

Exploring Potentialities of Direct Laser Deposition: Thin-Walled Structures

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Abstract. In the context of Industry 4.0, the interest towards the additive manufacturing processes is growing due to their numerous advantages, such as the possibility to prototype, the reduction of waste material, the inferior time to market, and so on. In particular, a promising technology is the Direct Laser Deposition, which uses a focused laser beam to melt powders as they are deposited. In opposition to the well-established powder-bed fusion technologies, there are still some issues related to this process. This work aims to solve one of them, exploring the potentialities of DLD in printing thin-wall structures. For this purpose, the influence of the adopted deposition strategy and of the layer thickness on the geometrical accuracy and mechanical properties has been investigated. The results have pointed out that the first variable strongly influences the workpiece. It is possible to deposit thin-wall structures with a ZigZag strategy and consider a layer thickness equal to 90% of the height of the single track, printed with the same process parameters.

Introduction

Industry 4.0 is based on nine core pillars that affect the manufacturing growth [1]: big data, autonomous navigation [2,3], simulation [4–6], additive manufacturing [7], internet of things [8], cloud computing, augmented reality, horizontal and vertical integration and cyber security [9].

In particular, additive manufacturing is currently proving its ability to revolutionize the manufacturing industry, considering that it is based on the increment of material, in contrast to the traditional subtractive processes [10]. Additive manufacturing, both for polymers or composites [11,12] and for metals, is characterized by various advantages, such as for example rapid prototyping, high design flexibility, and the possibility to reduce the time to market.

Among the additive manufacturing processes, Direct Laser Deposition (DLD) is an innovative technology for additive manufacturing of metal parts [13]. It is particularly interesting for industrial applications because of the reduction in material waste, the fact that material is only used where it is desired. Indeed, unlike powder bed fusion techniques, DLD processes are not used to melt a material that is pre-laid in a powder bed but is used to melt materials as they are being deposited [14,15]. Another great advantage is the possibility to repair an object or to print a multi-material workpiece in a unique process [16]. Nevertheless, there are still some issues related to the process, and one of them regards the thin-walled structures. This paper aims to i) explore the feasibility of printing thin wall structures using the DLD process, ii) better assess the influence of the deposition strategy, iii) study the influence of layer thickness on the geometrical accuracy and mechanical properties.

Materials and Methods

Materials. The substrate used is a 316L stainless steel with a dimension of 200x80x20 mm³. The feedstock employed are gas-atomized powders of hot-work tool steel H13 (supplied by Sandvik

Osprey Ltd., U.K), shown in Fig. 1. The chemical composition of the powder was 0.4%C, 5.2%Cr, 1.6% Mo, 0.5%Mn, 1.0% Si, 1.17% V, and Fe bal. [17].

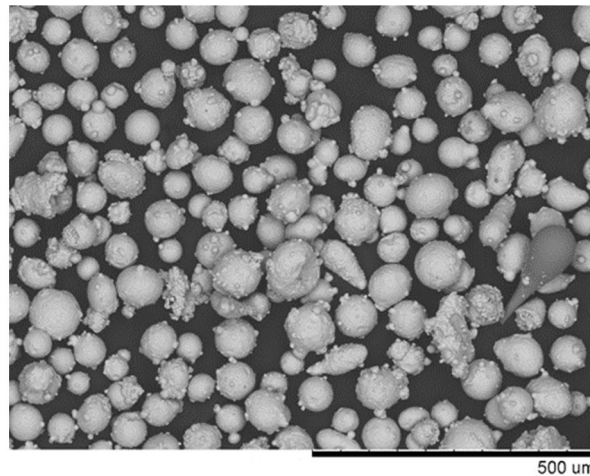


Fig. 1 Micrograph of H13 powders employed for Direct Laser Deposition of single walls.

Experimental campaign. A preliminary experimental campaign composed of single tracks has been carried out with laser power equal to 1600W, powder feed rate equal to 15 g/min, scanning speed equal to 1000 mm/min, and a flow rate of career gas and shielding gas set, respectively, to 5 and 6 l/min, in order to calculate the height of the single tracks. Three values of layer thickness equal to 60%, 75% and 90% of the height of single tracks have been employed to deposit single walls. In other words, samples with variable layer thickness, i.e. 0.4 mm, 0.5mm and 0.6mm, have been 3D printed with the above mentioned fixed process parameters. Moreover, two kinds of deposition strategy have been studied, the Zig strategy and the ZigZag strategy, illustrated in Fig. 2: the dot-lines represents the movement of the laser head with the beam laser turned off, the arrows represent the movement of the laser head during the deposition process, in particular, the orientation of the arrows indicate the deposition direction.

