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Article

Analysis of the process parameter influence in laser cladding of 316L stainless steel

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Abstract: Laser Cladding is one of the leading processes within Additive Manufacturing technologies, a fact which has concentrated an important amount of effort on its development. In regard to the latter, the current study aims to summarize the influence of the most relevant process parameters in the laser cladding processing of single and compound volumes (solid forms) made from AISI 316L stainless steel powders and using a coaxial nozzle for deposition. Process speed, applied laser power and powder flow are considered to be the main variables affecting laser cladding in single clads, meanwhile overlap percentage and overlapping strategy become also relevant when dealing with multiple clads. By means of setting appropriate values of each process parameter, the main goal of this paper is to develop a processing window in which a good metallurgical bond between the delivered powder and substrate is obtained, trying simultaneously to maintain processing times in their lowest value possible. Conventional metallography techniques were performed on the cross sections of the laser tracks to measure the effective dimensions of clads for dilution analysis, height and width for the values of overlap between contiguous clads and layers, and also to analyze them for physical defects such as porosity and cracks. The resulting solid piece was 8 mm high at 800 mm/min.

Keywords: laser cladding; powder flow; 316L stainless steel

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1. Introduction

Current development in Additive Manufacturing (AM) has tweaked the product design process itself, by adding to it the possibility to work on a CAD model and create solid metal parts directly from such a model [1]. Within this group, Laser Metal Deposition (LMD) or Laser Cladding (LC) stands as one of the most relevant AM processes in development and, thanks to its versatility as an AM process [2,3,4], LC technology has become a powerful process for designing and generating parts with complex structures in the industry [5,6]. This novel manufacturing process allows manufacturing parts or pieces without limitation of size, or the need of an expensive tooling and adjusting the amount of material necessary to the actual design piece by adapting the laser spot size to the geometry to be built and minimizing material waste [7,8]. In addition to the latter, when dealing with already manufactured parts, LC is often used as a mean of increasing the wear or corrosion resistance of diverse surfaces and as way of repairing damaged surfaces. Elements such as tools and dies are able to achieve longer life-times thanks to the addition of functional layers on their surface [9], by coating less noble surfaces with noble materials, thus achieving better surface properties.

When related with the making of new parts, LC is used to generate tridimensional geometries on top of a surface [10], like the way inserts or protrusions are placed in a mold. This type of LC process starts with the slicing of CAD model components with whom a sequence of equally spaced layers are extracted to be used as an input to the process. Using this information, deposition strategies are generated in order to be able to fill the non-empty areas of each layer [11]. These strategies must comply with specific requirements of each material such as overlap percentage, energy density and powder flow to accomplish a good metallurgical bond between the deposited layer and substrate [12]

In this direction, for instance, dilution phenomena are very relevant results to examine when looking for an appropriate process window for these parameters. Quantitatively, dilution can be calculated as the ratio of molten substrate to molten material during a LC process. The importance of dilution control lies on the fact that, as a consequence of fusion of the substrate material, mechanical and corrosion properties of the deposited layer can be heavily degraded due to the mixture with the substrate [13]. In comparison with a higher energetic process as arc welding, dilution of the melted substrate in LC is lower but it is nonetheless difficult to find the optimization of process parameters to guarantee the efficiency of the metallurgical bond [13]. Another disadvantage is that it is considered a slow process when compared with other welding processes like arc welding process [14].

But besides dilution, physical defects such as porosity and cracking can also be found on clads and their appearance can lead to significant decrease in the mechanical properties of the cladded volume as a whole. These appear mostly when dealing not only with individual clads, but when overlapping one onto another horizontally or vertically. Main parameters as speed of the process, applied power and powder flow can affect in different forms the way the geometry of a cladded volume is formed at the end of a process and, therefore, defects may appear within the deposited material.

