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Evaluation of laser polishing as post-processing of Inconel 625 produced by Directed Energy Deposition

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Abstract

As one of the Additive Manufacturing (AM) technologies, Directed Energy Deposition (DED) inherited common concerns from the AM concept, such as the layer discretization process, which brings about the staircase effect, and the complex thermal reheating cycles that occur due to the scanning strategies. In this regard, diversification in slicing strategies and the application of post-processing techniques arises as a feasible way to reduce defects and the usual poor surface finishing of DED parts. This study combines the non-planar slicing strategy as toolpath for laser polishing (LP) in DED parts, evaluating the influence of such post-processing for surface finishing, geometry and hardness of the Inconel 625 truncated pyramid built by DED. This geometry was built by using planar slicing and zigzag scanning strategy in BeAM M250 DED equipment. The non-planar coordinates of the LP were applied at an offset in the external profile of the pyramid with support of an open-source software Slic3R. The workpieces were built with laser power of 500 W delivered at the 800 μm spot diameter with scanning rate at 2000 mm/min and powder flow of 7.5 g/min. Laser polishing was performed considering three levels of energy density (9.38, 11.25 and 14.06 J/mm^2) and the number of iterations (once, 3 and 5 times). Both, deposition and LP, were performed with local Argon gas shielding. Among the results, LP has shown to be a feasible post-processing technique to L-DED parts, which can improve surface finishing and shape, maintaining hardness. The energy spent LP causes the remelting of satellite particles and shown to be not enough to rearrange the microstructure. The non-planar slicing applied, as toolpath to the LP, comprises a new possibility allowing DED parts to have better results towards surface finishing with a clean and quick method of post-processing. This has shown to be beneficial to the efficiency of the post-processing stage by leading to a greater assertiveness of the process, less post-processing time and no waste of material.

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Keywords: Additive manufacturing; non-planar slicing strategy; staircase effect; non-conventional post-processing; surface roughness

1. Introduction

Manufacturing Inconel 625 parts and features with complex shapes through conventional methods has been a challenge due to the material high hardness, low machinability and low thermal conductivity [1]. Thus, early in its development, Additive Manufacturing (AM) appear as an alternative process in that chain, overcoming some of those adversities, triggering a readily adoption to manufacture Inconel 625 components [2]. Several AM processes using laser, electron beam or plasma arc as an energy source for melting Inconel 625 powder and build parts have been developed [2]. The two categories of AM processes that has been reported to produce Inconel 625 are Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) [3].

DED is an AM technology that adds material in a layer-by-layer motion, by the simultaneous deliver of material (powder or wire) to a melt pool generated by a focused energy source (laser, electron beam or plasma arc) [4]. This technology has been successfully introduced in industries by the appeal of a more economical alternative for refurbishing worn and damaged regions in mechanical components, molds and dies, etc. Also, DED has been used to build complex-shaped parts without the aid of support structures [5]. Although DED technology is just starting to be widely used and its sales are exponentially

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increasing [6], DED systems are deeply responsive to working conditions and related to high energy consumption and production costs, which are still configuring a critical challenge to the process [6].

For example, powder-fed DED systems can produce fine parts when compared to wire-fed systems, but the conveying line makes the system highly sensitive to the environment conditions, e.g. temperature, humidity, etc. Additionally, any variation in laser power, scanning rate and mass flow has been proven to affect the printed geometry, resulting in staircase effect, depending on the scanning strategy, and directly interfering with the surface finishing [6]. Therefore, post-processing operations are frequently adopted to achieve product specifications.

Overall AM processes requires the stage of slicing three-dimensional objects and their subsequent translation into coordinates to be transferred to equipment, in which the 3D printing will indeed occur. Most slicing software works by slicing the model into discrete parallel layers with regular height and then, stacking the layers [7]. Although planar slicing is a widely used strategy, it leads to some differences between the original object and the final printed one, namely the staircase effect [8].

An alternative to improve the quality of the final parts would be to trace non-planar coordinates around the final object, in order to allow simultaneous post-processing to the manufacture. In an attempt to improve surface finishing, Pelzer and Hopmann [9] propose variable height of non-planar deposition for Fused Deposition Modeling (FDM) systems, including new nozzle configurations for extrusion to increase the range of non-planar parts. Ahlers [10] implement an algorithm for non-planar slicing in the open source software Slic3r, also considering the angle of collision between the nozzle and the printed part. The non-planar slicing in software Slic3r combines the traditional inner construction by planar layers with the outer offset of non-planar layers, giving to the final surface a closer shape to the original model by the reduction of staircase effect.

