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Microstructural investigation of Selective Laser Melting 316L stainless steel parts exposed to laser re-melting

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Abstract

Although Selective Laser Melting (SLM) provides many advantages compared to conventional machining, limited surface quality is one of the major drawbacks encountered in the process. Secondly, little residual porosity (1-2%) in SLM parts may be problematic for some applications where high strength and fatigue resistance are necessary. As a remedy, laser re-melting is employed during or after the SLM process. Laser re-melting means that after scanning a layer and melting the powder, the same slice is re-scanned before putting a new layer of powder. If done for each layer, it results in substantially longer production times. It can also be applied to only the last layer or the outer skin of the part if the aim is to reduce the roughness or to enhance the surface properties. In this study, laser re-melting is applied using a continuous wave laser during SLM of AISI 316L stainless steel parts mainly to study the microstructural changes by applying different process parameters.

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Keywords: Selective laser melting, Roughness, Laser re-melting

1. Introduction

Selective Laser Melting (SLM) is one of the layer additive manufacturing (AM) processes which refer to a group of technologies used for building physical models, prototypes, tooling components and functional parts, all from 3D computer-aided design (CAD) data or 3D scanning systems data, medical scanners, or other geometry representations. SLM uses the energy of a focused laser beam to bind powder particles to each other in a layer-wise manner to produce high density functional parts with high degree of geometrical complexity (See Fig. 1). Although the SLM process provides many advantages compared to conventional machining, low surface quality is one of the major drawbacks encountered in the process.

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Secondly, in spite of the fact that the process is capable of making almost full dense (~98-99%) parts, little residual porosity may still be problematic for some applications where high strength and fatigue resistance are necessary. In the scope of this study, laser re-melting is employed during or after the SLM process to overcome these problems. That is after scanning a layer (intermediate or final layer) and melting the powder, the same slice is scanned again before putting a new layer of powder. This solution might increase the production time substantially depending on the selected scan speed and scan spacing, but on the other hand, it can be the ultimate solution for applications where a density of 98-99% is not sufficient or where surface density is very critical for crack formation and propagation. Laser re-melting can also be applied to only the last layer or the outer skin of the part if it is aimed to enhance the surface quality or density. In this case, the process is named Laser Surface Re-melting (LSR).

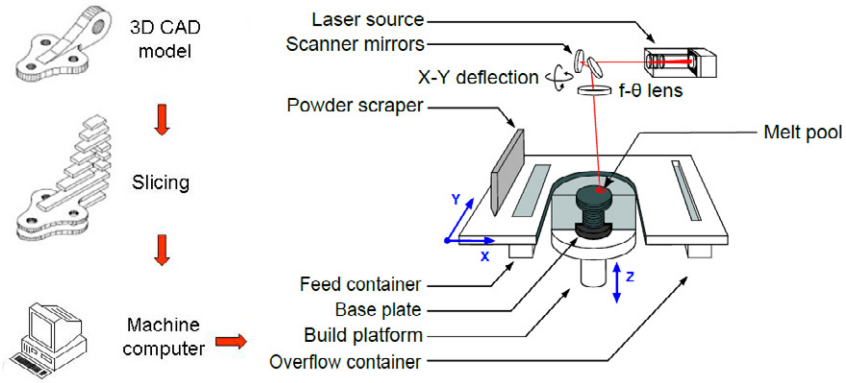

Fig. 1 Overview of Selective Laser Melting from CAD file to the process

In the literature, laser re-melting is mainly studied for surface modifications: such as for lower roughness values and surface densification, higher hardness, better friction and wear behaviour, improved corrosion resistance and wettability and customized microstructural properties [1]-[4]. Laser re-melting is also reported to reduce the residual stress in the top layer with about 55% when sufficiently high energy per unit area in re-scanning is selected (12.4 J/mm^2 which is 150% of the forming energy of a layer during SLM) [5]. However, an experimental study of residual stresses at K.U.Leuven shows that laser re-melting after every layer, in other words post-scanning, improves the residual stresses only about 10% [6]. Although laser re-melting is a common method for surface modifications of parts produced by conventional techniques, the use of laser re-melting during an additive manufacturing technique is not studied in detail regarding many aspects such as densification, surface roughness improvement and microstructural effects. Results regarding higher density and lower surface roughness were published elsewhere [7], [8]. This paper mainly reports about change of surface and subsurface properties (density and microstructural features) of SLM parts that are exposed to laser re-melting.