With this in mind, a valid focus to take is to study the LC process in a two-step iterative process: in the beginning, the main process parameters mentioned earlier can be evaluated in order to obtain those with which quality clads with appropriate dilution [15]. Afterwards, these parameters can be used to be able to start a LC process with overlapped clads, and the transient changes that must take place in the process in order to minimize the probability of obtaining defects (power decrease in time, overlapping percentage between clads, etc.) become the input variables of the studied process, the progressive optimization of a LC process, setting processing time (the less the better), quality of the clad and energetic process efficiency as output variables. Following this approach, the main goal of the current work is to present an introductory study of laser cladding, in the way to achieve a high production manufacturing process. In order to achieve this goal, the influence of each main parameter of the LC process in individual and overlapped clads will be studied as well as the strategy to manufacture solid pieces.

To be able to form clads, a coaxial nozzle is used for powder deposition and a fiber 6 kW IPG YLS-6000 is used as a laser power source with a 5 mm diameter spot. It is important to note that with this type of nozzle it is possible to deliver the powder flux coaxially with the laser beam, thus applying almost equally distributed amounts of powder radially. The latter makes it possible to perform the deposition in all directions of the substrate and, as a side effect; it makes it easier to control the accumulated temperature on the workpiece, so that the coaxial laser cladding process may be considered to be independent of the laser track direction [16]. As for the materials used, carbon steel S355 will serve as substrate for making clads composed of AISI 316L deposited and molten powders.

The first set of experiments were single deposited clads, and the optimization was performed by setting different values in the main LC process parameters (power, process speed and powder flow) to analyze the influence of each one. The second set of tests consisted in the fabrication of solid, tridimensional figures which were deposited over a plane substrate. The measured effective dimensions of single laser clads from the first set was used to calculate overlap of contiguous clads. To be able to grow layer by layer to form the figures, temperature was tried to be kept constant by regulating laser power for each subsequent layer. Moreover, the strategy of the overlap distribution was studies by proposing three approaches: Contour, Zig Zag and Parallel clads. Each one of them is

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analyzed since they perform well in controlling the accumulated heat during the process [9, 17] and are also appropriate to achieve enough dilution between the delivered powder and the metal substrate.

Summarizing, this work is focused on a long term goal achieving a robust LC manufacturing process for tridimensional pieces. Less processing time and good quality are the qualitative variables taken into account. This study will allow the development of a work methodology in order to get information about a LC process in a progressively staged mode. By this way, physical characteristics inherent to each one of the moments of the process will be carefully selected and studied, leaving a cleaner way to optimize the process window. Here, for instance, the geometry of the cross section of the clad will served as the primary way of understanding individual clads paved the way to search for the best results when manufacturing multiple clad volumes.

2. Materials and Methods

2.1. Material Preparation

AISI 316L (EN 1.4404) powder, with a particle size range of 44 and 106 μm, was used as additive material. Its chemical composition is listed in Table 1.

Table 1. Chemical composition (wt %) of 316L stainless steel. [1]

	C	Cr	Ni	Mn	P	Mo	Si	O	Fe
wt %	≤0.03	17.5	11.5	≤2	0.02	2.3	0.4	0.05	balance

A common carbon steel (S355) of thicknesses 8mm was used as a substrate, to study the influence of the process parameters in a single laser cladding tracks and to manufacture bigger coating with the overlapping of single cladding tracks.

2.2. Deposition System

The experimental equipment used for current study consists on a high power fiber laser, (IPG YLS-6000) releasing radiation at a wavelength of 1070 μm, guided to the optical head by means of a 1000 μm core diameter optical fiber. The optical head is mounted in a 3 linear axis system. This optical set up includes a 120 mm collimating lens and a 550 mm focusing lens generating a 5 mm diameter spot.

A coaxial nozzle was used for experimental tests. Nitrogen was used as a carrier gas to deliver the powder from the powder feeder to the melt pool and the same gas was used to generate a protective atmosphere during the deposition process. Metallic powder particles were placed in a powder feeder from GTV and delivered to the process zone through the nozzle. A schematic layout of the laser cladding system is shown in Figure 1.