Although this slicing strategy has been used in other AM technologies, the non-planar strategy still faces challenges: a certain degree of difficulty in implementation, limitation of specific geometrical cases and lack of standardization in commercial equipment. There has been no report on the use of the non-planar strategy to the build of metal components by DED operations so far, nor the benefit of this concept to build toolpath coordinates for post-processing operations that uses the same CNC setup. Simultaneous post-processing promotes the integration of manufacturing process, with significant time savings, less equipment set-up and better surface quality.

Besides improving surface finishing during deposition, many methods, such as abrasive blasting, electrochemical polishing, electro polishing and plasma spraying can be required as post-processing [11]. These traditional polishing techniques usually depend on removing material from the surface. However, these methods can be time consuming, bringing up environmental hazards and some of them may not be feasible to parts with complex geometries [12]. The surface finish of mechanical components is often of great importance and directly affects its functionality in most applications [13].

In this regard, Laser Polishing (LP) emerges as a potential non-conventional post-processing technique to be used for reducing surface roughness in AM parts [14]. This technology has been applied to metals [15], diamonds [16] and micro-optical components [17], and its concept relies on the laser remelting higher peaks and filling valleys of the surface, using the movement of the melt pool. By redistributing the material on the surface to the same horizontal level due to surface tension and gravity, this process can effectively reduce surface roughness, being a suitable and clean alternative, as post process for laser DED (L-DED) parts [18].

Compared with manual polishing, mechanical polishing and chemical-mechanical polishing, LP brings up a high-efficient, flexible and automated method to be applied in CNC environment as a post-processing process [19]. Some of the advantages of LP are the consistent and good surface quality, it is a process free from abrasive forces, a clean method that gives no emissions to the atmosphere, and the feasibility to perform selective polishing of small areas, if needed. Thus, LP can show interesting results in different industrial applications, such as precision molds [20] and high-performance components [21], in which, surface finishing must meet 1 μm SA or less.

Besides all its benefits, the LP process on a metallic surface may become quite complicated, if the right conditions and combination of parameters are not employed. When the surface is manufactured by AM, the metallic powder melted by laser can lead to metallurgical defects, such as porosity and non-melted dust, due to rapid cooling rates and directional solidification [22]. Parts made by AM are more frequently deformed, or distorted, due to the high energy of the LP process. Additionally, with a sweep at high speeds during the process, the melt pool tends to elongate, becoming unstable and separating into small spheres to maintain uniform pressure within the melt pool [23].

Since the LP process can be performed at the same L-DED environment, it has good assertiveness in improving surface finishing and it can reduce manufacturing times, allowing to increase productivity and to reduce production costs. Furthermore, the benefits of non-planar slicing concept, as shown hereby, opens an opportunity for the application of the built offset toolpath into the post-processing of metal parts, such as LP. By combining the non-planar slicing toolpath with the post-processing of LP, the final quality of L- DED produced parts could benefit first and foremost in complex trajectories, in which the staircase effect has major influence on the part.

In such context, the present work aims at evaluating 3D shapes made of Inconel 625 obtained by L-DED. Truncated pyramids were built, and post processed by LP using an offset trajectory, which was based on the non-planar slicing concept proposed by Ahlers [10]. To evaluate how the post-processing trajectory, energy density and number of iterations affects the quality of DED metal parts and production chain, some outcomes such as roughness, shape, microstructure and time of processing were investigated.

By fundamentally applying concepts from multidisciplinary areas within AM processes, this work expands the field of application for the non-planar slicing, by combining it as source of toolpath for the laser polishing of metal parts produced by

L-DED. By doing so, it also enables new possibilities towards a non-planar slicing optimization for L-DED operations, which will be addressed in further work.

2. Experimental setup

Figure 1 shows the 3*D* model from the truncated pyramid geometry to be deposited. This particular geometry was chosen due to its planar stacking nature, which results in the staircase effect. The model dimensions were defined in order to allow a safe build up with no collision between the workpiece and the laser nozzle. The pyramids were built by the conventional slicing method, which is planar in nature so the layers have a predetermined height – specified at the slicing step. The non-planar systems for AM include hybrid slicing, which consists of building planar (inner) slicing to support a non-planar offset (outer) printed in the last layers. In this study, the non-planar offset will be used as toolpath strategy for the post-processing of LP, as presented later in this section.

