was polished by laser. According to a two dimensional laser path (Fig.12), the offset parameter varied during the laser polishing process. This type of path enables to simplify the laser polishing programming.

In order to eliminate form deviation after laser polishing, the energy density was decreased regarding previous tests. A 100 w power and 3000 mm/min feed rate for a five pass strategy was used. As a result, the ALM surface is smoothed after laser polishing process (Fig.13) and no geometrical deviation is highlighted. A 62% surface roughness reduction is obtained for an initial S_a of 14 µm and a final S_a of 5.39 µm. Moreover, the final surface roughness is less optimized than with a 210 w laser power. The decrease of energy density enables to eliminate the geometrical deviation but increases final surface roughness.

As a conclusion, the laser polishing process must be optimized according to two objective functions, which are surface roughness and geometric deviation.

However, the protection gas is heterogeneous and the final topography is not optimized. The protection gas defect is highlighted by a surface color gradient. As a conclusion, the offset parameter variation enables to smooth a complex surface according to a simple laser path. An investigation of five axis and normal strategy to the surface can improve the final polished topography.

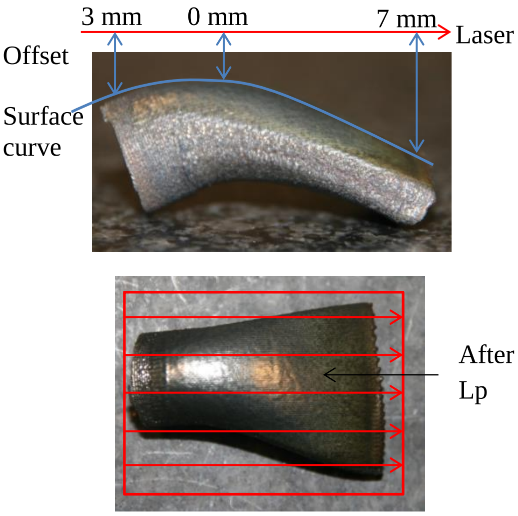

Fig.12: laser polishing strategy of real ALM complex and thin part

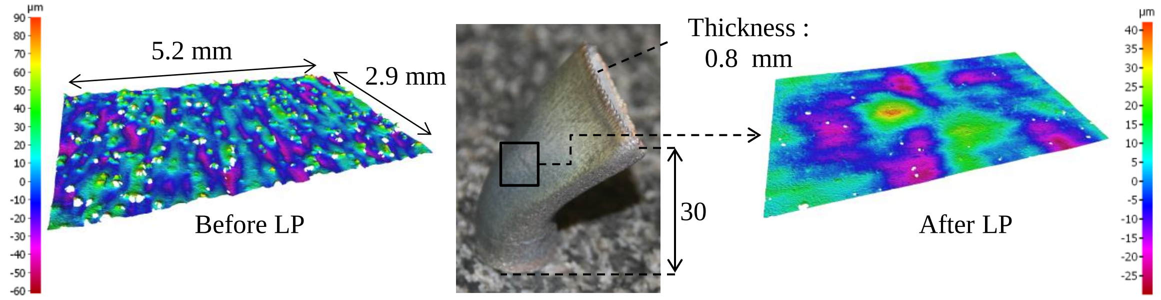

Fig.13: complex and thin part polished by laser

7. Conclusions And Further Research

This study focuses on the laser polishing of ALM surfaces according to a thin and complex manufacturing part context. Based on experimental investigation, this study enables to optimize ALM surfaces according to laser polishing parameters, and laser polishing strategy. As a result, the initial topography is smoothed, and the integrity of the surface is improved. Finally a real laser polishing of ALM part is presented. After investigation more conclusions can be established:

- The laser polishing process improves considerably the surface quality of ALM parts.
- The increase of number of passes improves the smoothing and decrease the silicon oxide drop phenomenon.
- The master of argon flow during ALM process improves the surface integrity after laser polishing.
- The multi-pass strategy enables to eliminate the micro-cracks created on the first laser polishing scan.
- Laser parameters settings must be correlated, with initial topography, material and topology of parts.
- The multi-pass strategy operated according the same laser parameters, enables to simplify the laser polishing optimization.
- Laser polishing process enables to smooth thin section parts obtained by ALM process.
- A simple laser polishing strategy enables to improve a complex ALM surface quality.
- The laser polishing process must be optimized according to surface roughness and geometric deviation

Further research will be focusing on a five axis laser polishing strategy, in order to treat an entire complex ALM surface. Due to a re-melting process, more metallurgical analysis will be taken into consideration such as hardness, microstructure fatigue behavior, and corrosion resistance. The final objective will focus on the final topography prediction according to an experimental methodology.

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