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REVIEW PAPER

Laser Powder Bed Fusion of Metallic Materials: Process Fundamentals, Critical Parameters, Defect Mechanisms, and Future

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Abstract

The advent of Metal Additive Manufacturing has greatly changed the face of modern manufacturing, enabling the fabrication of intricate metallic components from three-dimensional computer-aided design (CAD) models. Among the available metal additive manufacturing techniques, Laser Powder Bed Fusion (LPBF) is considered one of the most advanced and widely used methods due to its ability to produce near-net-shaped products with high dimensional accuracy and good mechanical properties. The technique has gained popularity in industries ranging from aerospace and biomedical to automotive, energy, and tooling, where lightweight and customizable designs are required. Although there are many advantages, the quality of LPBF-manufactured components is heavily influenced by process parameters, thermal histories, powder characteristics, and melt pool dynamics. An inappropriate choice of parameters frequently leads to flaws such as porosity, lack of fusion, residual stresses, cracking, and poor surface finish, which affect the structural integrity of the parts produced. This paper reviews the basic concepts of LPBF, the impact of key process parameters on part quality, and the common mechanisms underlying defect formation, microstructure evolution, and mechanical performance. Moreover, advancements in process monitoring, quality control, and intelligent manufacturing are mentioned. Finally, existing problems and future perspectives are examined to advance reliable and sustainable LPBF manufacturing.

1. Introduction

Manufacturing has continued to develop to meet the demands of creating lightweight structures, complex geometries, high-performance materials, and faster product development. Conventional manufacturing processes such as casting, machining, forging, and welding remain extremely valuable in mass production; however, they can be quite limited when used to create complex inner channels, lattices, or customized products. In recent years, the alternative manufacturing technique known as additive manufacturing (AM, or 3D printing) has gained popularity because it can overcome the aforementioned limitations in manufacturing by creating parts in a layer-by-layer manner, starting from computer-aided design. Among additive manufacturing techniques, metal additive manufacturing (MAM) has become increasingly popular because it enables the production of functional metallic parts with less raw material, shorter cycle times, and greater design flexibility. This type of manufacturing process has become especially useful in the aerospace industry, where components require reduced weight and excellent performance, in the biomedical industry, where patient-specific parts are required, and in the automotive industry, which needs rapid prototyping and specialty production.

Laser Powder Bed Fusion (LPBF) is considered to be one of the most developed metal additive manufacturing processes. In this process, a thin layer of metallic powder is placed onto the build platform, and the high-powered laser melts the powder

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along the sliced geometry of the part derived from the CAD model. Once the laser completes melting the layer, a new layer of powder is added, and the process repeats itself until the whole part is produced. Layer-wise manufacturing enables the production of highly complex geometries that cannot be produced using traditional techniques. Despite the great capabilities of LPBF in terms of design freedom and the mechanical properties of the produced parts, there are complex interrelations among laser energy, powder particles, melt pool dynamics, rapid solidification, and repetitive thermal cycles that greatly influence the final microstructure and mechanical properties of the part. Process parameters such as laser power, scanning speed, hatch spacing, layer thickness, and scanning strategy significantly affect melt pool dynamics, cooling rate, grain structure, and defect formation. Improper parameter selection can result in porosity, lack of fusion, residual stresses, cracking, distortion, and reduced fatigue resistance. Apart from process optimization, modern LPBF studies are mostly oriented towards intelligent manufacturing through in situ process monitoring, machine vision, thermal imaging, data analysis, and artificial intelligence.

The objective of this review is to provide an overview of the LPBF process by explaining its mechanism, key processing parameters, defect formation, microstructure formation, mechanical properties, and research trends. This article also discusses the current limitations and prospects of LPBF technology.

