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Improvement Surface Quality of SLM Parts by means of the Combination of Different Scanning Strategies

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***Abstract*—Selective Laser Melting (SLM) stands out among additive manufacturing techniques due to the possibility to obtain full-functional complex metallic components. Despite this technique is already suitable for using in automotive and aerospace industries, its installation has not been as expected due to the high quality standards of these industries. Quality of SLM parts can be understood as a combination of different properties of the parts, particularly surface finishing quality and mechanical properties. With regard to quality, works carried out up to date, show that the scanning strategy can influence this quality. Some of the strategies can improve surface finishing while others improve mechanical properties. In this work the adequacy and benefits of using different scanning strategies in the same part are analysed.**

***Index Terms*—Scanning strategies, SLM, Surface finishing quality**

I. Introduction

SELECTIVE Laser Melting (SLM) stands out among additive manufacturing techniques due to the possibility to obtain full-functional complex components. In this technique, parts are manufactured layer by layer by melting a powder bed using a high power-density laser scanning system. The benefits of this technique make it suitable for using in applications in aerospace and automotive industries. However, the very high requirements of these industries, related to the quality of the components, has not fulfilled the expectative for installing and widespreading of this technique. One of the reasons is the poor surface finishing quality of the SLM parts.

Until today, different research works have been developed that analyse the influence of different SLM operation parameters on the final quality of the parts. The scanning strategy used for melting the powder bed stands out among them. The strategy is used in order to reduce the surface tension and it has been demonstrated that has a remarked influence in the surface finishing quality of the parts [1]. In addition, it has been also stated that the strategies have an important influence in the mechanical properties of the parts [1], [2]. Therefore, something that could be interesting in order to obtain better quality SLM parts, should be the combination of different scanning strategies during the manufacturing of the same part.

In this work, the possibility and benefits of using different types of SLM scanning strategies in the same part is analysed, in order to improve both the quality of the surface finishing and the mechanical properties. With this aim, different scanning strategies and combinations of them were analysed to determine the best for improving the mechanical properties and the best for improving the surface quality. For this purpose, several SLM specimens were built using different combinations of scanning strategies. Specimens material was stainless steel 17-4PH and the SLM machine was a 3DSystems ProX 100. Some of the specimens were used to determine the best strategy in terms of surface quality. The surface quality was measured with a contact profilometer Mitutoyo SJ-500 [3]. Other specimens were used to evaluate both the hardness, by means of a Brinell test, and the metallography quality.

II. Material and Methods

In this work, a SLM ProX 100 machine distributed by 3DSystems was used (Fig. 1). This SLM machine allows to manufacture parts up to 100 mm x 100 mm x 100 mm, in different metallic alloys. Other features of the machine are shown in Table I.

Fig. 1. ProX 100 3DSystems SLM machine.

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TABLE I
PROX 100 MAIN FEATURES [4]

Property	Units	Value
Laser max. Power	W	50
Laser Type	-	Fiber Laser
Laser Wavelength	nm	1070
Min. Layer Thickness	µm	10
Present Layer Thickness	µm	30
Repeatability X, Y, Z	µm	20, 20, 20
Typical Accuracy (min.)	%	0.1 - 0.2 (50 µm)

The alloy used in this work is a 17-4PH stainless steel supplied by 3DSystems [5]. This alloy has an outstanding combination of high strength and good corrosion resistance up to 300 ºC. Moreover, it has good mechanical properties in as-built condition and they can be improved with an adequate heat treatment [5], from 620 MPa to 1100 MPa in the case of yield strength. The SLM process works with several parameters that can influence the final quality of the parts, such as laser power, scan speed, hatch spacing or layer thickness. These parameters were tuned based on results of previous works [6] as shown in Table II. An inert atmosphere of nitrogen obtained with a generator connected to the SLM machine was used during the manufacturing of the specimens.

TABLE II
PROX 100 SETUP PARAMETERS

Parameter	Units	Value
Laser Power	W	38
Scan Speed	mm/s	140
Hatch Distance	µm	70
Layer Thickness	µm	30

As usual in SLM processes, melting of the powder layer can be carried out using different strategies. These strategies define the trajectory followed by the laser spot during the operation. As it was already stated in other works [1], [2], the strategy used can influence the surface finishing of the part and its mechanical properties. Moreover, this strategy can have influence in the level of residual thermic internal stresses supported by the parts, because of the different melting of the powder bed. The type of strategies that can be used and their characteristics depend of the Computer Aided Manufacturing (CAM) software used and the machine performance. In this case, three main strategies can be used: hexagonal, concentric and normal.