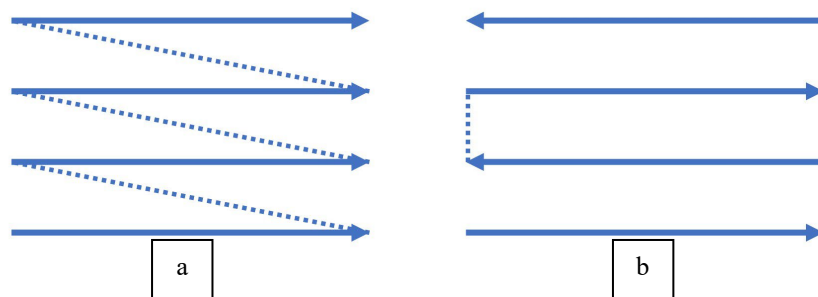


Fig. 2 Deposition strategies in DLD process: a)Zig and b)ZigZag.

Manufacturing procedure and characterization. DMG MORI LASERTEC 65 3D hybrid machine (LT 65 3D hybrid, DMG MORI AG, Pfronten, Germany) has been employed for all laser deposition experiments, in collaboration with the ProM Facility Laboratory. A CAD/CAM software (Siemens NX) associated with the DLD machine has been employed to produce the G-code file.

The 316L substrate has been sandblasted and degreased with acetone before the deposition process. Then, six single walls have been deposited, with a dwell time of 15 minutes between one deposition and another. Single walls have been cut and cross-sectioned via electrical discharge machining (EDM) in the middle of single walls to ensure the analysis of the section in which the process is stable

Then, the specimens were hot mounted in an acid-proof resin. The metallographic preparation has included water-cooled silicon carbide paper (200 mm diameter) for the grinding stage; the grit size selected also depends on the technique used to generate the cut surface. The used grit sequence was

240, 320, 400 and 600-grit. Then, specimens were polished with 9, 6 and 1 μm diamond abrasive suspension to the polishing cloths [18].

Microstructure characterization has been performed on polished metallographic cross-sections after chemical etching with Vilella's reagent, employing optical microscopy (OM) and scanning electron microscopy (SEM), an Hitachi TM3000. Microhardness Vickers measurements have been conducted on the metallographic cross-sections with a dwell time of 15 s, as suggested by the standard ASTM E92-82 [19].

Results and discussion

The first consideration regards the feasibility of building single walls using a Zig strategy. More than one attempt has been made in the experimental phase on the DLD machine, Fig. 3. illustrates an example made with this kind of deposition strategy and layer thickness 0.5 mm. It is possible to note that only three layers can be deposited, reaching acceptable results in terms of shape and geometrical accuracy. With ten layers, the structure begins falling down at the end of the layer (hereinafter point B), that is to say, when the laser turns off. On the other hand, it is also possible to note an initial hill on the left side (hereinafter point A), that is to say, when the laser turns on again, layer by layer. After these preliminary results, it has been assessed to decrease the laser power from the 4th layer onwards, specifically 100 W each layer until 1200 W. Therefore, with the single wall composed of 35 layers, the final result shows an over-deposition around point A, while the structure completely collapses towards the point B.

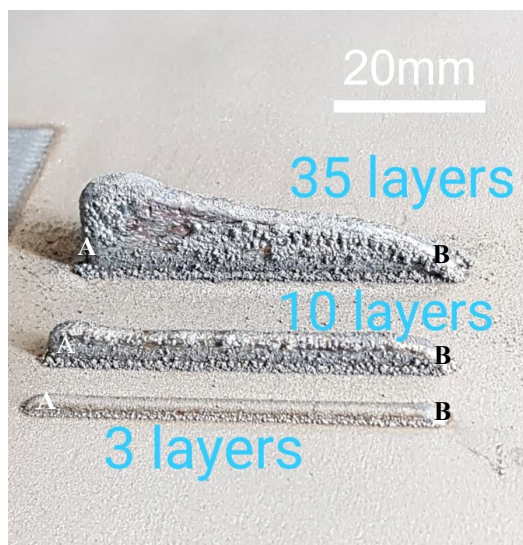


Fig. 3 Direct Laser Deposition of H13 single walls with Zig strategy.

Consequently, in the author's opinion, the Zig strategy is not recommended to make thin wall structures due to the above-described defects.

The characterization analyses have been carried out on all the specimens produced with the ZigZag deposition strategy. In particular, the SEM analysis has pointed out the presence of several defects in each sample, such as cracks, porosities, voids and unmelted powders, as shown in Fig. 4.