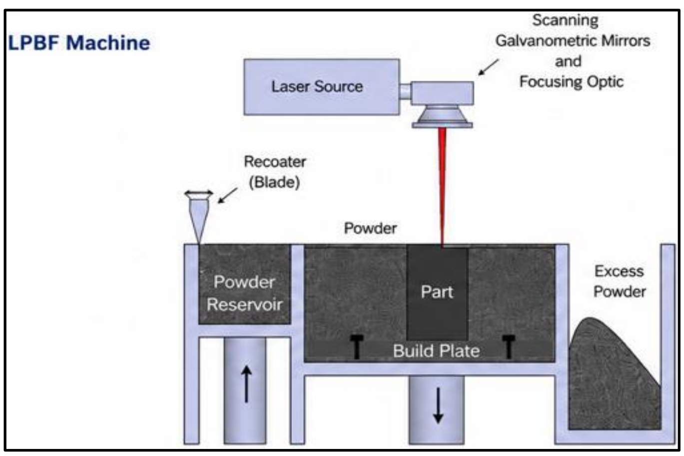

Figure 1: Schematic illustration of the Laser Powder Bed Fusion (LPBF) process (adapted from Bevans et al., 2023).

Figure 1 illustrates the fundamental working sequence of the Laser Powder Bed Fusion (LPBF) process, highlighting powder deposition, laser-based selective melting, and layer-wise part fabrication. The schematic shows the coordinated operation of the powder reservoir, recoater, build platform, laser source, scanning system, and focusing optics during additive manufacturing.

2. Fundamentals of Laser Powder Bed Fusion

Laser Powder Bed Fusion (LPBF) is one of the most sophisticated metal additive manufacturing processes based on powder beds, enabling the fabrication of fully dense metallic components with highly complex shapes and high dimensional accuracy. The process enables the fabrication of components directly from three-dimensional Computer-Aided Design (CAD) models by selectively melting metallic powder layers using a high-powered laser beam. Compared with traditional manufacturing processes, LPBF substantially reduces material waste while allowing designers to produce lighter, topology-optimized structures.

The LPBF manufacturing process starts with preparing a three-dimensional CAD model, which should be converted into an STL file. The STL file is further sliced into multiple thin layers using dedicated slicing software. During fabrication, the metallic powder layer is uniformly spread on the build platform using a recoater. Next, a focused laser beam scans the powder bed, melting selected areas into a solid layer. After each completed layer, the build platform descends by the layer thickness, and a new layer of metallic powder is supplied onto it.

A typical LPBF machine includes several main subsystems, such as a fiber laser, galvanometer scanning mirrors, powder feeding, recoater blade, building platform, inert gas chamber, optical control system, and monitoring system. The fiber laser produces enough thermal energy to fully melt the metallic powder, while galvanometer mirrors quickly direct the laser beam along the defined path. The role of the recoater is to spread the powder evenly, while the inert gas atmosphere prevents oxidation and removes fumes and spatters produced during the process.

The success of the LPBF process depends on the interaction between the laser beam and the metallic powder. When the laser hits the powder bed, the powder melts rapidly, forming a molten pool. Then, the molten material cools at an extremely high rate, forming a refined microstructure and good mechanical properties. However, cyclic heating and cooling result in significant thermal gradients, which affect grain growth, stress generation, and dimensional stability. One of the reasons LPBF has been adopted so extensively is its ability to produce highly complex parts with very little material waste. Internal cooling channels, lattice structures, conformal cooling, and patient-specific implants can all be manufactured without the tooling constraints of traditional manufacturing techniques. In addition, the technique enables rapid design modification, short production cycles, and optimal use of costly engineering materials. Even though this technique has many benefits, there are still certain technical challenges that need to be addressed. This process is very complicated due to thermal effects and involves rapid melting, solidification, and reheating. These factors affect the stability of the melt pool, residual stresses, porosity creation, and anisotropic material properties.

