Additive Manufacturing via Laser Powder Bed Fusion: A Review

Muhannad Ahmed Obeidi[1,2,3*], Ahmed R. Al-Hamaoy[4], Jim White[3], and Inam Ul Ahad[1,2]

[1]School of Mechanical and Manufacturing Engineering, Dublin City University, Dublin, Ireland
[2] I-Form Advanced Manufacturing Research Centre, Dublin, Ireland
[3]Nammo Ireland Ltd, Dublin, Ireland
[4]Department of Laser and Optoelectronics Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq
muhannad.ahmedobeidi@dcu.ie

Abstract. Additive manufacturing (AM) has expanded significantly in recent decades as a result of considerable advancements in laser technology and metal powder fabrication. It enables the quick production of near-net-shape designed parts from a digital CAD file without the need of dies or moulding. Nevertheless, one of the major challenges in Laser-Powder Bed Fusion (L-PBF), for example, is the disparity in the characteristics of the manufactured parts. The fundamental reason for this is the non-stationary character of the melt-pool area, which is accompanied by weld fumes, metal evaporation, plasma, and spark production. These effects become more pronounced within the individual printer as the amount of fumes suspended and circulating with the inert gas increases over time. Furthermore, depending on the build chamber size and gas flow design, these effects vary from printer to printer. This article is focused on investigating the (L- PBF) process in a step-by-step basis and presenting it to researchers, technologists, and even manufacturers, particularly those who are new to or have little knowledge of this technology. The study focuses on the key difficulties that must be studied and learned in order to build a functional metal part in an Additive Manufacturing (AM) facility.

Keywords: 3D printing; Additive Manufacturing; Laser Powder Bed Fusion; Process Optimisation

1 Introduction

Metal part manufacture using the L-PBF process has evolved rapidly in recent years. Globally, the market of additive manufacturing expected to growth up to 27 billion USD by 2027 [1], with L-PBF being the leading technique [2]. This innovative AM technology melts powder in a metallic powder bed system using a high energy source. By melting the metal powder at preset areas in the powder bed according to the given CAD design file, the process may be tuned to produce products with excellent mechanical qualities. Ciraud in 1973 [3] was the first to patent the idea of fabricating

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powders of metals into any needed structure using lasers of high energy beam from. The required structure is designed by CAD model, this model will split into thin layers to be used in the L-PBF process, and then each of the sliced layers is micro-welded one layer over the other. This operation is repeated until the metal part with the geometry specified in the CAD file is created. PBF has been used in a variety of industries, including machine tooling, aerospace, biomedical, and automotive. This is due to different factors, such as the ability to process must of the printable metals, alloys, and composite powders. Many studies described the manufacturing of Additive manufacturing parts of various metals such as the Ni alloys Haynes HX, Inconel 718, and Inconel 625 [4-5]. Obeidi et al. [6] investigated a comparison of the mechanical properties of SS 316L pieces printed on different parameters. Another researches looked on the mechanical properties variations of cobalt chromium, aluminium, and titanium alloys parts printed by L-PBF [6-9]. This article focuses on explaining and detailing the L-PBF in a step-by-step manner with the goal of simplifying and making the process clear for manufacturers, technicians, and engineering students.

The L-PBF process employs a number of technologies to convert an engineering part from CAD file (as digital) to solid part. In general, a printer is equipped with high power laser system (usually Nd:YAG or fibre laser), this beam of laser is transmitted via a flexible optical fibre connection to the machine's moving optics axis, which houses the 3D scanner (galvo), that contains a set of high-speed movable lenses and mirrors that controls the laser beam movement. After loading metal powder into the printer's powder reservoir, an inert gas is purged into the build chamber until reaching a certain oxygen level, to offer a nonflammable environment, then the building process can start. During the process the ambient gas should be filtered through a controlled movement from the build chamber to a central filtration unit. These technologies can be created in a variety of models, using different build volumes, laser type/energy, printed material range, positioning accuracy, fabrication rate, and cost. Optional research items may be added such as high-speed cameras, (IR) thermal camera or pyrometer to investigate the building process from different approaches, measuring the turbulent movement of metal powder, the evaporation negative pressure surrounds the melt-pool, or its real-time in- situ temperature measurement. The data collected from these devices can be in video format, as in the case of the IR camera, or in tables presenting the temperature values versus the (x,y) coordination on the construction plate.