2. Experimental Procedure

All experiments are carried out on a Concept Laser M3 Linear machine which employs a Nd:YAG laser. The laser can be operated in either Q-switched or in continuous modes. In this study, laser re-melting and SLM are conducted in the continuous mode whereby the maximum laser output power is approximately 105 W. It is possible to adjust the laser spot diameter to two settings: $Ø_{1/e^2}$ to 70 and 130 µm ($Ø_{99\%}$ respectively 80 and 180 µm). AISI 316L stainless steel powder is used as material during the experiments.

The parameters used during additive melting (SLM) of a layer are the standard SLM values for AISI 316L optimized for maximum density (scan speed 380 mm/s, laser power 105 W, scan spacing 125 µm (a_1=70%) and spot diameter 180 µm with island scanning) and recommended by the machine maker. Various strategies of laser re-melting with different parameter sets are tested. It is applied after each layer, either only to the layer contour or to the whole scanned layer area. Alternatively, laser re-melting can be employed after the SLM process is completed on either top or inclined part surfaces.

3. Experimental Results

Laser re-melting is proved to improve the surface quality and reduce the porosity for AISI 316L, Ti6Al4V and maraging steel 300 [7]-[10]. The average roughness, R_a, of AISI 316L stainless steel samples produced by SLM decreases from 12 µm down to 1.5 µm when laser re-melting is applied with appropriate energy density settings (see Fig. 2a). The density enhancement with laser re-melting is demonstrated in Fig. 2b. The SLM part with no laser re-melting exhibits a porosity of about 0.77% (measured with optical microscopy images) while the laser re-melting reduces the porosity down to 0.036% when the parameters are selected properly.

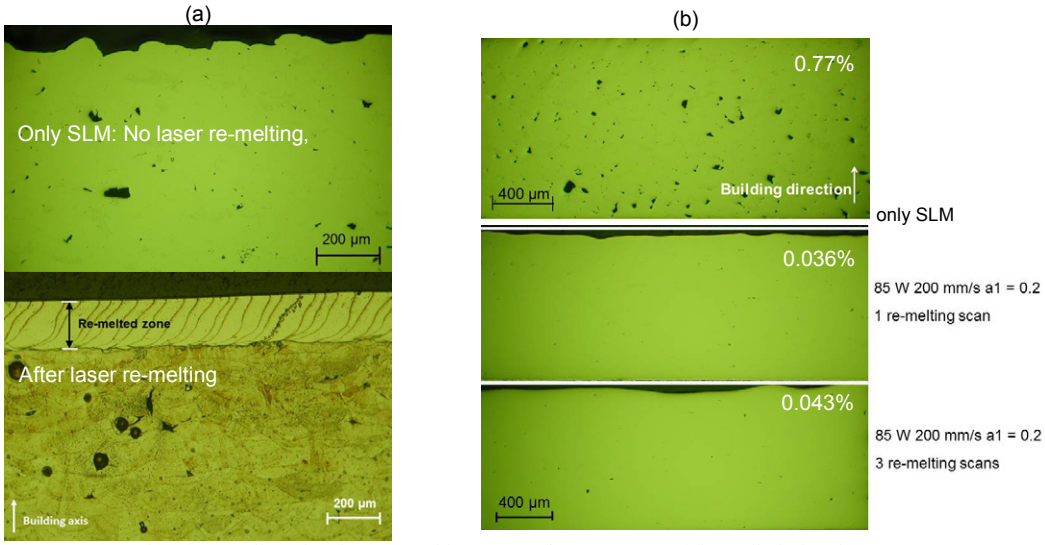

Fig. 2 (a) Improvement of surface quality when laser re-melting (50 mm/s, 85 W, a1=0.1) is applied after the SLM process on top layer (top) (b) cross-sectional OM images of samples without laser re-melting (top), and with laser re-melting with different parameters

