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Laser Powder Bed Fusion of Steels: Processing, Mechanical Properties, Microstructure, Defects, Control Methods and Current Challenges – A Review

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ABSTRACT

The most versatile metal additive manufacturing technology, known as laser powder bed fusion, has been shown to produce geometrically challenging, high-performance metallic objects in near net shape with up to 99.9% relative density in a shorter amount of time. The most common engineering materials utilized for structural and sub-structural applications are steels and iron-based alloys. Steels have distinguished themselves from other metallic materials thanks to their availability in more than 3500 grades and a variety of qualities, including high strength, corrosion resistance, good ductility, low cost, and recyclability. However, the LPBF process for steels and iron-based alloys has not yet been fully adopted in industrial applications because there is little information about the processing conditions currently available, there are no specific materials standards, a lack of knowledge to correlate the process parameters, and there are other technical challenges like part variability, dimensional accuracy from a design model to an actual component, limited feedstock materials, and manual post-processing. The purpose of this review is to provide an overview of the steels and iron-based alloys used in the LPBF process by summarizing their key process parameters and microstructure evolution during solidification, as well as highlighting metallurgical defects and potential control methods, all of which have a direct impact on mechanical performance.

Keywords - LPBF process, Steel, Mechanical properties, Current challenges.

1. INTRODUCTION

Steel is one of the most significant materials in engineer ing for its distinctive mix of strength, durability, as well as adaptability. It is widely used today in the manufacture of machinery, aerospace, automotive, medical, nuclear reactors, marine/oil and gas, shipbuilding, food and transportation, electronics and consumer applications. Steel's remarkable strength-to-weight ratio, which makes it the perfect material for structures that must withstand huge loads, is one of its main advantages. Steel is ideal for use in hostile situations due to its great resistance to corrosion, can endure high temperatures, and can bear high pressures, low cost and nearly 100% recyclability. Steel is quite easy to perform tasks with and is available in a broad range of sizes and forms. This makes it an effective source for many applications, from basic domestic products to sophisticated industrial apparatus

According to the World Steel Association, approximately 3500 distinct steel grades with special physical, chemical, and environmental characteristics are manufactured based on their uses. Low carbon alloy stainless steels (SS), notably 316L SS, have been one of the most popular types among steels due to their affordability, processing ease, excellent corrosion resistance, and superior toughness even under extreme working conditions.

The outstanding combination of good corrosion resistance, higher strength and higher mechanical properties are the important features of martensitic type steels. Martensitic type steels such as precipitation-hardened (PH) steels are basically used in aerospace, chemical, petrochemical, food processing, general metal working, oil & gas, powerplant and injection molding industries. The key characteristics of martensitic type steels include their exceptional combination of superior corrosion resistance, increased strength, and superior mechanical qualities. Precipitation-hardened (PH) steels, a form of martensitic steel, are primarily employed in the injection moulding, chemical, petrochemical, food processing, general metal working, oil & gas, and aerospace sectors [1]. Tool steels meet this need because they combine strong corrosion resistance with increased hardness, yield strength, and ductility, as well as superior weldability and abrasion resistance. The carbon-free maraging steels (18Ni-300) are the most often used tool steels in the metal AM process [2]. `

The objective of this essay is to offer a critical review of the LPBF process for steels. First, a brief introduction to steels, AM, LPBF, and their respective uses is covered in the review. The next section is structured to give an overview of the main process variables that affect the phase transition and evolution of microstructure in the LPBF process. The discussion in the next area is on how defects develop, how to control them, and frequent problems that occur when different steels are processed with LPBF. In the following section, the microstructure, mechanical behaviour, including the hardness, tensile, and fatigue characteristics of LPBF of steels, are analysed. The summary and the future scope are highlighted in the concluding part.