2 L-PBF Process

The general principles and main features of the metal additive man manufacturing by using this method can be explained as follows, see Fig. 1:

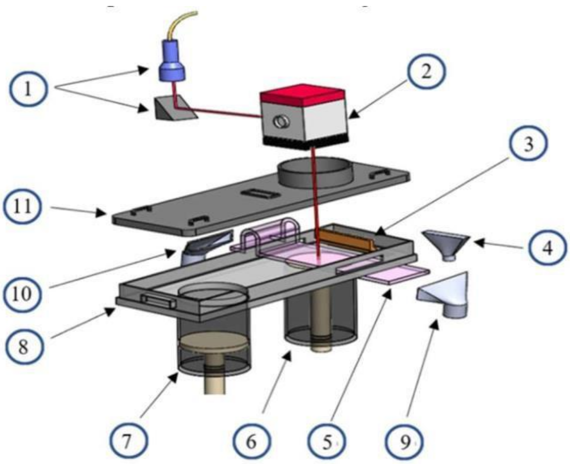

Fig. 1. Shows the build chamber and the main features in a typical metal printer [6]

- The process is carried out under inert gas conditions i.e., argon or nitrogen which is fed from an external supply and circulated between the build chamber (8) and a central filtration unit through the inlet/outlet ports (9) and (10).
- The metal powder is first loaded to the build chamber into the powder storage (7) then the first build layer is to be deposited on the build plate (6) manually. This step is necessary in order to assure the efficient metal powder deposition.
- The chamber lid (11) is to be closed, chamber interlocked by the machine CNC and then the purging process started by pumping and circulating the inert gas inside the build chamber. Oxygen sensor must be working during the entire build process in order to monitor and control the oxygen level for safety and also to reduce the presence of oxidation.
- Once the minimum oxygen levels was reached, the fusion and printing process can be triggered. The process is carried out layer by layer. The laser beam is transmitted on the powder layer via the optical fibre cable, collimator, optics assembly (1) and the 3D scanner (2) which translates the CAD file slices information into (x,y) coordination on the build plate for the fusion of the metal powder particles.
- When the fusion of the deposited layer is completed, the build layer moved downward with the amount of the preset layer thickness value as a preparation for the deposition of the new powder layer. The powder recoater (deposition) mechanism (3) moves to the front, the powder supply moves up to supply the fresh powder and then the recoater moves back and deposit the powder on the machine bed and the previous layer.
- This process is repeated until the 3D part is fully produced.

3 The Process Parameters

The process is affected by more than a hundred processing parameters that influence the additive manufacturing process and the qualities of the manufactured items [2-8]. Therefore, a pilot scanning test is important to identify the most significant parameters and their level of importance for usage during manufacturing of component. Other processing parameters of lesser importance can be set to the optimum levels indicated by an assessment scanning test. Since the process is thermal, then the most effective input parameters must be those calculating the amount of the input thermal energy applied to the metal powder. Those can be nominated as; the laser beam power (W), the laser beam scanning speed (mm/sec), the metal powder layer thickness (mm), the laser beam spot size (mm), and the laser tracks hatch spacing (mm). Other processing parameters that can affect the printing process with less significance can be explained as; the metal powder type, and the particle size and geometry. The latter factors affect the laser-material interaction and the amount of thermal energy absorbed by the powder layer. Also, the inert gas type and flow rate. For example, adopting nitrogen gas alters the chemical and mechanical properties of the produced part and applies higher cooling rates compared to argon gas environment and thus higher input thermal energy levels are necessary [9]. Another important factor is the build chamber size and the inert gas entrance with refence to the laser fusion sequence and direction. This arrangement controls the amount of fumes, plasma and metal vapor covering the melt-pool and negatively affect the laser-materials interaction [6].