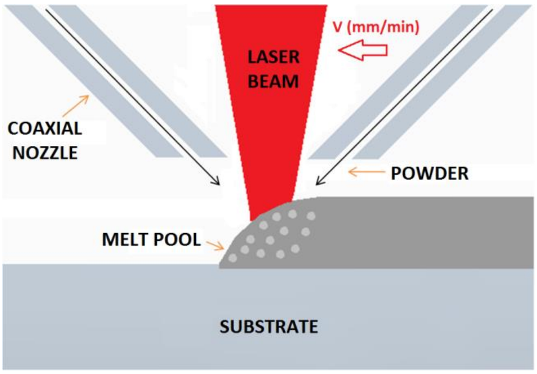

Figure 1. Schematic layout of the coaxial laser cladding system.

2.3. Experimental Procedure

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In the first part of the experiment the main parameters involved in manufacturing of single clads were studied. Range of levels of the main laser process parameters studied in this paper have been between 2000-4000W for the laser power, 800-1600 mm/min for the process speed and between 12-31 g/min of powder flow. Other process parameters were kept constant and are resumed in Table 2.

Table 2. Common process parameters.

Laser Focus Distance (mm)	**Carrier gas (l/min)**	**Shielding gas (l/min)**
550	3	5

In second place, multiple clad forms were manufactured by performing few overlapped cladding tracks, increasing the coating thickness layer by layer. The purpose of building solid forms after doing single clads is to develop a stable coating process in longer areas, seeking to minimize lack of fusion and to maintain good mechanical properties of the deposited material. To achieve this stability, temperature was tried to be kept constant by modulating power input for each new layer during the coating process.

The value range of the main parameters was derived from the first part and, as well, the effective dimensions measured in single clads experiments were taken into account for the calculation of the overlapping percentage used (between 25% and 40%). In particular, the width of the clad is used for calculate the percentage of overlap between contiguous clads and the height is used to calculate the mean increase per each new layer (with multilayered volumes). For the latter, the height of a layer was measured with a gauge and this value was added to the distance between the nozzle and the workpiece for the next layer. The dimension range of the solid forms created is between 20x20 mm^2 and 30x30 mm^2, and their height depends on the number of layers deposited.

Besides the overlapping percentage, the strategy used for generating deposited layers was also used as process parameter for solid forms. Figure 2 shows the sketches of the three types of strategies applied to deposit the powder flow. The first strategy consists on creating a contour for the form, by growing a wall with square form in the first place. The second draws Zig Zag tracks as the coaxial nozzle moves back and forth parallel to the same direction all the time [18]. Finally, the third one is called Parallel (also known as Raster strategy [14]), the laser clads are deposited in parallel, starting and finishing at the same point.

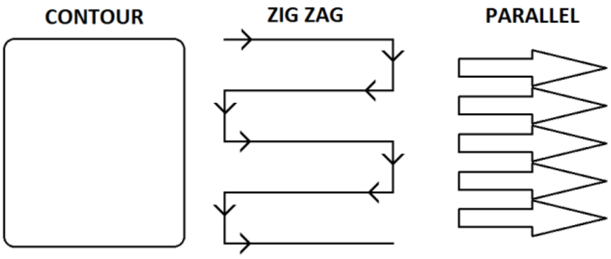


Figure 2. Sketches of type of strategies applied.

Conventional metallography techniques were performed on the cross sections of the laser tracks to measure the effective dimensions of clads, polishing cross sections of clads and, then, they were etched with V2A etching. Micrographs of cross sections were analyzed using an optical microscope and a CMOS camera with 5 Megapixel sensor attach.