However, this paper will not go deep in the results of surface quality or density improvement. The paper focusses on the microstructural changes when laser re-melting is applied. Before presenting the microstructures of laser re-melted parts, the microstructures of SLM parts with no re-melting are first presented to allow comparison.

3.1. SLM parts with no laser re-melting

The top view and a cross-section of a SLM part with no re-melting taken with an optical microscope are shown in Fig. 3. The scan tracks are clearly visible and the direction of the laser scanning is shown with the arrows in Fig. 3a. From the figure, the width of the melted track is measured to be approximately 110-120 µm.

In Fig. 3b, the cross-sections of the melted scan tracks are visible showing that the stainless steel powder particles are completely fused together within melted and solidified zones having curved edges. The laser tracks overlap so that each melted track is bonded onto the other tracks surrounding it. Fig. 3b also indicates that during SLM a fully melt pool with a depth higher than the layer thickness is formed (~100 µm versus layer thickness of 30 µm).

Fig. 4 depicts scanning electron microscope (SEM) images of the cross-section of a SLM part with no re-melting. A fine cellular/dendritic structure is visible. This microstructure is formed as a result of rapid solidification due to very high cooling rates encountered in SLM like in casting [11]. It is a common microstructure obtained by laser processing techniques.

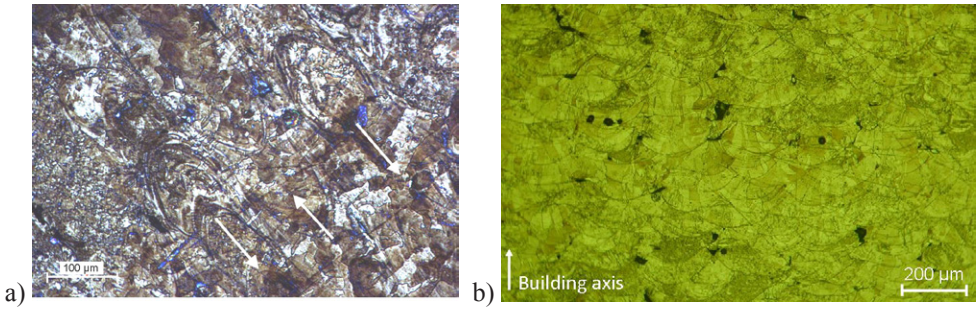

Fig. 3 OM images of a SLM part without laser re-melting (polished and etched) a) top surface b)cross-sectional view