2. ADDITIVE MANUFACTURING

At present, the majority of steels used in structural and automotive applications are made using traditional techniques including casting, extrusion, and powder metallurgy [4, 5]. Despite extensive applications of the products made using these conventional methods, several problems still persist. The cause was that slow cooling rates during the casting process result in a coarser microstructure and the simultaneous existence of flaws linked to intrinsic features (porosity, part shrinkage), which combined destroy the mechanical capabilities. Also, due to prolonged and separate procedures (materials preparation, manufacture, and assembly) involved in the typical process of fabricating steels, it is less efficient. The bigger benefit of constitutive production of complex, functionally graded materials (FGM) for structural components in AM is time, cost, and flexibility advantages (Fig 2).

More significantly, compared to other traditional welding and joining procedures, the AM process eliminates weight and stress concentration factors. Despite the fact that some traditional manufacturing issues persist in the AM process, comparative analysis reveals that the AM process or LPBF process has been successful in fabricating defect-free good quality parts with excellent mechanical properties when compared to conventional processes such as casting and extrusion [6]. Technology is advancing at an exponential rate; thus, manufacturing is no longer only about making physical items. To adapt to the changes in customer needs, product nature, manufacturing economics, and supply chain dynamics, a fundamental transformation is required. Future research and development efforts will emphasize developing smart steel products that require less post-processing, have designer surface topography and mechanical performance, are extremely dense and dimensionally correct, and have components that are close to net shape.

The AM method belongs to a group of technologies where the material is added rather than taken away to create the finished product. Unlike the typical manufacturing process, which entails shaping or carving raw materials into the necessary end components by removing various elements from it. Three-dimensional components are created directly from 3D CAD files using additive manufacturing (AM), which involves depositing or melting successive layers of feedstock materials inside a closed chamber. AM is regarded as the direct manufacturing method that allows for the creation of components with intricate features using both internal and exterior layouts while also consuming less material. The materials used in AM process can be in the form of powder, wire, sheet, etc.

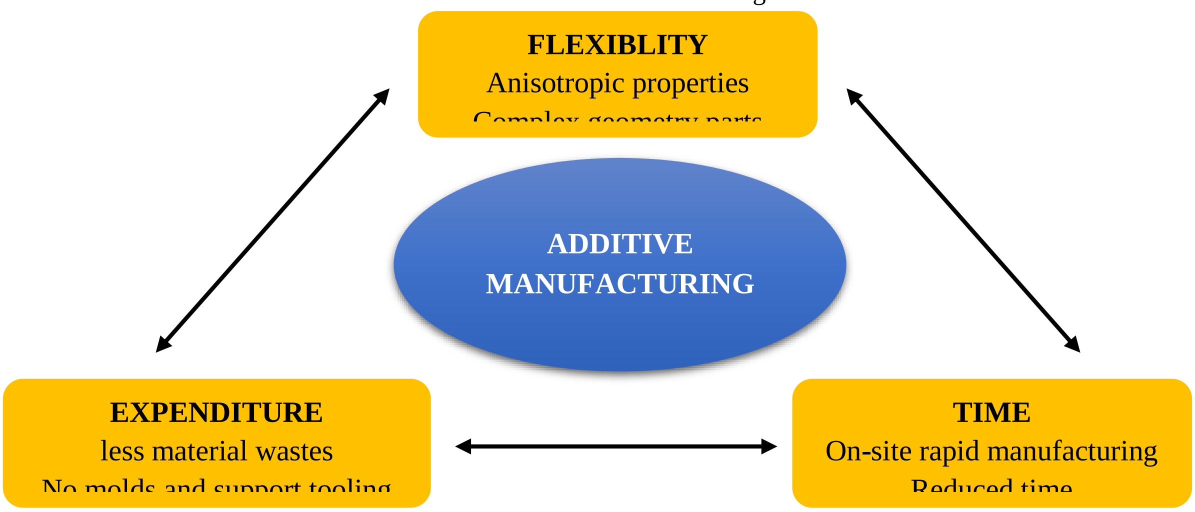

Fig 1: Correlation between Additive manufacturing (AM) key features and its advantages.