4 The Build Scanning Strategy

The build strategy involves multiple parameters by itself. In general, it refers to the path in which the laser beam is chasing in order to fuse the entire deposited powder layer. This path must be designed and efficiently considered in order to avoid or minimise any heat accumulation or temperature gradient across the build layer. The following Fig. 2 shows examples of common scanning strategies for printing one singular layer of a cuboid (square cross-sectional). The black colour borders represents the CAD file outer dimensions which is usually called “Contour” while the red vectors represent the laser beam tracks. Figure 2 (a) shows the simple and “Single” direction scanning in which the laser beam tracks are always start from left to right. This scenario result in a high temperature difference on both sides with the higher temperature is always with the laser beam propagation direction, right in this case. This in turn will result in variant microstructure, chemical composition and mechanical properties which are some of the main drawbacks of this technology. In contrast, Fig. 2 (b) shows the “Bidirectional” where this problem was significantly reduced but not eliminated and equal temperature levels were obtained with noticeable increase at the bottom (finish) side compare to the top (start). Several studies reported that rotating the hatching pattern by a specific angle of 67° in each consecutive layer produces parts with optimised microstructure and mechanical bonding between the build layers [10-19].

Another strategy is shown in Fig. 2 (c) called the “Stripe” scanning where stipes of any adjustable width can be performed in bidirectional way with controlled overlap between the consecutive strips and Fig. 2 (d) shows the “Chess board” strategy. In both of the latter strategies, the temperature difference is reduced due to the smaller division zones. In most scanning strategies, a significant increase in the temperature is observed in the core of the part. This is always expected to occur due to the high cooling rates and heat dissipation to the cold surrounding powder particles. As a proposed solution for the problem, the “Spiral” scanning strategy shown in Fig. 2 (e) can reduce this temperature levels by fusing the metal powder from inside-out. Finally, the “Contour-Fill” scanning strategy (with no laser vectors) is used to apply only consecutive/expanding contours from inside-out with well-considered offset value to fully melt the build layers. This strategy is relevant when producing parts with small section in order to avoid the increase in temperature associated with the multiple reflection of the short laser vectors.

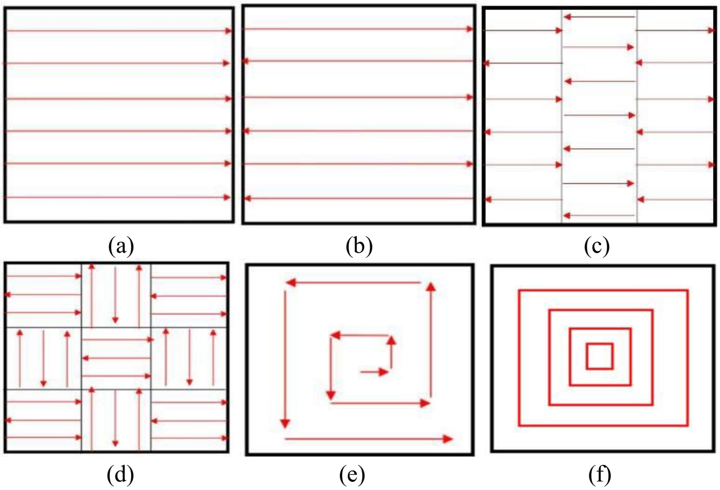

Fig. 2. The most common scanning strategy scenarios used in L-PBF [10]

It is worth noting that the spacing between the laser vector is scientifically known as the “Hatch Spacing”. This is a very important processing parameters and must be calculated and applied accurately and only based on experimental measurements. For example, single laser tracks are the most significant approach to obtain the exact value of the hatch spacing [17,20]. The following Fig. 3 shows the method applied in calculating the hatch spacing values.