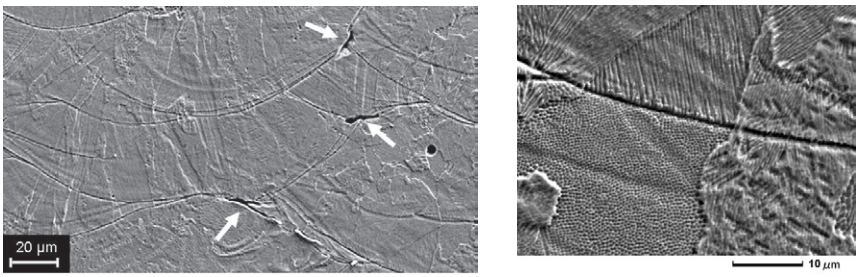

Fig. 4 SEM images of a cross-section of a SLM part without laser re-melting

3.2. SLM parts with laser re-melting after every layer

Fig. 5a depicts one of the samples treated with laser re-melting after each layer with following parameters: a scan speed of 200 mm/s, a laser power of 100 W, a spot size of 180 µm, a scan spacing of 20 µm (a_1 of about 10%) and three re-melting scans after each SLM layer. The contour and its connection with the core of the part are clearly distinguishable. In the contour zone, the cross-sections of the melted scan tracks are visible having curved edges. The layered or lamellar structure inside the part shows a smaller thickness than a SLM layer and that re-melting erases the scan tracks contours visible after SLM (see Fig. 3b) and causes more uniform and smooth layers to appear. The thickness of visible layers in the optical microscopy picture of this part was found to be around 20 µm whereas the actual depth of re-melted zone is about 200 µm as measured from laser surface re-melting samples or from the last re-melting scan (see Fig. 2a). The distance between horizontal lines and depth of re-melted zone depend on the process parameters of laser re-melting. For comparison, the optical micrographs of laser re-melted

parts with various process parameters are presented in Fig. 5b together with a SLM part with no laser re-melting. The figure reveals that a higher number of scans in laser re-melting leads to a significantly finer lamellar structure. The fact that the interlayer lines are not straight in Fig. 5a and rise to the edge of the part is due to the "edge effect".

The layers in laser re-melting are actually visible as horizontal dark lines due to very low scan spacing (5-10%). The cross-section of multiple scan tracks that overlap significantly appear as a line instead of curved melt lines which is also shown in Fig. 2a (bottom). In Fig. 5b, the cross-sectional view of the part which was re-melted with a scan spacing factor of 20% depicts less visible horizontal bands compared to the parts with a scan spacing factor of 5 or 10%. Due to the reason that laser re-melting efficiently reduced the pores formed in between neighbouring melt pools in the borders (see arrows in Fig. 4, left), lamellar structures are desired for improved density leading to better mechanical properties and avoiding failures of SLM parts. SEM images of two parts exposed to laser re-melting with different parameters given in Fig. 7 clearly show the lamellar structure where no irregular pore is present. Fig. 8 depicts the very fine microstructure encountered with laser re-melting (38 A, 200 mm/s, a_1 of 10%, big aperture and 3 scans). Both microstructures reveal a size of less than 500 nm.