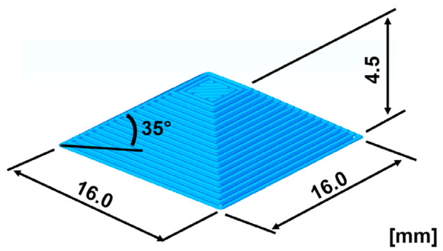

Fig. 1. Geometrical modeling of the truncated pyramid

The main parameters of laser power, scanning speed and Z increment were chosen after the performance of initial tests. In these tests, the geometries of lines, thin walls and blocks were investigated in order to generate good microstructure with minor number of defects such as pores and lack of fusion. First, at the line stage, laser power, scanning speed and powder feed rate gives the bead geometry width to the height ratio amidst 3 and 5. Since the powder feed rate is kept constant, three to five combinations of laser power and scanning speed are evaluated into the build of thin walls. Second, within the thin wall layers, dilution may be considered in order to maintain the Z increment the same as the layer height, therefore the process do not lose focus. Third, the best laser power and scanning speed parameters are adapted to the build of blocks. At this set of experiments, the layer height may vary since there is an influence on the bead stepover into the layer height. After adjusting these parameters, blocks were evaluated in regard to microstructural analysis, therefore the best set of parameters were chosen to build the pyramids.

The deposition tests were performed in a CNC DED machine M250 from BeAM, with laser spot size of 800 μm. Since the focus of this study is on the post-processing technique by LP, no variation was included into the parameters of DED, since that would affect the quality of the workpiece as built. Therefore, all the deposition tests were carried out at 500 W laser power, 2000 mm/min scanning speed and a constant Z increment of 0.36 mm. The geometry of a truncated pyramid was built based on the zigzag toolpath with raster rotation of 90° between layers of planar slicing.

Table 1. Typical chemical composition (W_t%) of Inconel 625 powder [24].

Cr	Nb	Mo	C	Ni
21	4	9	≤ 0.010	Balance

Inconel 625 powder from H. C. Stark Co. (see Tab. 1 for powder composition and Fig. 2 for powder shape) with particle sizes of 45 to 90 μm distribution was delivered at the rate of 7.5 g/min by the conveying line of Argon gas at 3 L/min. Secondary gas at the rate of 6 L/min prevented the melt pool from oxidizing whilst the central gas (3 L/min) protected the optics lenses against back-flow of contaminants.

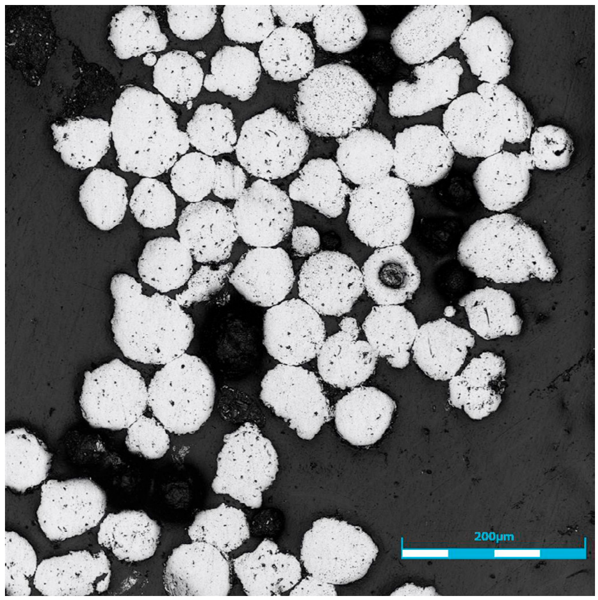

Fig. 2. Microscopy of the cross section of Inconel 625 powder

Some porosity was already present in the powder, as seen in Fig. 2. The post-processing by LP was performed to the truncated pyramid (as built) in an offset strategy generated by the non-planar slicing code from Ahlers [10], and zigzag toolpath at the same printing setup to avoid positioning errors. Considering the laser power of 300 W and the scanning speed of 1600 mm/min, 2000 mm/min and 2400 mm/min, the post-processing promote the energy density (E_d) of 14.06 J/mm^2, 11.25 and 9.38, respectively, to the workpiece surface, in three levels of iterations (once, 3 and 5 times). The raster rotation of 90° between LP iterations was determined to allow the redistribution of material into the grooves left on the surface by the remelting principle. Figure 3 presents the schematic for laser