Among various AM techniques, the LPBF process is now the most used powder bed fusion method for fabricating metallic materials. [7]. Metal additive manufacturing has caught the interest of several academics and companies as a result of its distinctive uses. In recent years, metal additive manufacturing (AM) has been utilized to develop medical equipment, aerospace and military uses, automotive, industrial, and consumer applications.

3. LASER POWDER BED FUSION PROCESS OF STEELS

A high-power laser beam is used in the laser powder bed fusion method, also known as selective laser melting, to melt only the specified shapes in successive powder layers. By cooling, the molten metal pool quickly solidifies [8]. A laser beam melts certain area in each layer to create a 3D cross-section of the finished part. As a result, the construction platform underneath is lowered, and then another coating of powder is applied using the powder coater/wiper mechanism. Up to the construction of the three-dimensional solid object, this cycle is successively repeated. To prevent oxidation, the unfused powder is removed and recycled during the whole process, which takes place in a chamber filled with inert gas like argon, nitrogen.

The increased density and finer microstructure of LPBF-fabricated products contribute to the components' exceptional mechanical properties, improved surface quality, and dimensional accuracy. This layer-wise production strategy gives the LPBF process an advantage over conventional processes in that it enables consolidated parts with elaborated internal features for complex assembly, higher production rates, fewer design iterations, and quicker market introduction of new products/prototypes that were previously thought to be impractical to manufacture functional end-use products. Complex thermodynamic and heat transfer processes are used in the LPBF process. Throughout the printing process, the surface finish of the scan track is uncontrolled and unpredictable, affecting the final quality of LPBF goods. The most frequent issues are the oxidation of feedstock materials and process-induced inescapable thermal residual stresses produced during complicated thermophysical events.

According to different LPBF process settings, the laser contact with the metallic powder typically results in the development of a smaller molten pool that measures between 0.9 and 1.4 mm in length, 0.16 to 0.63 mm in depth, and 0.12 to 0.38 mm in width. [9,10]. The cooling rates can reach up to 103 –108 K/s due to very fast movement of the laser beam, again relying on the LPBF processing parameters, type of the material used, and its various physical and chemical properties [11]. Such a high cooling rate can sometimes impede grain growth and segregation of alloying elements.

The mechanical performance of the laser powder bed fusion (LPBF) treated steel components has significantly improved thanks to the thin continuous refined