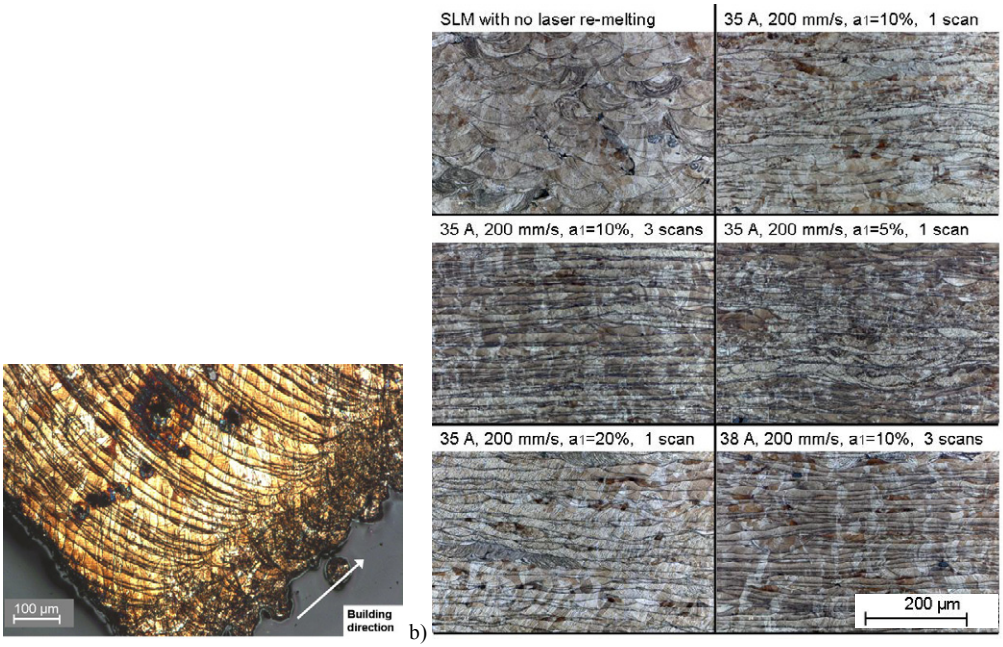

Fig. 5 a) Cross-section of a part with laser re-melting after each layer b) cross-sectional views of parts with different laser re-melting parameters applied after each layer together with a SLM part with no re-melting (38 A = 100 W of laser power whereas 35 A = 85 W of laser power)

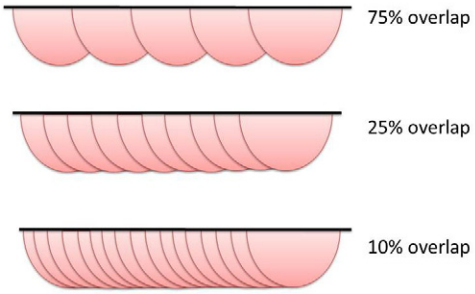

Fig. 6 The influence of overlap factor on the appearance of consecutive melt pools

4. Conclusions

Selective Laser Melting (SLM) is an advantageous additive manufacturing process to make functional three-dimensional prototypes, products and tools with very complex geometries although it suffers from 1-2% porosity and insufficient surface quality. In this work, laser re-melting was experimentally studied in order to enhance the SLM process. It is found that laser re-melting is a promising method to increase the density of SLM parts to almost 100% and to enhance the surface roughness of about 90% at a cost of longer production times as shortly discussed in this paper. The pores formed in between neighbouring melt pools disappear when laser re-melting after every layer is applied. As expected, higher density leads to better mechanical properties. Moreover, it is observed that re-melting already melted and solidified material (by SLM) again refines the microstructure.

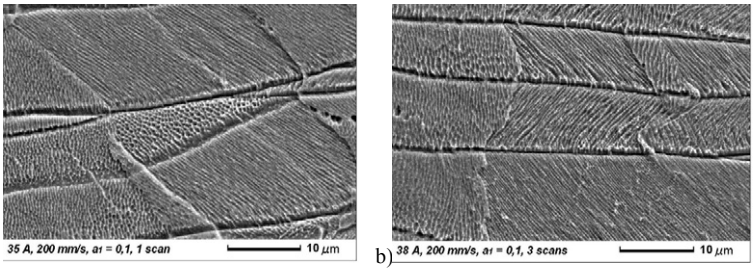

Fig. 7 SEM images of two SLM part with laser re-melting at different parameters showing almost full density a) 35 A (85 W of laser power), 200 mm/s, a1=0.1 and 1 scan b) 38 A (100 W of laser power), 200 mm/s, a1=0.1 and 3 scans

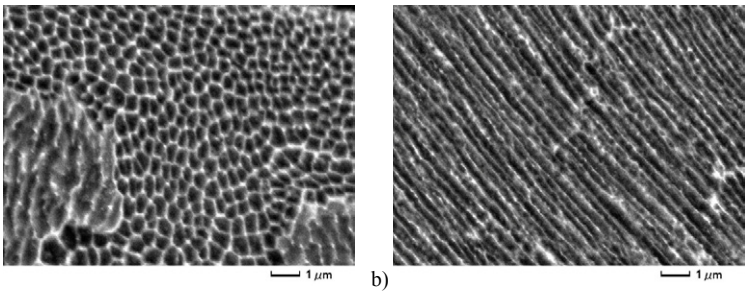

Fig. 8: SEM pictures of a part with laser re-melting a) cellular structure b) dendritic structure

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