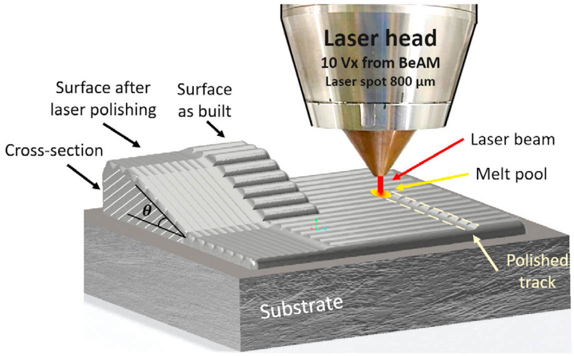

Fig. 3. Schematic of laser polishing by using non-planar toolpath strategy

polishing carried out with non-planar toolpath combined with zigzag strategy.

Additionally, all sets considered the standoff from laser polishing in focus, and the laser beam to be orthogonal to the base of the pyramids. By combining the non-planar strategy for the LP toolpath, it is believed that the surface finishing after the post-processing would present lower levels of roughness and higher levels of reflectivity when compared to the ones only obtained by DED. Table 2 summarizes the parameters and their levels hereby used.

Table 2. Laser polishing settings.

Trial	f (mm/min)	E_d (J/mm^2)	# LP iteration
A1	1600	14.06	1
B1	2000	11.25	1
C1	2400	9.38	1
A3	1600	14.06	3
B3	2000	11.25	3
C3	2400	9.38	3
A5	1600	14.06	5
B5	2000	11.25	5
C5	2400	9.38	5

Surface roughness and the part shape were evaluated in a 3D Confocal microscope LEXT 4100 by Olympus. The measurement of 3D roughness considered the region of interest of 2.5 mm x 2.5 mm (6.37 mm^2) and the cutoff of 0.8 mm. Then, the workpieces were sectioned in half and submitted to sanding, polishing and etching with Marble's reagent (distilled water 50 ml, HCl 50 ml and $CuSO_4$ 10 g). Microhardness Vickers tests were performed using a Buehler 1600 – 6300 micro hardness tester on the cross sections of the samples using a test load of 0.05 kgf (0.5 N) and a dwell time of 15 s, to obtain the microhardness profiles (LP zone and DED). The distance from each indentation was defined at the micro hardness tester, by a micrometer, and measured at the 3D Confocal microscope LEXT 4100 by Olympus, for more accurate data.

3. Results and discussion

Figure 4 presents a typical surface and cross section of the truncated pyramid as built. Based on the building principles,

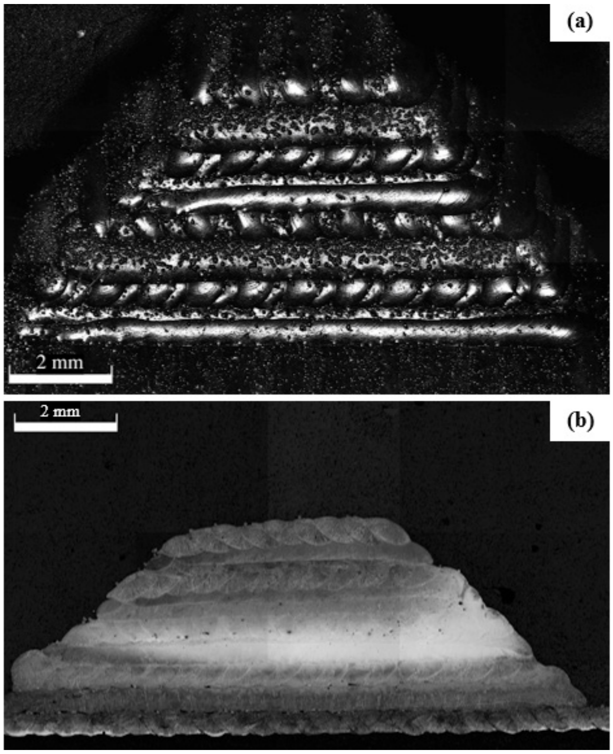

Fig. 4. Microscope image from the truncated pyramid on its (a) side and (b) cross section, both as built.

