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Femtosecond laser Additive Manufacturing with self-produced Stainless Steel powder at low Scanning Speed and low Energy

Iñigo Ramon-Conde[a,b], Ainara Rodriguez[a,b], Santiago Miguel Olaizola[a,b], Mikel Gomez-Aranzadi[a,b,*]

[a]*CEIT-Basque Research and Technology Alliance (BRTA), Manuel Lardizabal 15, 20018 Donostia / San Sebastián, Spain*
[b]*Universidad de Navarra, Tecnun, Manuel Lardizabal 13, 20018 Donostia / San Sebastián, Spain*

Abstract

The use of USP lasers for AM entails a more complex laser-matter interaction and greater difficulty in producing heat accumulation compared to the laser sources present in industrial systems, due to the usage of ultra-short intense pulses. Usually, the strategy followed with USP lasers in order to trigger the melting of particles is to use a high frequency regime (around 10 MHz) to accumulate heat. In this work, a novel low frequency (<1 MHz) and low power (<1 W) strategy is presented. With it, a minimum wall thickness of 100 µm has been achieved thanks to our own-produced stainless steel powder particles, which is in line with other works. This new strategy enables a more precise control of the spatial distribution of heat, where the minimum size will depend not on the type and power level of the laser source, but on the size and quality of the powder grains.

Keywords: Femtosecond laser; Laser Powder Bed Fusion; Ultrashort pulse; Stainless Steel Powder; High precision manufacturing

1. Introduction

Over the past few years, Additive Manufacturing (AM) has become increasingly integrated into various industries, impacting every day in their operations (Kai Chua, How Wong, & Yee Young, 2017). As time progresses, the industry's demand for more precise, intricate, and superior parts has risen to meet the needs of society across diverse applications and sectors. Concurrently, the advancement of AM research has presented opportunities for fabricating a wider range of parts.

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* Corresponding author. Tel.: (+34) 943 212800.
E-mail address: mgomez@ceit.es.

Among the various areas of AM research, micro-scale Additive Manufacturing (mAM) has witnessed an accelerated growth. While mainstream manufacturing technologies have mastered the production of larger components, the challenge lies in reducing the size of products to meet the growing demand for tiny metal parts. Numerous industrial sectors require smaller parts with heightened technological capabilities to overcome future challenges and advance the development of new technologies (Ostendorf, Neumeister, Dudziak, Passinger, & Stampfl, 2010). However, significant challenges persist regarding available materials, resolution, throughput, and the ability to fabricate true three-dimensional geometries.

The primary hurdle in mAM is scaling. Depending on the process employed, the scale dimension may vary, and in every “scale” the parts must fulfil some standards and requirements concerning surface quality and dimensional accuracy. Direct scaling poses significant difficulties, as traditional technologies are typically limited to their designated production zone, i.e., the size range for which they were originally designed. Achieving size reduction in the final parts may even necessitate structural changes to these conventional processes and machines. However, the drawbacks associated with well-established AM technologies also provide an opportunity to explore alternative unconventional methods (Presz, 2018).

This study focuses on investigating the potential of utilizing a femtosecond laser as a tool for creating thin-walled structures. As it can be assessed, femtosecond lasers have quite potential to more precisely control the heat accumulation submitted to the material, which leads to a more flexible melt pool; as a result, spatial resolution is enhanced, opening up the possibility of manufacturing finer and more complex structures.

2. Materials

The irradiation source is a diode-pumped ultra-fast fibre laser system (Amplitude Satsuma HP) of λ = 1030 nm and 280 fs pulse duration, with a maximum average power of 10 W at a repetition rate of 500 kHz. The properties of the laser beam are modified and controlled by the different modules of the micromachining setup (LASEA LS-Lab). Finally, an F-theta lens focuses the laser beam to a 29.9 µm diameter spot on the processing area. Optical Microscopy (OM) (LEICA M205 FA) and Scanning Electron Microscopy (SEM) (ZEISS SIGMA and JEOL JSM 7100F) have been used to evaluate the quality of the processes and to measure the thickness of the profiles.

Own-produced gas atomized AISI 316L stainless steel powder (Pasupathy, Martín, Rivas, Iturriza, & Castro, 2016) grains have been used, with size distribution below 20 µm. AISI 304L stainless steel cut into slabs of 125x100x5 mm was selected as a substrate to deposit the powder and carry out the processes.

3. Methods

To fabricate thin-wall structures well defined processing parameters are needed, so the metal powder is efficiently melted. Apart from that, it is also very important an efficient distribution of the powder in layers. A control of the heat submitted to the material is crucial; therefore, it is therefore of paramount importance to analyse the efficiency of the laser pulses into the material. Establishing our previous studies as a starting point for this investigation, the parameters used to fabricate the thin-wall structures were obtained from (Ramon-Conde, Rodriguez, Olaizola, & Gomez-Aranzadi, 2023). On this work, femtosecond laser pulses are used as energy source in LPBF processes, performing different parameter studies; the results obtained evidence that using pulse repetition below 1 MHz and with average power levels lower than 1 W, control of the powder melting can be achieved. This study has achieved this goal with lower parameters than any other author, and on stainless steel powder.