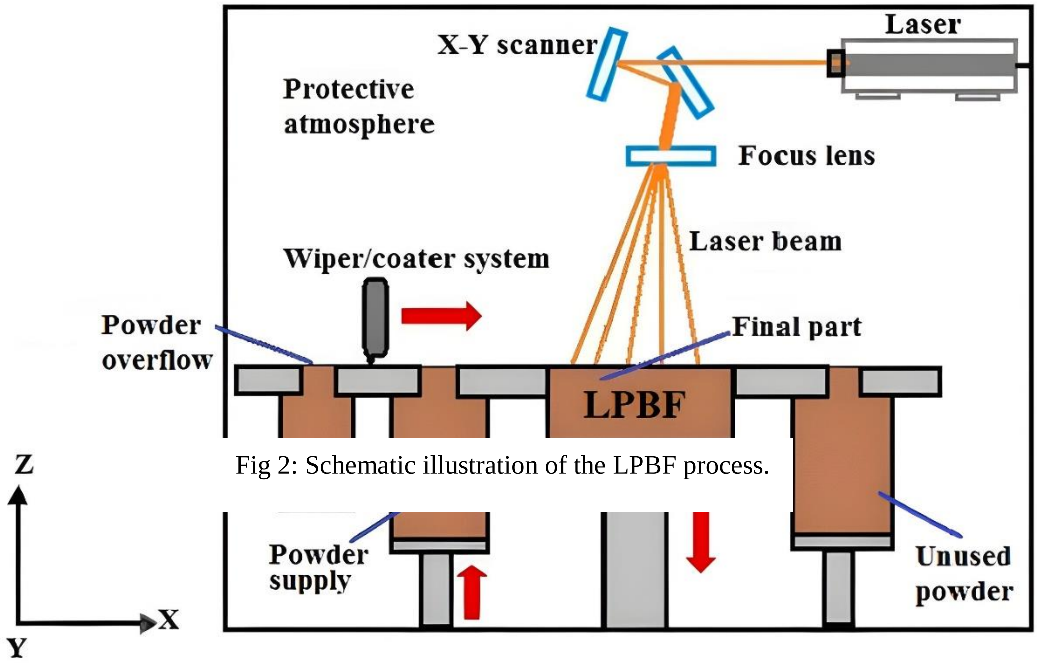

Fig 2: Schematic illustration of the LPBF process.

microstructure that has been created. It is critical to have both tiny and big powder particles: smaller particles are easily melted and profit from a reasonably excellent part density and design quality surface polish, whilst larger particles benefit from ductility, mechanical strength, hardness, and toughness [12,13].

Laser power (LP), scan speed (SS), hatch spacing (HS), layer thickness (LT), chamber gas, and pressure are a few of the crucial process factors. We examine how they affect the different physical and mechanical behaviours of LPBF steels. The stability of the process, which impacts the quality of the LPBF products, is significantly influenced by the ratio between hatch spacing and spot size. Smaller hatch spacing causes a continuous, thin layer to develop as a result of heat build-up and sluggish cooling in a molten melt pool [14]. It is advised to select an average hatch spacing to spot size ratio between 0.6 and 1.5 to achieve process stability and high-quality LPBF products [15]. Low fusion (LOF) or incomplete fusion hole defects result from insufficient energy input penetration between the melt track layers caused by lower energy input or thicker layers [16,17]. The energy input is also considerable for comparatively slower scan speeds and fixed or higher laser powers, leading to increased thermal stresses and keyhole porosity flaws. More energy input creates a bigger temperature differential, which, when paired with higher thermal residual strains, commonly results in thermal fractures [18,19]. On the other hand, when the laser power is comparatively lower and the scan speed is faster, the low energy input that is provided is insufficient to completely melt the surrounding powder particles, which results in the production of balling defects [20]. It is also clear that increased energy density decreases product dimensional accuracy, making process optimization challenging and perhaps compromising specimen dimensionality and flaws [21]. Moreover, using thicker layers had a negative impact on relative density. For curved and sloped LPBF constructed surfaces, layer thickness selections greater than 0.1 mm will result in staircase problems [22].

The major goal of LPBF research on various kinds of steels and iron-based alloys has been to explore the processing parameters necessary to produce completely dense, high-quality components and the resulting microstructure. The main issue is understanding the process and manipulating the precise influence of each process parameter or combination of process parameters on physical and mechanical behaviour. As a result, it is difficult to determine if engineering components produced using the LPBF method meet industry requirements. The qualities of the metal powder, such as particle size, grain dispersion, and packing density, have a significant impact on the finished component's quality.

The characteristics of the metal powder (particle size and grain distribution, packing density) have a significant effect in defining the quality of the finished component in addition to the most important LPBF process parameters. The smaller, more readily melted particles were said to be to responsible, whereas the larger particles aid in undergoing higher elongation before failure. The authors concluded that the PSD impacts the mechanical characteristics and surface quality in addition to the part density [12]. The denser, better surface quality, stronger, and harder the powder particles with smaller diameters showed greater flowability led to higher density [23].

3. MECHANICAL PROPERTIES OF LPBF FABRICATED STEELS

3.1 Hardness

From the existing literature, Vickers hardness ratings for LPBF treated steels vary from 408 to 900 HV, which is unquestionably greater than for wrought materials. Increased hardness values enhance the wear resistance of LPBF-constructed components. When compared to the as-cast condition, the refined microstructure of LPBF treated tool steel samples comprised of a low martensite phase and a high amount of fine carbides, resulting in greater hardness values. [24].