The hexagonal strategy melts the powder bed following hexagonal paths. In each hexagonal path, the powder layer is melted along parallel trajectories separated by the hatch distance (Table II). In order to assure a correct fusion between the different hexagonal patches, this strategy applies an overlap distance between neighbours. This overlap distance, as well as the size of the hexagonal paths (i.e. the radio of the circle in which the hexagonal path is circumscribed) were tuned as default, 50 µm and 5000 µm, respectively. In the case of the concentric strategy, the laser spot follows closed trajectories parallel to the edge of the part and separated by the hatch distance. In case of manufacturing a vertical cylinder, these trajectories are concentric circles. The sequence for melting the powder along these trajectories is configurable to be from inside to outside of the part, or vice-versa. In this work, outside/inside sequence was used. Finally, the normal strategy melts the powder bed following parallel trajectories separated by the hatch distance from edge to edge of the part. This strategy is similar to hexagonal, but without dividing the powder bed into hexagonal paths.

In this work, the possibility to combine different scanning strategies during the manufacturing of the same part is analysed, in order to improve both its mechanical properties and its surface finishing quality. For this, three cylindrical specimens of 20 mm of diameter and 7 mm of height were manufactured using hexagonal, concentric and normal strategies. The top surface of the specimens is shown in Fig. 2a, Fig. 2b and Fig. 2c, respectively. A scheme of the part orientation during the manufacturing, with the axis of the cylinder parallel to the vertical, is shown in Fig. 2d. Once they were manufactured, the surface roughness was measured in the top surface by means of a Mitutoyo SJ-500 contact profilometer equipped with a 5 µm radio tip. Roughness evaluation was carried out following the recommendations of ISO standard 4288 [3], along 6 radii distributed in each specimen. Then, an average of Ra, Rt and Rz parameters was obtained for each specimen.

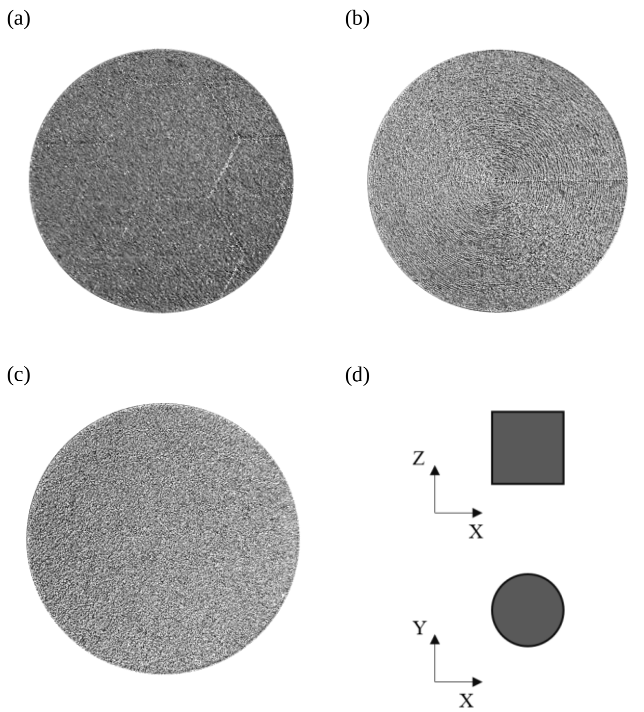

Fig. 2. Top surface of specimens: hexagonal (a); concentric (b): normal (c); and manufacturing orientation (d).