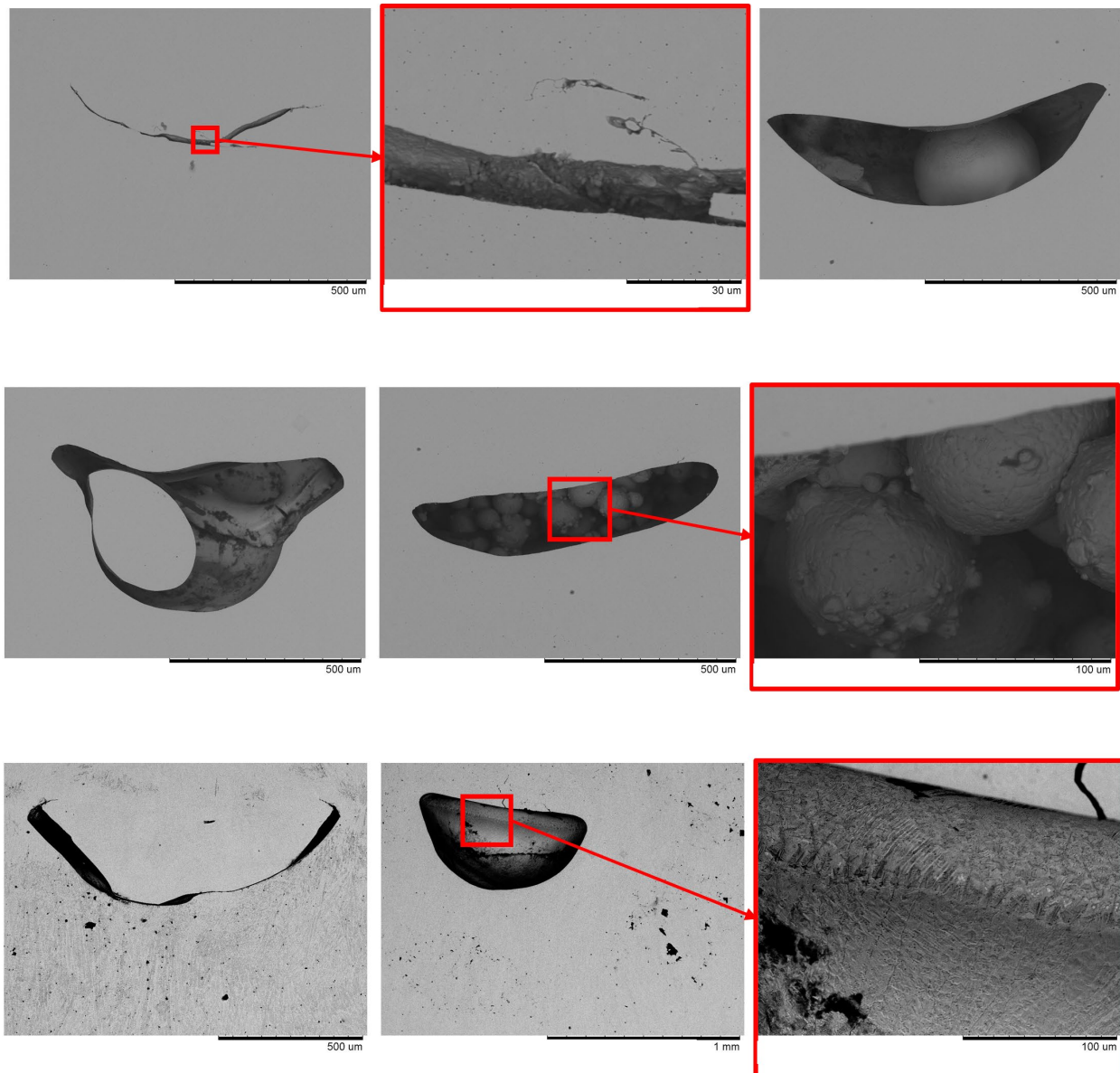


Fig. 4 Defects in DLD-H13 single walls.

Although the presence of many defects, the mean value of the microhardness is near to one stated in literature [20]: 603HV, 623HV and 629 HV, respectively, for 0.4, 0.5 and 0.6 mm of layer thickness. Referring to Fig. 5, it is possible to note a general increasing trend of the microhardness from the bottom to the top, probably due to the fact that the physical phenomena involved in the DLD process [21,22], such as for example the Marangoni effect, led to a mixing of 316L, the material of the substrate, and H13 powders, deposited during the process through the nozzle. Consequently, these phenomena affect the microhardness values.