3.2 Tensile Properties

Tensile characteristics of LPBF-fabricated samples in the vertical direction are inferior to those of samples constructed along the horizontal direction [25]. In order to obtain the higher tensile properties, besides the position of the sample in the horizontal direction, the laser fluence also plays an equally important role. For a low laser power, it, resulted in higher porosities. The porosities act as the main sites for crack initiation triggering brittle fracture with limited plastic deformation, causing cracks propagation under tensile loading conditions. It is worth noting that LPBF fabricated steels are strengthened without losing their ductility, unlike work-hardening that improves the tensile strength by sacrificing ductility.

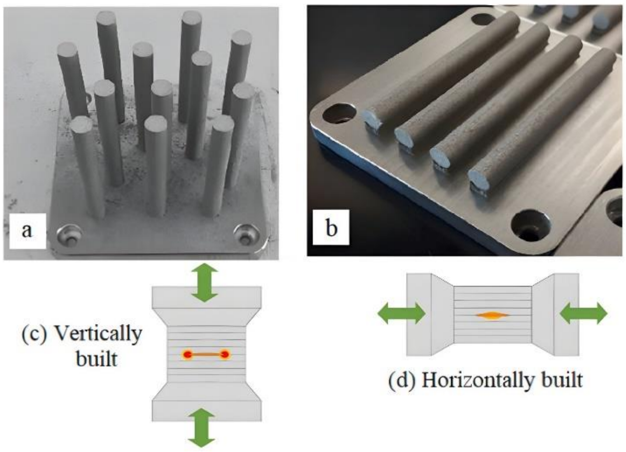

Fig 3: Schematic illustration of LPBF build directions and stress concentrations associated with it, (a) vertically built, (b) horizontal built LPBF specimens

3.3 Fatigue properties

The fatigue limit of LPBF fabricated part mainly depends on its surface finish. It is commonly believed that fatigue crack initiation starts at the surface of metallic materials. LPBF made steels, like traditionally manufactured steels, are highly influenced by the rough surface finish, as well as other surface defects caused by micropores, surface defects, and un-melted and partially melted powder particles stuck on the surface. Moreover, the unstable molten melt pool exacerbates surface roughness. More surface roughness allows for larger local stresses under dynamic loading circumstances, resulting in lower fatigue limits and, as a result, a shorter fatigue life for LPBF treated steels. High cycle fatigue (HCF) limit is strongly dependent on the surface roughness related defects compared to low cycle fatigue (LCF). As a result, the HCF performance of LPBF steels may be enhanced by reducing surface roughness and flaws on the component surface [26].

4. MICROSTRUCTURE CHARACTERISTICS

Microstructure evolution during LPBF is not trivial. It is difficult to generalise a given type of steel's microstructure properties to all other types of steels. Tan et al. studied the microstructure evolution of LPBF process of maraging steels. The authors noticed a massive submicron sized hexagonal cellular grains uniformly distributed at the centre, and a needle-shaped elongated grains prevalent at the boundaries of the melting tracks [27].

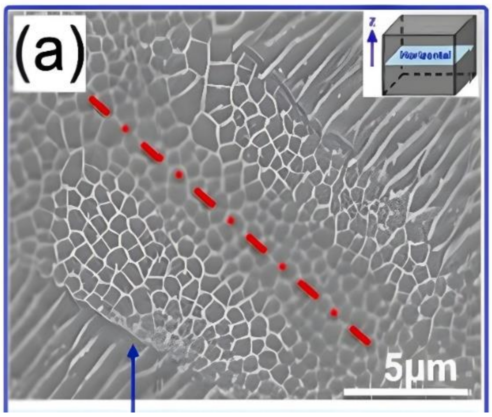

Fig 4: characteristic morphologies of the horizontal and vertical cross-sections

These microstructure characteristics would form in response to the instant melting and rapid solidification at higher cooling rates during LPBF processing of maraging steels.