one can observe the toolpath strategy, as for the raster rotation between layers and the well-defined staircase effect. There are also satellite particles attached to the surface (Fig. 5a.). These

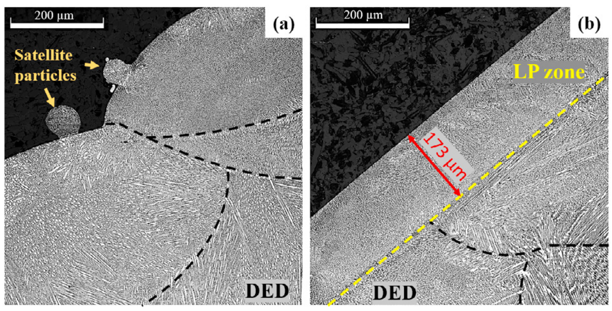

Fig. 5. Image from the side of the truncated pyramid (a) as built and (b) with laser polishing trial A5.

particles are likely to be partially melted. This can happen because the energy delivered to the melt pool is enough to partially melt the last layer, catch some more powder to build the actual one, and to dissipate to the environment during cooling. Yet, at outer layers, the beam energy that is being dissipated at the sur-

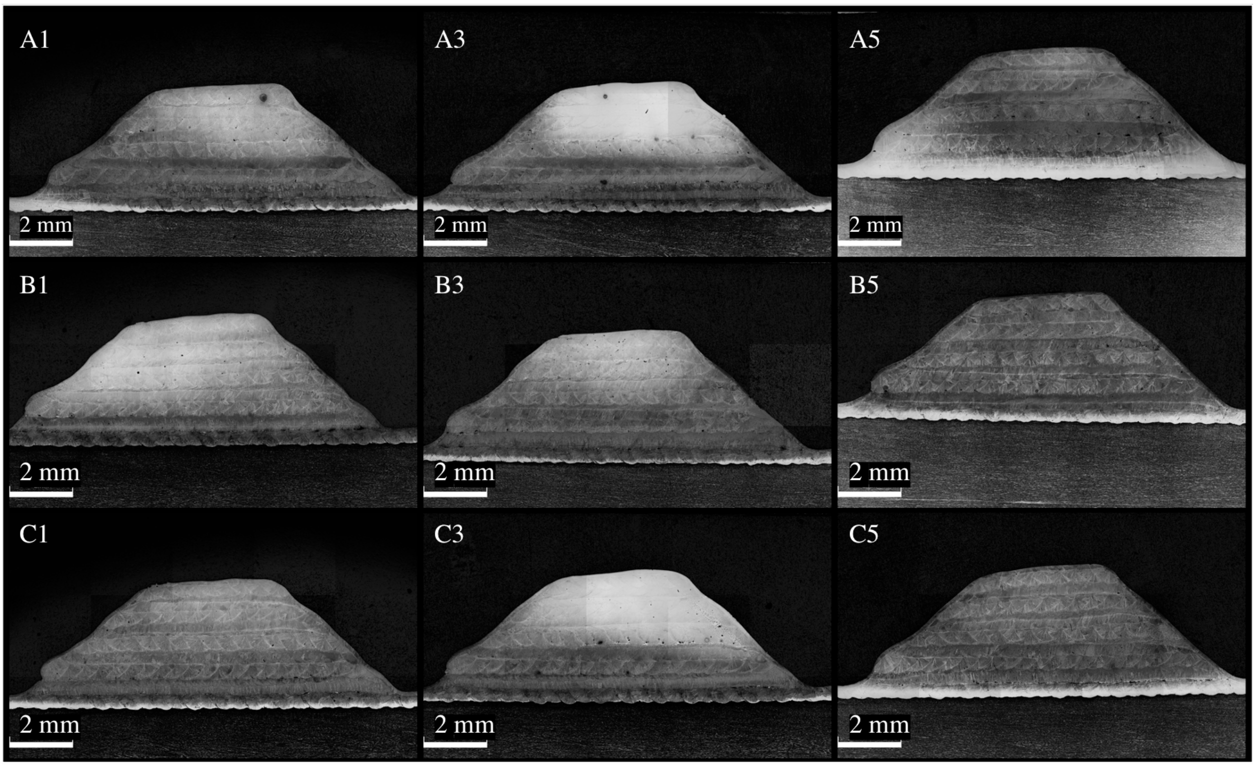

Fig. 6. Typical microscope image (scale: 2 mm) from the truncated pyramid cross section with laser polishing trials.

face may not be enough to melt all adjacent particles in regions nearby the melt pool.