On the other hand, other specimens were produced to analyse the possibility to combine different scanning strategies during the manufacturing of the same part. This functionality is not really available in the CAM software of the machine. So, in order to achieve this objective, it was necessary to program the manufacturing of two parts, where one part is built over the top surface of the other part, using different laser scanning strategies. Thought this procedure, three additional cylindrical specimens were built, in this case with a diameter of 10 mm and a height of 10 mm. As it was already revealed in other works [1], the scan strategies that

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divide the powder bed in different patches allows better mechanical properties. So that, in this work the combination of the hexagonal strategy with others was analysed; in particular, a specimen with hexagonal strategy at the base and concentric strategy at the top, a specimen with hexagonal strategy at the base and normal strategy at the top and a specimen with hexagonal strategy both at the base and the top. The thickness of the base in all cases was half of the total height of the specimens, as is represented in Fig. 3.

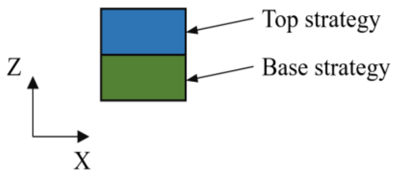

Fig. 3. Scanning strategy combination in the same part.

Once these specimens were manufactured, they were cut off from the build-up plate by means of wire electrical discharge machining. In order to analyse the hardness of the specimens at different heights, they were divided in two parts in a vertical plane, using a metallographic saw with an adequate disc. The first part of each specimen was used to verify cohesion between the zones manufactured with different scanning strategy. For it, a metallographic analysis was carried out using a chemical etching composed of distilled water, hydrochloric acid and potassium metabisulfite. On the other hand, the second part of each specimen was used to analyse the hardness in three different zones. These zones are illustrated in the Fig. 4 and correspond to the area of each scanning strategy (top and base zone) and to the area where top and base join (middle zone). The hardness was tested in three points in each zone using the matrix distribution shown in Fig. 4 (test points separated 2 mm in each direction). The hardness test used was Brinell, HBW 2.5 / 187.5 [7].

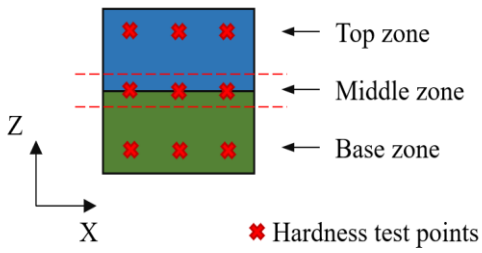

Fig. 4. Hardness test zones and points.

III. Result and Discussion

Fig. 5 shows the results obtained for the roughness measurements of the top surface of the specimens (Fig. 2). In this case, the roughness of the hexagonal strategy has not been considered. The reason is that despite of using the recommendations of the ISO standard, it was found that this technique and its filter recommendations are not appropriate to verify the roughness of surfaces manufactured using patches scanning strategies. The effect observed in the roughness in this type of surfaces was that the filters recommended by the standard produce aberrations in the roughness profiles close to the overlap zone between patches. In the case of concentric and normal strategies, as can be seen in Fig. 5, the normal strategy leads to a finer roughness grade.

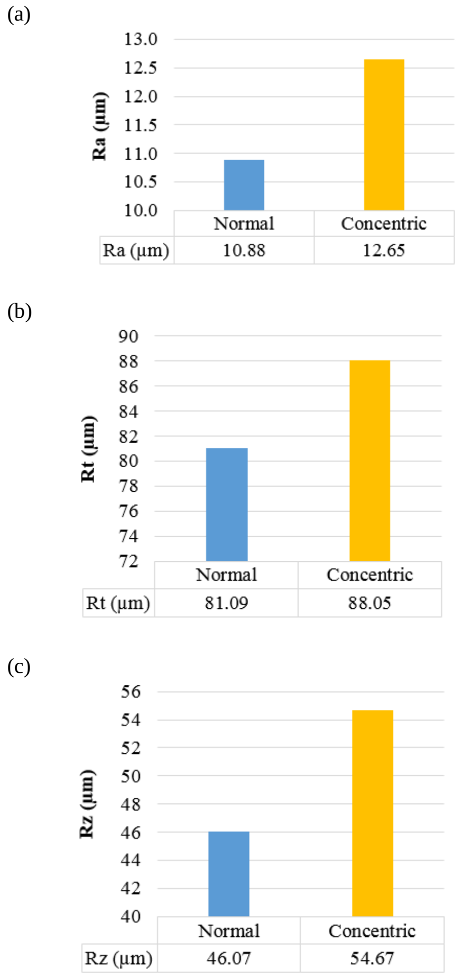

Fig. 5. Roughness measurement results: (a) Ra; (b) Rt; (c) Rz.