3. Results and Discussion

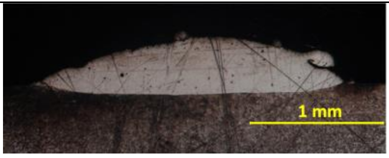
3.1 Individual clad experiments

Results of the metallographic analysis performed in the cladded specimens are represented in the following paragraphs according to their corresponding values of powder flow. Results will be primarily evaluated according to their resulting dilution values, which should be in the range 10 % - 20 % according to the literature studied [17,19].

Beginning with the case of 12 g/min of powder flow, it can be found from the results shown in Table 3 that the mean height of clads was approximately less than 600 µm. Dilution values range from 20% up to more than 35 %, as observed in the tests 13, 19 and 20. The increase from the objective values (10 % - 20 %) can be understood from the fact that there might not be enough concentrated powder for the combination of spot size (ø5 mm) and the power values used. When this happens, a portion of the energy -which is higher than desired- affects the substrate directly because there is not enough powder to absorb it. The energy absorption in the substrate leads to a net heat increase, causing the surface to melt and therefore increase its absorption coefficient [20]. In the end, this results in remelting of the substrate, making the heat affected zone surrounding the clad to be bigger than with a more appropriate relationship between powder flow and laser power [21].

When checking the results with equal laser power and powder flow values, the height of the clads was higher for the minimum value of process speed (800 mm/min) than those made the maximum value (1600 mm/min), since going slower helped to deposit a higher amount of energy to the LC process. This is observed in the couples of tests for 2000 W, 3000 W and 4000 W shown in Table 3.

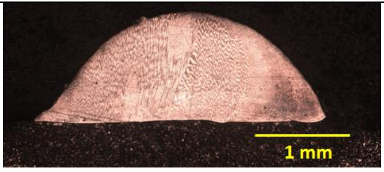
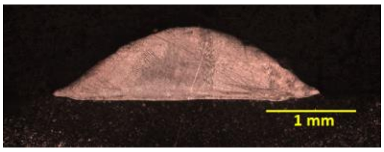
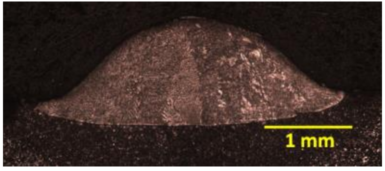
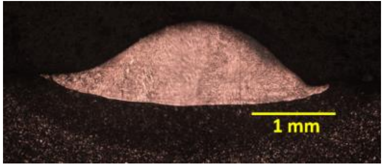
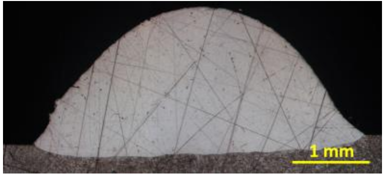
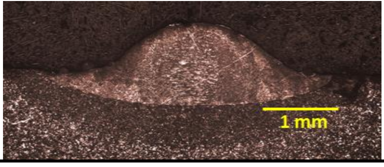
Table 3. Experiments with powder flow of 12 g/min.

800 mm/min, 2000W(test 7)	1200 mm/min, 2000W (test 10)
	
800 mm/min, 3000W (test 15)	1600 mm/min, 3000W (test 20)
	
1200 mm/min, 4000W (test 19)	1600 mm/min, 4000W (test 13)
	

The second value of powder flow to analyze is 25 g/min. In one side, for the tests 2, 4, 8 and 16 shown in Table 4, the mean percentage of dilution can be measured to be less than 20 % and the mean clad dimension found between this tests selection is composed by a height of more than 1 mm and a width of more than 3 mm. On the other side, the process speed values used in the tests 1, 3, 5 and 6 seem to be too fast for the power value used, achieving clads with less than 1 mm in height. Therefore, the interaction time found at higher process speeds did not allow the powder to have enough time to be completely molten. From this group, the test with the highest values of laser power and process speed (test 6) show a dilution ratio higher than 20 % (not desirable).