Z. Sun et al. employed a modified laser scan strategy by adopting relatively high laser power with smaller hatch spacing to improve the mechanical properties of LPBF processed 316L SS [29]. This modified approach leads to the formation of new crystallographic texture along the build direction instead of a regular texture. The modified crystallographic grain orientation favours twinning effect under deformation, as a result of this the material experiences higher strain hardening rates which profits in achieving superior mechanical properties (ductility and UTS) [29].

LPBF process of high-manganese steel was investigated by [30], the microstructure consisted of mainly austenite, together with α- and ε-martensite, along the small quantity of Mn segregation was observed as compared to cast (X30Mn22) steels [30].

5. FORMATION OF METALLURGICAL DEFECTS AND THEIR CONTROL METHODS

Metallurgical defects such as balling, porosities, keyholes, cracks, metal inclusions, residual stresses, warping, delamination, oxidation, loss of alloying elements, denudation, and so on are commonly observed during the metal LPBF process, as are surface asperities such as staircase effect, partially-melted/un-melted particles, spatters, re-entrant features, and so on.

5.1 Balling

Balling arises when the deposited melt track sometimes breaks up into spherical or half-cylindrical balls. Surface tension, viscosity, and density of the materials being deposited, together with scanning speed, are some of the process factors that affect this phenomenon. One of the serious processing flaws in the LPBF process is the balling phenomenon, which is one of the significant surface flaws. When the formation of individual melt tracks results in poor contact with the substrate underneath, the surface tension and capillary forces combine to cause the molten pool to shrink into its lower surface energy state (a sphere). Porosity, increased surface roughness, decreased density, lack of fusion between the powder particles/layers, uneven melt tracks, and, in extremely extreme cases, deposition process obstruction are all effects of the balling defect [31].

Viscosity and high surface tension are two crucial hydrodynamic factors that promote balling initiation. A wide region of contact with the substrate and a larger geometric molten melt pool are produced by higher laser energy density, which also causes more heat to be produced. The propensity of the metal to ball is limited by the larger and broader molten melt pool, which reduces viscosity and promotes liquid metal flowability (wettability) [32]. To improve the microstructure and prevent balling, laser re-melting can be used on each layer of totally molten metal. Similar to this, preheating the base plate can enhance the flowability between liquid metal and the substrate, resulting in the creation of a better metallurgical connection, which in turn lessens the (balling) contraction effect brought on by surface tension [33]. The preheating temperature during LPBF process of steels ranges from 80 to 900 ◦C.

5.2 Porosity

The degree of compactness in metal powders is typically low. Moreover, due to the quick cooling and solidification of the molten melt pool surface, any gas that is already present in the powder particles can rapidly diffuse into the molten melt pool. Hence, LPBF-fabricated steel pieces develop porosity [34]. On the other hand, at high temperatures, the gas solubility in liquid metal is often high, which also aids in the creation of pores. The voids, keyhole/or depression flaws, and incomplete fusion holes comprise the three types of porosity defects in the LPBF process. Insufficient energy input causes the metal particles to not melt entirely, and insufficient liquid metal penetration into previously hardened layers results in weak metallurgical bonding and incomplete fusion holes [35]. The gas bubbles trapped inside the powder particles of the powder mass are what give the keyhole pores their characteristic spherical form. As a result of trapped gases in the powders during the powder atomization process or in the molten pool during LPBF procedures, spherical pores are created.

Porosities can produce major metallurgical flaws, result in reduced component densities, and have a negative impact on the surface finish and mechanical properties of steels used in LPBF fabrication. Substrate preheating and using laser remelting are methods for reducing porosity [36]. During the LPBF process, it is thought to be advantageous to choose the right process parameters that will result in an acceptable amount of liquid metal and a longer molten metal pool lifespan.