To study the potential of above-mentioned laser parameters for fabrication of thin profiles, two sketches were designed, considering the scanning direction and the wall direction. These sketches are based on, as it can be seen in Fig. 1-a), two arrangements:

- Scanning direction and wall direction are parallel (Case 1), scanned lines have the length of the size (L) of the processed wall.
- Scanning direction and wall direction are perpendicular (Case 2), scanned lines have the length of the thickness (t) of the processed wall. This strategy forces the laser to process short lines, enabling to jump rapidly to the next line and stick every melt volume to next one.

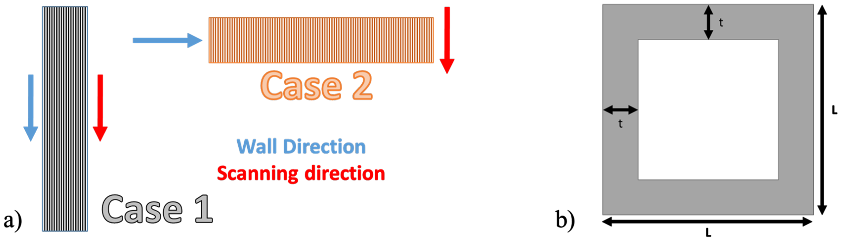


Fig. 1. a) Schematic of the case studies with parallel (Case 1) or perpendicular (Case 2) wall and scanning directions; b) Representation of the design of the square, where two vertical and horizontal walls are processed ("L" stands for the length of the wall and "t" stands for the thickness of the walls)

Using these scanning strategies, a series of different structures were created to know which was the minimum wall thickness that was achievable with the optimized parameters used (Ramon-Conde et al., 2023). Two sets of parameters were used [Laser Power, Scanning Speed, Hatch Distance]:

(A) 0.78 W, 2.5 mm/s, 5 µm
(B) 0.85 W, 2.5 mm/s, 7.5 µm

To integrate both scanning strategies in one single design, a collection of empty squares were created, like the ones shown in Fig. 1-b), with decreasing size and decreasing wall thickness. In all the experiments, the scanning direction was vertical, enabling the aforementioned scanning strategies depending on the design. The squares were formed by four 50-µm powder layers, resulting in 200 µm height structures. The thickness of the wall designs ranged from 1 mm to 5 µm with a wall length of 2 mm for all the structures, except from the largest structures, that was increase to maintain the proportion in size; the dimensions of the squares are given in Table 1.

Table 1. Dimensions of designed square processes

Square/Wall length (mm)	4	3	2	2	2	2	2	2	2	2	2	2
Wall thickness (µm)	1000	500	250	200	150	100	50	25	20	15	10	5

4. Results and Discussion

A collection of different structures were fabricated with wall thickness values ranging from 5 µm (which corresponded to a single scanning line in some of the cases) to 1 mm, resulting in various wall thicknesses. In Fig. 2 are shown the results of the 5 µm and 10 µm walls. For 5 µm wall it is visible how clean volumes of melted powder are formed, although they are not consecutively melted. In 10 µm wall, when the directions are perpendicular, the results are similar; in contrast, for the parallel processing the wall presents a more uniform and continuous melted wall. In both processes, the multiple free areas can be due to lack of melted powder in lower levels, making it impossible to form stable powder layer to be melted when processing on following stages.

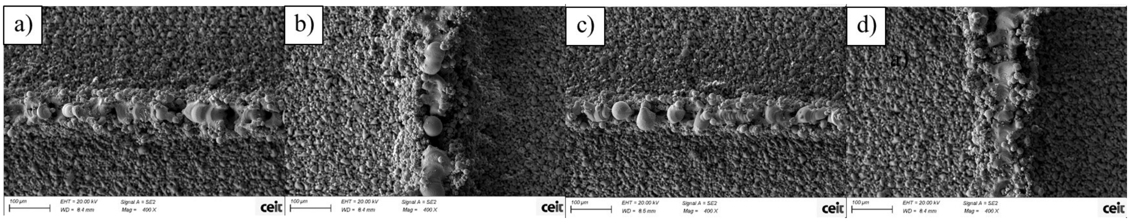


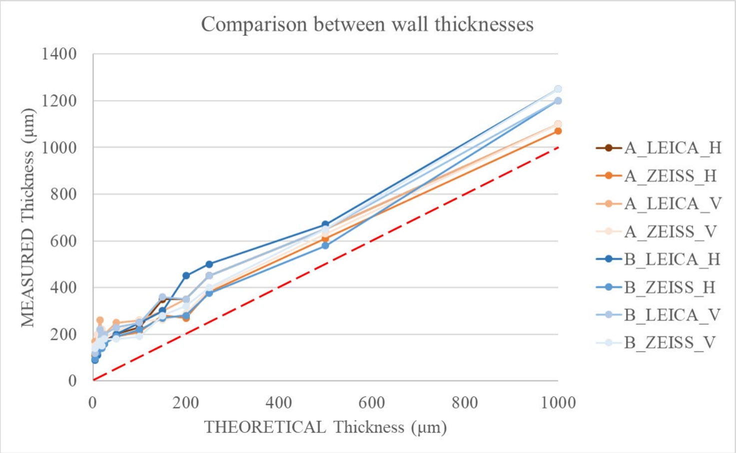
Fig. 2. SEM images of walls processed with femtosecond laser with A-processing conditions. Designs of a) and b) are 5 µm, designs of c) and d) are 10 µm. Resulting Thickness are: a) 110 µm, b) 160 µm, c) 140 µm and d) 200 µm