It is important to highlight that test 17 (2000 W, 1200 mm/min and 25 g/min) is not shown because there was not metallurgical bonding between laser track and the substrate, so the spallation of the clad occurred. In this case, laser value was the lowest in the design and velocity was set at its highest value, meaning that energy density (ratio of power to speed) reached a critical low on this particular test.

Table 4. Experiments with powder flow of 25 g/min.

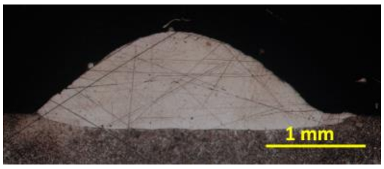
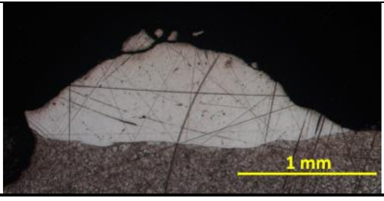
850 mm/min, 2200W (test 2)	1100 mm/min, 2200W (test 1)
	
800 mm/min, 3000W (test 8)	1200 mm/min, 3000W (test 4)
	
1500 mm/min, 3000W (test 3)	
	
800 mm/min, 4000W (test 16)	1600 mm/min, 4000W (test 6)
	
2000 mm/min, 4000W (test 5)	
	

The last value of powder flow analyzed was 31 g/min and metallographic results are shown in Table 5. It can be observed that only test 9 (highest laser power setting and minimum process speed) was able to achieve more than 1 mm in height and more than 4 mm in width, although the dilution percentage was 30 %.

Lower widths and heights found in the rest of the tests can be explained from the process speed values chosen for the experimental design, as they were apparently too high and therefore cooling time was left to be too short, meaning was not possible to melt all the delivered powder. Conclusions can be drawn also from the dilution percentage at different laser power value settings: when using 3000 W, dilution reached 20% and with 4000 W the dilution went up to more than 35 %.

Test 14 from Table 5 is particular because it had the same fate as test 17 in the previous powder flow level studied, so no results are shown either. This test showed no metallurgical bonding between laser track and the substrate, so again the spallation of the clad occurred. In this case, the energy carried by the laser beam was too low to melt as much powder flow, causing the powder grains to absorb most of the energy. Therefore, the substrate didn´t melt and dilution did not take place, leaving an inadequately bonded clad upon the surface of the substrate [20].

Table 5. Experiments with powder flow of 31 g/min.

1200 mm/min, 3000W (test 18)	1600 mm/min, 3000W (test 12)
	

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800 mm/min, 4000W (test 9)

1200 mm/min, 4000W (test 11)

3.2 Multiple clad experiments (solid forms)

From the single clad experiments, it is clear that the intermediate setting of powder flow (25 g/min) groups the best results when seeking to maximize the probability of having appropriate dilution ratios (between 10 % and 20 %). Within this group, on the other hand, tests with maximum height for the power levels studied were found to be those with lower processing speeds. This sets tests 2, 8 and 16 as reference process parameters for the fabrication of solid forms. Nonetheless, in preliminary tests it was found that power level of test 16 (4000 W) was difficult to control when laying multiple clads side by side, taking into account that power regulation was done only after a layer was finished. With this in mind, process speed value was set to be 800 mm/min and laser power values were switched between 2000 W and 3000 W for the fabrication of multiple clad volumes.

The first of the strategies to take into account is the Contour. The general aspect of the contour samples are shown in Figure 3, where it can be observed that the cladding showed good aspect in geometry. Analyzing the cross section of the wall in Figure 4, it is important to notice that the volume is free of porosity and cracking and that there is metallurgical bonding between the substrate and the deposited powder.