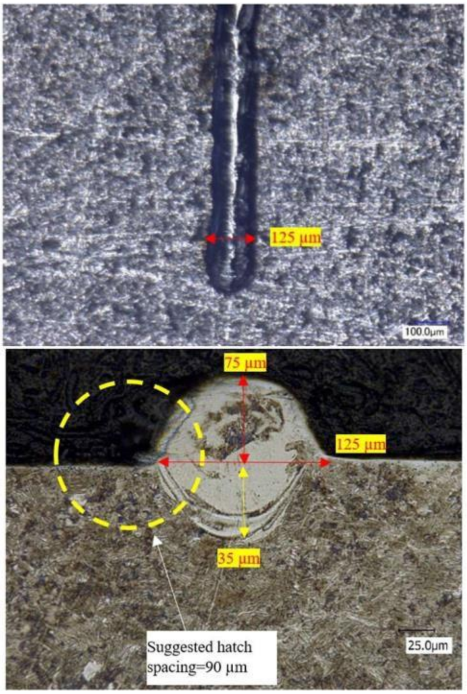

Fig. 3. The procedure used for calculating the hatch spacing in a L-PBF process [20]

Different levels of laser beam power, scanning speeds, and laser beam spot size are usually applied and the resulted weld track is characterised based on the measured width, quality of the weld, consistency, and the depth of melt in the cross-sectional view. The track width indicates the hatch spacing and the melt depth indicates the power level and scanning speed ranges to be applied for a sufficient melting and bonding with the previously melted layer. Under or over estimating the hatch spacing will lead to the over melting or scattered melt tracks respectively and then the distortion of the part.

5 Output Measures

Additively manufactured parts show asymmetrical properties in predominant. Such properties may include.

- Physical like the poor surface quality including high surface roughness and maybe coloration. The main reason behind the roughness is the sintering of the adjacent powder particles in a micro-welding process, see Fig. 4. The coloration appearances is mainly caused by the noticeable temperature difference between the early (bottom) and the later (top) build layers and the oxygen content or the inert gas quality. A post process for the surface cleaning and/or polishing is necessary for some applications. Figure 4 (left) shows SEM image for the surface quality before and after laser polishing (LP).

The processing parameters are adjusted precisely at the melting threshold to be only sufficient for the melting and relocating of the high peaks int the lower valleys with no loss of material [21].

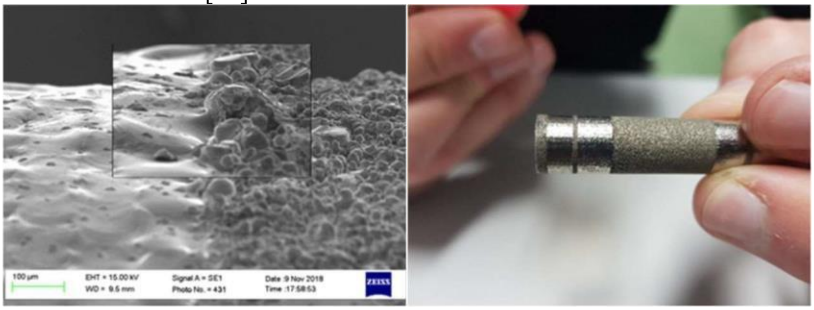

Fig. 4. SEM and optical images of an AM part showing the surface roughness before and after laser polishing [10]

Another important physical property to measure is the density of the produced AM parts. Low part’s porosity is expected as a result of in accurate input volumetric energy density (VED). High VED levels can lead to over-melting, metal evaporation, and the trap of fumes in a process known as key-hole formation while the lower VED values can results in lack of melting. Other factors affect the AM part’s density are the humidity content and raw metal powder impurities. The aim must always be to achieve near the full dense part (close to cast metal density). Producing parts with high density is the key to achieve improved mechanical properties (elastic modulus, ductility, tensile strength, and toughness). The latter properties can be enhanced in a post-process heat treatment.