Analysing the thickness of the fabricated walls, it was concluded that the heat submitted to the powder when processing singles lines or thin structures was enough to generate melting phenomena. In Fig. 3 the comparison between the theoretical (Th) and measured (Ms) wall thicknesses is shown. The thickness of the walls was measured using two different techniques (Optical Microscopy and Scanning Electron Microscopy), to be able to check the reproducibility of the measurements; despite some particular cases, the measurements do not differ strongly from each other. The values of the measured wall thicknesses are listed below, in Table 2.

Table 2. Wall thickness measurements for SEM and OM techniques,

	Th (µm)		5	10	15	20	25	50	100	150	200	250	500	1000
A	↔ Ms (µm)	OM	110	150	150	150	170	200	230	350	350	450	650	1100
		SEM	110	130	150	150	170	190	210	280	270	380	610	1070
	↕ Ms (µm)	OM	170	200	260	220	200	250	260	300	350	450	650	1100
		SEM	150	200	220	220	190	210	260	260	290	390	630	1100
B	↔ Ms (µm)	OM	90	110	150	150	160	200	250	300	450	500	670	1250
		SEM	95	125	140	140	160	190	220	270	280	375	580	1200
	↕ Ms (µm)	OM	120	150	220	200	200	230	250	360	350	450	650	1200
		SEM	140	160	170	150	180	180	190	280	320	400	650	1250

As the wall thickness decreases the Ms:Th ratio increases; for 1 mm wall thickness the ratio is 1.1-1.25, whereas for the structures below 20 µm in wall thickness the ratio increases up to 10-35. Interestingly, the measured wall thickness is always around 90-100 µm higher than the theoretical value. Despite this, the lower wall thickness that was possible to measure was around 90-100 µm, corresponding to the 5 µm wall perpendicular design (Case 2). Interestingly, there is a relatively constant fabricated wall thickness value, ranging from 120-130 µm to 200-220 µm) for design thickness of 10-50 and 100 µm (Fig. 4); this could mean that lower limit threshold could have been reached, due to which reduction of parameters like the spot size or the powder size distribution could be necessary.



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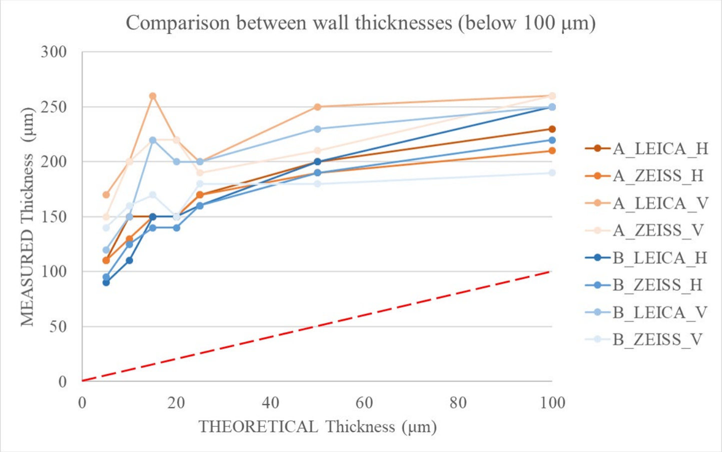

Fig. 4. SEM images of walls processed with femtosecond laser with A-processing conditions. Designs of a) and b) are 5 µm, designs of c) and d) are 10 µm. Resulting Thickness are: a) 110 µm, b) 160 µm, c) 140 µm and d) 200 µm. The red line indicates the 1:1 on Ms:Th ratio

5. Conclusions

In order to study the potential of ultra-short pulse lasers for fabrication of thin-wall structures, a femtosecond laser was used as energy source in LPBF processes, performing different studies with own-produced stainless steel powder with size distribution lower than 20 µm. The scanning strategy has been found as decisive to fabricate profiles with reduced thickness. For walls larger than 100 µm, where the thickness of the wall was much larger than the spot diameter, the scanning direction was not important, being more influential the above mentioned processing parameters; in contrast, when the wall was not much larger than the diameter spot, the different scanning strategies influenced strongly in the results. The lowest wall thickness has been set at 90 µm for a wall design of 5 µm. The rest of the measured thicknesses were around 90-100 µm higher that their theoretical value.

Further improvement of the process could be made reducing the laser spot diameter, in order to better target the energy applied to a smaller area. Moreover, reduction of powder maximum size could also bring benefits to the reduction of the wall thickness.

Acknowledgements

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