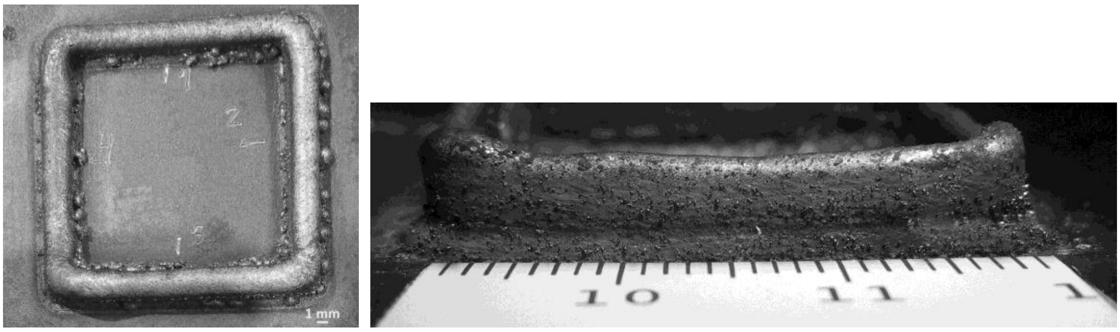

Figure 3. Picture of the contour, general view and a detail of the wall.

Figure 4. Micrograph of cross sections of a wall.

It is worth to mention that, due to the set up employed to manufacture this piece, to maintain a homogeneous height (4 mm) in the whole contour was difficult near the turning radius (corners of the square), because of the deceleration of the machine axis before reaching this points. This can be

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observed in Figure 3, where there is light variation in height in the middle of the wall comparing with the corner.

Following with the experiments of solid forms, next experiments applied the Zig Zag and Parallel strategies. Unlike the single clads, for the study of solid forms is necessary to add the percentage of the overlap between contiguous clads as an influence parameter. Furthermore, it is necessary to study the relationship between the percentage of the overlap and the amount of powder flow to be melted. It is important to seek for an optimal combination of both parameters to guarantee that there is not lack of fusion in the manufactured part, moreover, to achieve less processing time for the same area. As indicated earlier, the range of overlap percentage studied in this work was within 20 % and 40 %.

Figure 5 and Figure 6 show two tests that were manufactured following the Zig Zag strategy. The first one was made with 40 % overlap (one layer), while the second was set to 30 % (two layers). The main difference that can be seen from both tests is the homogeneity of the surface. In the test 1 is observed that the delivered powder is piled up, obtaining a rough surface due to the percentage of overlap. Instead, in test 2 the edges are not very sharp, but the surface is more homogenous than the former because the percentage of overlap used. Common aspects can be observed in both tests: they are free of porosity and cracking, and there is good adhesion between the substrate and the deposited powder.

Figure 5. Macrograph of a cross section following Zig Zag strategy.

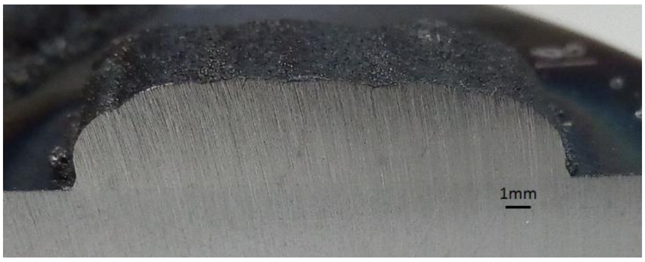

Figure 6. Macrograph of a cross section following Zig Zag strategy.

Finally, the volumes made with the Parallel strategy can be observed in Figure 7 and Figure 8. Only one layer is deposited in the case of Figure 7, allowing the study of the overlap between contiguous cladding tracks. In the results shown, good adhesion between the substrate is observed and no porosity or cracks appear.

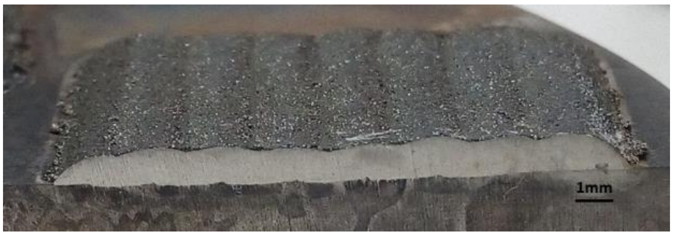

Figure 7. Macrograph of a cross section following parallel strategy.