- Chemical properties, elemental composition, and phase formation is highly affected by the setting of the input processing parameters and the resulting VED. Studies have been carried out in order to correlate the produced parts’ chemical composition compared to that of the raw powder with reference to the input VED. Obeidi et al. [22] reported the loss of nickel at high VED level during the L-PBF of nitinol parts which can be detrimental for some applications as this can change the part’s property from shape memory to a super alloy. Figure 5 (a) below show the significant temperature difference of up to 33% on a normalised scale, and the corresponding grain size during the print of a single layer of a (3×3×3 mm) cubes (b). Another increase in the melt-pool temperature can be observed when printing with higher powder layer thickness. This is due to the fact that the thermal conductivity of thick layers is less than that of thin layers because of the gaps and gas contents between the powder particles, see Fig. 5 (c). As explained in the previous sections, this temperature increase cannot be avoided but maybe reduced, nevertheless, its effect can be detrimental.

(a) (b) (c)

Fig. 5. (a) The melt-pool temperature profile [22], (b) optical micrograph showing the grain size distribution, and (c) the melt-pool temperature measure of 3 parts printed with 30, 60, and 90-microns layer thickness [9].

- Mechanical properties of AM parts are expected to be drastically different from cast and machined parts for the same reasons explained previously. AM parts are brittle in general with reduced toughness, fatigue resistance, and low strength accompanied by the presence of thermal residual stresses. These properties can be varied in the horizontal (x,y) and vertical (z-build) directions and the main reason behind this is the high and localised thermal energy and scanning speed applied by the laser beam. This in turn, result in high cooling rates between the molten material and the surround cold material. Post-processing, mainly by heat treatment is essential in order to produce parts with symmetrical properties, release of residual stresses and improving the performance under static and cyclic loading.

6 Conclusion

Additive manufacturing technologies, showed a proven achievement in laser manufacturing methods. However, when mass production is the aim, AM cannot compete with the traditional methods. Unless there is a reason that prevents the component from being manufactured by using the traditional methods, such as complex geometry, materials that are hard to machine, or several parts assembly that can be simplified into one part if AM was used, then die casting is the best choice for mass production if possible. A metal gear or a sprocket, for example, can take hours to build using any AM process, whereas a hundred of gears may be produced in one hour through die casting.

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References

1. "Additive Manufacturing Market to Reach USD 26.68 Billion By 2027 | CAGR of 14.4%: Reports and Data.", (2021), https://www.prnewswire.com/news-

releases/additivemanufacturing-market-to-reach-usd-26-68-billion-by-2027--cagr-of-144-reports-anddata-301163846.html, accessed Jun. 24, 2023