5.3 Oxidation

To manufacture components free of oxides, the LPBF processing chamber's atmosphere is crucial. Although the oxygen content in the working chamber is restricted by protective inert surroundings and a shielding inert gas flow, there is always a potential of a tiny percentage of undesirable oxygen content (0.1–0.2%) being present during the LPBF process [37]. This is because there is undetectable air between the powder particles. The powder's oxygen content may be immediately transferred into LPBF-fabricated specimens. Thick oxide inclusions limit the flowability of molten pools, restrict the absorption of laser energy, and intensify the effects of surface tension. Moreover, these oxide inclusions cause metallurgical flaws such balling, inadequate melting between powder particles, and cracking, which lowers the mechanical characteristics.

The use of clean, dry powders is required to reduce oxidation while still maintaining a low enough oxygen partial pressure. Nonetheless, there are situations when the surface oxidation might be useful. Improved laser absorptivity was achieved by the development of continuous, nanometer-scale, and thermodynamically stable oxide coatings on the surface of 316L, H13, P20, and 18Ni300 steel powders.

5.4 Common issues associated with LPBF process of steels

In addition to the already discussed different process induced metallurgical defects, there are other most common issues that arise during LPBF fabricating of steels components are as follows:

[1] Due to the succeeding rapid cooling, which substantially affects the mechanical characteristics, it is predicted that during the LPBF process of low carbon steels, hard and brittle high-carbon martensite would occur.

[2] Solidification cracking is caused by low melting alloy components like sulphur and phosphorus, whereas manganese's high vapour pressure can result in localised depletion.

[3] As a result of the presence of oxides and carbides, the creation of large molten melt pools draws in additional powder particles, which decreases wettability and favours the production of defects.

[4] Steel powders with poor flowability can prevent powder particles from spreading, which affects the consistency of layer thickness and results in surface roughness in LPBF manufactured parts.

[5] Large components for aerospace, marine, and other industrial applications are challenging to make since the present LPBF systems are only able to generate small and medium-sized parts because of the size restriction of the construction chambers.

6. Conclusion

Metals' LPBF process is becoming more and more well-liked while showing notable growth and expanding into unique and modern technologies to make it more capable and economical. Because it allows for more design freedom, the LPBF method is excellent for creating unique or customised products, particularly for the automotive, aerospace, and healthcare industries. Examples include huge components with great strength and low weight that are medical implants and high temperature resistant materials. The set of effective and efficient manufacturing techniques that aid in resource conservation and environmental protection includes LPBF technology. According to sustainability studies on the LPBF process, the two other main advantages are a large decrease in material waste and fuel use.

Despite the many exciting possibilities and benefits provided by the LPBF process, there are still certain barriers that prevent its rapid development. These include size limitation, manufacturing times, a limited supply of materials, machine and production costs etc. LPBF machines' capabilities should be increased as well so that they can mass-produce components with high design surface quality in addition to their exceptional mechanical qualities.

Genetic algorithms, artificial intelligence, machine learning, and other similar computer automated systems that are useful to optimise process parameters can be added to LPBF technology to improve it. Moreover, by doing away with time-consuming, expensive trial-and-error procedures to conduct the physical experiments, these intelligent LPBF systems are useful for predicting the shape of the liquid melt pool, microstructure, surface quality, and mechanical qualities. Advanced numerical modelling and simulation techniques, along with in-situ detection of flaws in real time, might be used to regulate metallic imperfections.

Steels subjected to the LPBF process experience process-related greater residual stresses, as well as unavoidable internal flaws such porosities, balling, and thermal fractures that increase surface roughness. Any surface abnormalities or metallurgical flaws have a negative impact on the final part shape, which affects the surface quality and mechanical performance of the LPBF-fabricated components. In order to consider all of these interdependencies of process-related characteristics while conducting a minimum number of tests, special and effective statistical procedures are thus required. Additionally, according to the available literature, the majority of experiments that were conducted were based on suggested parameter settings offered by vendors of LPBF/AM machines, which may have caused uncertainty in the process's results depending on the operator or the vendors' expert knowledge.

Since manufacturers require continuous processes and systems that perform seamlessly together, a larger connection between the equipment, materials, and software is anticipated. To provide an end-to-end flawless LPBF process workflow, all of these components would thus need to come together and cooperate.

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