On the other hand, the hardness results of the specimens (Fig. 4) are shown in Fig. 6. As can be seen, there are not remarkable differences between the different zones in each specimen and among specimens. Only a small reduction in hardness is remarkable in the case of the top zone in the three specimens. A possible explanation of the inferior advantage of the hexagonal strategy with respect to the others may be that the hardness test was done in the vertical plane instead of the horizontal one, unlike other works. Another explanation can be that, in this work, the hardness was evaluated in parts without any heat treatment, which can produce important changes in this property.

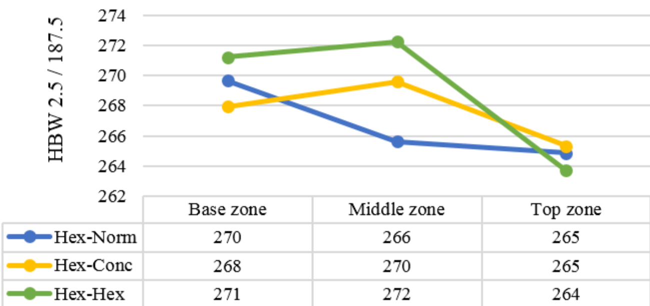

Fig. 6. Brinell hardness obtained in the zones of the specimens.

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Finally, in a simple metallographic test, no remarkable defects were found in the case of the multi-strategy specimens. As can be seen in the Fig. 7, for the specimen with hexagonal and concentric strategy combination, the analysis allows to observe the molten pool left by the laser spot during the melting of the powder bed [8]. Moreover, some phases can be observed. An in-depth analysis is necessary in order to determine if exist remarkable differences among specimens.

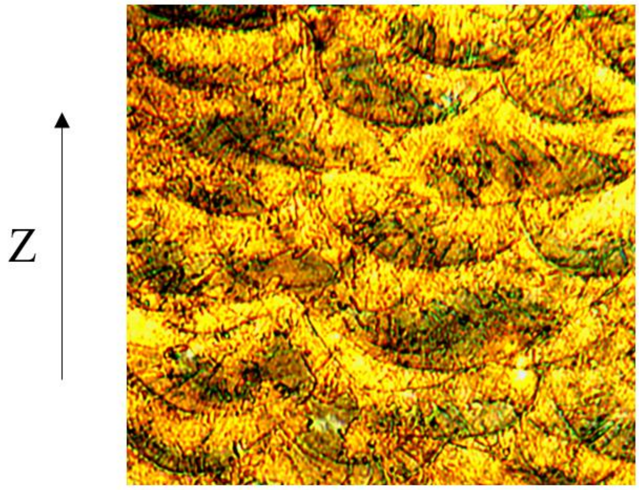

Fig. 7. Microscopy image of the hexagonal-concentric specimen.

IV. Conclusion

In this work, the possibility and benefits of using several types of SLM scanning strategy during the manufacturing of the same part have been analysed. The aim is to improve both the quality of the surface finishing and the mechanical properties of the part. Some specimens were built and it was determined that the most advantageous strategy was the normal for achieving the best surface finishing. Moreover, it was observed that the current ISO standard recommendations should to be modified with regard to the filters setup to evaluate this property, in order to avoid aberrant results in the case of surfaces manufactured by patched strategies.

On the other hand, despite the limitations of the current CAM software, it was demonstrated the possibility to manufacture parts using various scanning strategies. In the specimens built, it was determined that there were not remarkable differences among the different strategies in the case of the hardness in the as-built state of the parts. Furthermore, there were not observed remarkable internal defects in the multi-strategy specimens with regard to the mono-strategy specimen. Moreover, a simple metallographic test of the multi-strategy was carried out. In this test, the melt pool produced by the laser spot and the distribution of different phases in the material were observed. However, an in-depth analysis has to be carried out as future work.

As final conclusion, in this work the possibility to manufacture a SLM part with several scanning strategies has been demonstrated. Based on the results obtained in other works, the best combination to improve the mechanical properties of the part and the surface roughness quality is the hexagonal and the normal strategies combination. The best option is using the hexagonal strategy in the core of the part and the normal strategy in the shell.

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