2. “Metal Additive Manufacturing market valued at EUR 2.02 billion in 2019,” AM Power Report, 2019. https://additive-manufacturing-report.com/additivemanufacturing-market (accessed Jun. 24, 2021).
3. C.L.I. Marie, “Method and device for manufacturing any articles from any meltable material,” Dec. 28, 1971.
4. N. Jeyaprakash, C. H. Yang, and K. R. Ramkumar, “Microstructural, mechanical and wear behaviour of Inconel-718 produced through laser-powder bed-fused additive manufacturing,” Mater. Sci. Technol. (United Kingdom), vol. 37, no. 3, pp. 326–337, 2021, doi: 10.1080/02670836.2021.1893457.
5. G. Marchese et al., “Microstructural evolution of post-processed Hastelloy X alloy fabricated by laser powder bed fusion,” Materials (Basel)., vol. 12, no. 3, 2019, doi:10.3390/ma12030486.
6. M. A. Obeidi, A. Mussatto, R. Groarke, R. O’Connor, D. Brabazon, “Comprehensive assessment of spatter material generated during selective laser melting of stainless steel”, Materials Today Communications 2 (2020) 101294, https://doi.org/10.1016/j.mtcomm.2020.101294
7. R. McCann, C. Hughes,´E. McCarthy, D. Egan, R. Vijayaraghavan, et. al, “In-situ sensing, process monitoring and machine control in Laser Powder Bed Fusion: A review”, Additive Manufacturing 45 (2021) 102058
8. S. Yin, R. Lupoi, “Influence of processing parameters on density, surface morphologies and hardness of as-built Ti-5Al-5Mo-5V-3Cr alloy manufactured by selective laser melting”, Journal of Alloys and Compounds, (2022), https://doi.org/10.1016/j.jallcom.2022.164760
9. M. A. Obeidi, S. Uı´ Mhurchadha, Alex Conway, D. Tormey, D. Brabazon, ”Comparison of the porosity and mechanical performance of 316L stainless steel Manufactured on different laser powder bed fusion metal additive manufacturing Machines”, Journal of materials Research and technology (2021); 13:2361-2374
10. M.A. Obeidi, “Metal additive manufacturing by laser-powder bed fusion:Guidelines for process optimization”, Results Eng, 15 (May) (2022), Article 100473, https://doi.org/10.1016/j.rineng.2022.100473
11. M. Dimter, R. Mayer, L. Himmeler, R. Salzberger, J. soil, “Method and Device for Manufacturing a Three-Dimensional Object”, United States Patent, 2011
12. M. Seo-Yang,J. Kamg, J. Kim, K. Kim, Da. Kim, et. al, “ A study on the mechanical properties of an automobile part additively printed through periodic layer rotation strategies”, materials, 2022
13. Y. Ansoy, L. Criales, T. Özel, B. Lane, S. Moylan, A. Donmez, “Influence of scan strategy and process parameters on microstructure and its optimization in additively manufactured nickel alloy 625 via laser powder bed fusion”, Int J Adv Manuf Technol (2017) 90:1393– 1417, DOI 10.1007/s00170-016-9429-z
14. J. Robinson, I. Ashton, E. Johns, P. Fox, C. Sutcliffe, “The effect of hatch angle rotation on parts manufactured using selective laser melting”, School of Engineering, The University of Liverpool, Rapid Prototyping Journal, 25/2 (2019) 289–298, DOI 10.1108/RPJ-06- 2017-0111
15. Z. Snow, A. Nassar, and E. Ruetzel, “Invited Review Article: Review of The Formation and Impact of Flaws in Powder Bed Fusion Additive Manufacturing”, Additive Manufacturing, vol 36, (2020), 101457

16. N. Nadammal, T. Mishurova, T. Fritsch, I. Munoz, A. Kromm, C. Haberland, et. al, " Critical role of scan strategies on the development of microstructure, texture, and residual stresses during laser powder bed fusion additive manufacturing", Additive Manufacturing 38 (2021) 101792
17. Y. Huang, M. Leu, J. Mazumder, "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and recommendations", Journal of Manufacturing Science and Engineering, 2015, Vol. 137 / 014001-1, 2014
18. Mussatto, R. Groarke, A. O'Neill, M. A. Obeidi, Y. Delaure," Influences of powder morphology and spreading parameters on the powder bed topography uniformity in powder bed fusion metal additive manufacturing", Additive Manufacturing 38 (2021) 101807
19. M. A. Obeidi, "Additive Design Mimics the Strength and Architect of Nature." Journal of Material Science and Technology Research 10 (2023): 1-11.
20. M. A. Obeidi, "Achieving high quality nitinol parts with minimised input thermal energy by optimised pulse wave laser powder bed fusion process", Results in Materials vol 14, June (2022), 100279, https://doi.org/10.1016/j.rinma.2022.100279
21. M. Obeidi, A. Mussatto, M. Dogu, S. Sreenilayam, S. Keaveney, "Laser surface polishing of Ti-6Al-4V parts manufactured by laser powder bed fusion", Surface & Coatings Technology 434, (2022) 128179
22. M. A. Obeidi, C. Hughes, D. Bourke, M. Nur Dogu, J. Francis, M. Zhang, I. Ul Ahad, D. Brabazon, "Laser beam powder bed fusion of nitinol shape memory alloy (SMA)", Journal of Materials Research and Technology vol 14, (2021), Pp 2554-2570, https://doi.org/10.1016/j.jmrt.2021.07.126