3.3 Parameter reduction and building of a solid form

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In order to test one of the strategies used in the previous section, a multiple clad, multi-layered volume was made with the process settings chosen between Parallel and Zig-Zag strategies. The Parallel strategy was found to have a more continuous height and, therefore, a more homogeneous surface and, thus, was used as an input for the solid piece proposed.

The multiple clad volume generated was built layer by layer in a Parallel strategy with a total of 10 layers, and the result obtained is presented in the Figure 8. In this case, the surface was machined to analyze if porosity, crack or lack of material appears and the aspect was found to be similar to a bulk material (no porosity was found). Total height was measured to be around 8 mm. It is important to notice that, even though a single clad grows more than 1 mm under the process parameters chosen, continuous, multiple clads will have a different net height because of the overlapping final geometries [22].

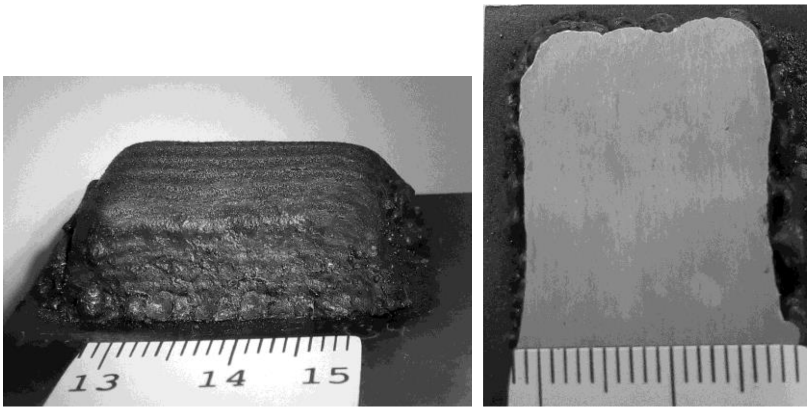

Figure 8. Pictures of general views of a solid piece and its machined surface.

Following the steps in this work, process parameters chosen to be suitable for cladding 316L stainless steel in solid forms with the coaxial nozzle used are:

- Power: 1700 W - 2500 W
- Velocity: 800 mm/min
- Powder Flow: 25 g/min
- Overlap percentage: 30 %
- Height increase per Layer: 0.8 mm

4. Conclusions

This paper seeks to analyze the influence of the main laser process parameters (laser power, process speed and powder flow) in the geometry of a single laser clads in order to subsequently achieve optimal process parameters to build, layer by layer, a solid piece as a first approach. The main conclusions derived from this study are the following:

- A good metallurgical bond was achieved, thanks to the good relation between 25 g/min of powder flow and 30 % of overlap, which guaranteed a dilution value of less than 20 % in less time of process and, in the case of solid forms, without lack of fusions. In addition, it is necessary the power modulation for coating process (from 3000 W to 1700 W), in order to have the control of the process, avoiding overheating of the piece.
- Regarding the strategies studies, it can be seen that the Zig Zag strategy is better to increase the height of the deposited layer faster; and Parallel strategy is used to achieve a good finishing surface.
- Value range of the process parameters studied get valid restrictions, allowing extrapolating results more easily from simpler to more complex experiments.

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Author Contributions: P. Alvarez. Her main contribution is conceived and designed the experiments in performed the experiments, analyzing the micrographs, discussion the results, and she has been in charge of write the article.

MA. Montealegre. Main contribution in conceived and designed the experiments, discussing the results and supervising the paper

J.F. Pulido. Main contribution in performing the tests, and discussing the results.

Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest."

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