The post-processing by LP gives the additional energy to melt the satellite particles and remelt some of the out layers, redistributing the material and lowering the surface roughness in most cases (see Fig. 5b.). Figure 5a. shows in detail the staircase effect formed in the inclined profile of the pyramid with the planar slicing and deposition. The use of LP in non-planar movement in truncated pyramid (Fig 5b.) showed a significant improvement on the inclined profile of the pyramid, eliminating the steps of the layers and forming a controlled offset around the part.

The shape of the post-processed pyramids is represented at the microscopy images from its cross section in Fig. 6. By comparing the number of iterations, the pyramids with five iterations presents lower waviness due to the staircase effect than the ones with three and one iteration. That occurred for all three LP energy density evaluated. When comparing the energy density influence at the same level of iteration, one can see that the higher the energy density, the better the surface shape. In this respect, the better set – in terms of surface finishing – is presented in Fig. 7.

LP gives to the metal part surface higher uniformity, also increasing the reflectivity levels when compared to the ones achieved with DED only. This is also a result from the improvement in surface finishing.

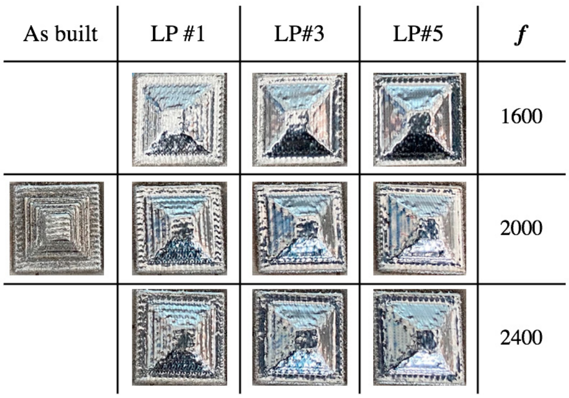

Fig. 7. Pyramids as built and after laser polishing according to the parameters used. LP#n indicates the number of iterations of the laser beam on the surface

From Fig. 7, one can see that the staircase effect still shows after one LP iteration, particularly with the C1 set of parameters, which has the lower energy density evaluated in this study. This effect decreases as the number of iterations and energy density increase. Visually, the shinier truncated pyramid was produced with the A5 (1600 *mm*/*min*, #5) set for LP, followed by A3 (1600 *mm*/*min*, #3) and B5 (2000 *mm*/*min*, #5). This visual effect is an outcome from the redistribution of material on the surface and can add value depending on the application.

It is also important to highlight that not all the defects produced during DED can be completely eliminated with LP. If there are geometrical distortions coming from deposition, it is likely to be minimized by LP, but not completely removed. To such cases, other post-processing techniques, e.g. machining and grinding, would be recommended, before LP. That sequence of post-processing will be investigated in future works.

Table 3. Surface roughness (Sa) as built and after LP trials.

Trial	f (*mm/min*)	Sa (μm)	2σ (μm)
As built	–	150.879	31.00
A1	1600	12.920	1.60
B1	2000	18.916	3.00
C1	2400	23.155	4.74
A3	1600	12.178	1.56
B3	2000	12.489	0.96
C3	2400	16.289	1.60
A5	1600	12.342	3.36
B5	2000	10.861	1.50
C5	2400	17.218	6.54

To quantify the finishing of the parts, surface roughness data is presented in Tab. 3. The surface of the pyramid as generated by L-DED presents Sa to the level of $150.879 \pm 31.0\ \mu m$, which configures a poor surface finishing to a component, reinforcing the need for a post-processing. When comparing it to the finishing given to the surface after LP, it can be pointed out that LP was able to effectively decrease the average surface roughness from 6.5 to 13.9 times the initial surface condition. The lower surface roughness were obtained at the sets A3, A5, B3 and B5, which presents no significant difference.