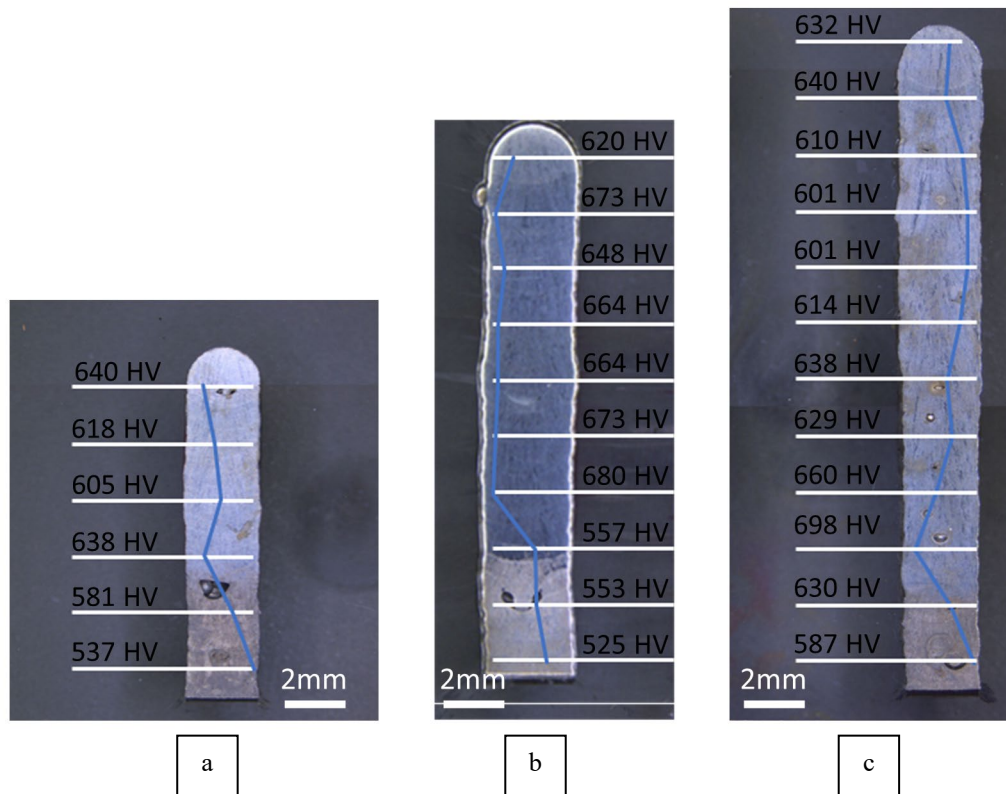


Fig. 5 Microhardness in DLD-H13 single walls with layer thickness equal to: a)0.4mm, b)0.5mm and c)0.6mm.

Moreover, it is clear that the layer thickness influences the workpieces; the height increases with the increasing of the layer thickness, precisely from 0.4 to 0.6 mm, the mean height is equal to 12, 17 and 22 mm. On the premise that in the design project, the total height of the single wall is always 23 mm, it means that 0.4 and 0.5 mm are too low values for the layer thickness, which implies an incorrect position of the focal point of the laser and, consequently, affects the total height of the wall in combination with irregular shape. In conclusion, only one single wall has respected the design data and reached the desired height in combination with an acceptable shape; it is shown in Fig. 6 and it has been obtained with a layer thickness equal to 0.6.



Fig. 6 Direct Laser Deposition of H13 single walls with ZigZag strategy.

Conclusions

In this work, the potentialities of the Direct Laser Deposition process to print thin wall structures have been investigated. For this aim, single walls of hot-work tool steel H13 have been deposited on a 316L substrate, by varying both layer thickness and deposition strategies, with fixed laser power, powder feed rate and scanning strategies, respectively 1600W, 15 g/min and 1000 mm/min. On the

basis of the experimental outcomes, it is possible to answer the open questions designed in the introduction. The following conclusions can be drawn:

- i) Thin wall structures can be printed via DLD, with particular attention to the decreasing of the laser power in combination with the increasing of the layer. Specifically, for the H13, it has been assessed a reduction of 100 W for each layer starting from the 4th layer in the single walls.
- ii) The deposition strategy strongly affects the final workpiece result; in particular, the Zig strategy is not suitable for the thin wall structures. On the contrary, the Zig Zag strategy is recommended.
- iii) The setting of the proper layer thickness is crucial to obtain an acceptable result in terms of geometrical accuracy and good mechanical properties. In particular, referring to the H13 single walls, the microhardness slightly increases with the increasing of the layer thickness, as well as the total height of the samples. In conclusion, the layer thickness suggested is equal to the 90% of the height of the single track deposited with the same process parameters (0.6 mm for H13), which is the case with the major microhardness value, ~630HV, in combination with the achievement of the total height stated in the design stage. Nevertheless, on the basis that DLD is a promising process for thin wall structures, the experimental analyses have also pointed out several defects, such as voids, cracks and unmelted powders, suggesting the necessity of further research in this field.

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