Figure 8 presents the microhardness Vickers profiles (load 0.5 N) against the distance from the surface taken at the cross sections of the samples. It can be observed that the microhardness obtained for all conditions was approximately 260 $HV_{0.5}$, remaining constant near the surfaces towards the centers of the parts. Therefore, the LP did not significantly influence the microhardness of Inconel 625, which resulted from the remelting process at lower levels of energy density in comparison to the ones needed at the L-DED stage. L-DED do not give enough energy and time to change the microstructure of the material, thus, hardness levels tend to prevail after the LP.

Last but not least, Fig. 9 shows the post-processing time of the LP conditions. Those data show that for greater scanning speeds post-processing time proportionally decreases, which is also demonstrated for higher LP iteration. The longest process time was obtained with A5 set, which configures LP with 5 iterations of 1600 mm/min scanning speed and 300 W laser power, adding 214 s to the operation.. In Tab. 3, the sets A3, B3 and B5 presents similar surface finishing to this particular A5 set. However, in terms of the surface waviness, the B3 set is closer to A5 workpiece. Set B3 can be produced in 108 s, almost half the time from A5. Therefore, the choice for a good LP parameter requires a balance between surface roughness and waviness (outcomes) with time of operation and energy density (input). In this respect, the B3 set is able to produce good finishing to the surface as well as to require half the time of operation in comparison to A5, which represents less costly production.

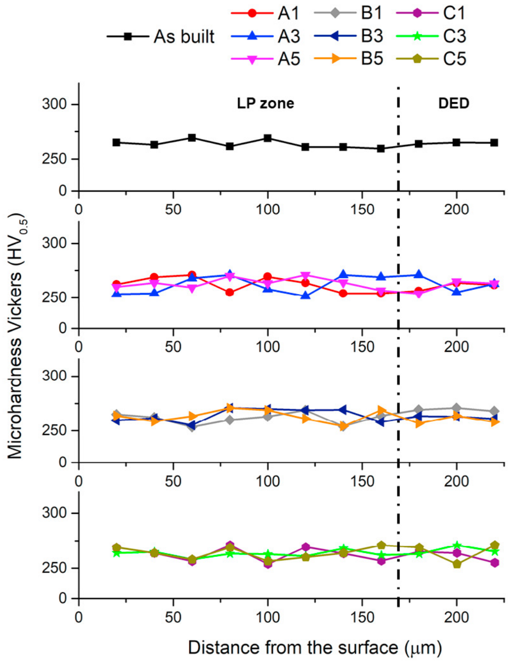

Fig. 8. Microhardness Vickers against distance from the truncated pyramid surface.

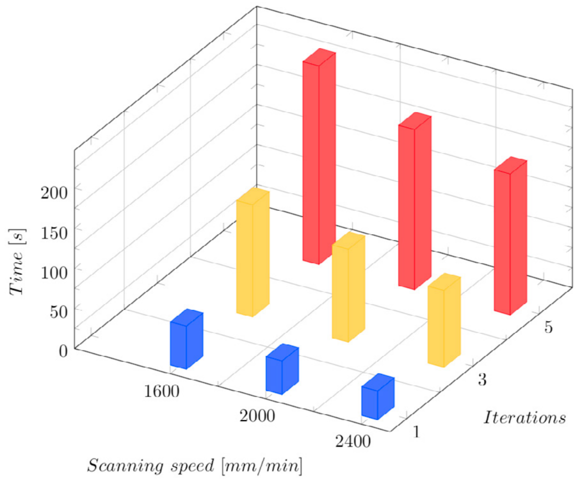

Fig. 9. Processing time for the laser polishing trials.

4. Conclusion

The present work introduces a novel plan for performing laser polishing in angled geometries such as truncated pyramids. Based on the findings, the main contributions of this work are:

- The non-planar slicing strategy, which has only been reported to the building of layers in FDM technologies, was successfully applied to the building of offset trajectories to the LP of Inconel 625 produced by L-DED. This brings the possibility of significant improvements on surface finishing of complex L-DED metal parts even in 3-axis CNC machines.
- The satellite particles and the staircase effect, proper of the slicing strategy, may have a major influence on the surface finishing of DED parts as build if no post-processing is performed.
- The laser polishing did not significantly modify the microhardness of the deposited Inconel 625. This is likely due to the lower energy levels that are promoted during LP not being enough to rearrange the microstructure of the material.
- A right balance between surface finishing and iteration times when using LP is necessary to improve productivity. With the range hereby tested the best combination was scanning speed of 2000 mm/min and 3 LP iterations (set B3).

Acknowledgements

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