Table 1 summarizes commonly employed metallic materials in Laser Powder Bed Fusion (LPBF), along with their principal applications and key performance benefits. The listed alloys demonstrate diverse characteristics, including high specific strength, corrosion and wear resistance, thermal stability, biocompatibility, hardness, ductility, and dimensional stability, supporting their use across multiple industrial sectors.

Table 1: Common Metallic Materials Used in LPB.

Material	Typical Applications	Major Advantages
Ti–6Al–4V	Aerospace, Biomedical	High strength-to-weight ratio, corrosion resistance
Stainless Steel 316L	Medical, Marine, Industrial	Excellent corrosion resistance, good ductility
Inconel 718	Aerospace, Turbines	High-temperature strength, oxidation resistance
AlSi10Mg	Automotive, Aerospace	Lightweight, good thermal conductivity
Co–Cr Alloy	Dental, Orthopaedic	Excellent wear resistance, biocompatibility
Maraging Steel	Tooling, Molds	High hardness, excellent dimensional stability

The choice of materials directly affects the efficiency and applicability of products manufactured using the LPBF process. Depending on the engineering alloy, its properties will differ in thermal, mechanical, and metallurgical parameters. For instance, titanium alloys, particularly Ti-6Al-4V, became the most studied materials owing to their excellent strength-to-density ratio, corrosion resistance, and high biocompatibility (suitable for use in aerospace and biomedical fields). As for stainless steel 316L, this material is named for its high corrosion resistance and weldability, whereas nickel-based superalloys like Inconel 718 are preferable when operating in high-temperature environments (because of their high thermal and oxidation resistance). On the other hand, aluminum alloys (for example, AlSi10Mg) can provide an effective reduction in weight when used in automotive and aerospace applications; at the same time, cobalt-chromium alloys are used in dental and orthopedic implants because of their high wear resistance and biological compatibility. Although the above-mentioned materials have different physical and mechanical properties, successful processing with the LPBF method is possible only if a proper combination of laser energy input, powder properties, and thermal conditions is used. Material-specific parameters such as melting temperature, thermal conductivity, absorptivity, and cooling rate directly impact defect formation, and grain structure.

3. Critical Process Parameters

Several interrelated processing parameters strongly influence the quality and performance of components produced through Laser Powder Bed Fusion. During fabrication, the interaction between laser energy and metallic powder determines melt pool formation, heat transfer, solidification behavior, and layer bonding. Even small variations in processing conditions can significantly alter the density, surface finish, dimensional accuracy, microstructure, and mechanical properties of manufactured components. Consequently, the optimization of processing parameters has become one of the most active areas of research in metal additive manufacturing. The most influential parameters include laser power, scanning speed, hatch spacing, layer thickness, scanning strategy, and volumetric energy density. A comprehensive understanding of these parameters is essential for minimizing manufacturing defects and achieving consistent component quality.

3.1 Laser Power

Laser power represents the amount of energy supplied by the laser source to melt the metallic powder during fabrication. It is one of the primary processing parameters controlling melt pool formation, penetration depth, fusion between adjacent layers, and overall part quality. Appropriate laser power ensures complete melting of powder particles and strong metallurgical bonding between successive layers, leading to dense components with improved mechanical properties. When the applied laser power is insufficient, the delivered thermal energy cannot completely melt the powder particles. As a result, incomplete fusion occurs between adjacent tracks and layers, producing irregular melt pools, increased porosity, poor surface finish, and reduced mechanical strength. These lack-of-fusion defects significantly decrease the structural integrity and fatigue life of LPBF components. Conversely, excessive laser power introduces an excessively high energy input into the melt pool. The elevated temperature may cause metal evaporation, unstable melt pool behavior, excessive spatter formation, and keyhole porosity.

Several experimental investigations have demonstrated that an optimal laser power range yields maximum relative density and improved tensile properties. The optimum value depends on material type, powder characteristics, machine configuration, and other processing parameters such as scanning speed and layer thickness. Consequently, laser power should always be optimized alongside other process variables rather than considered independently.

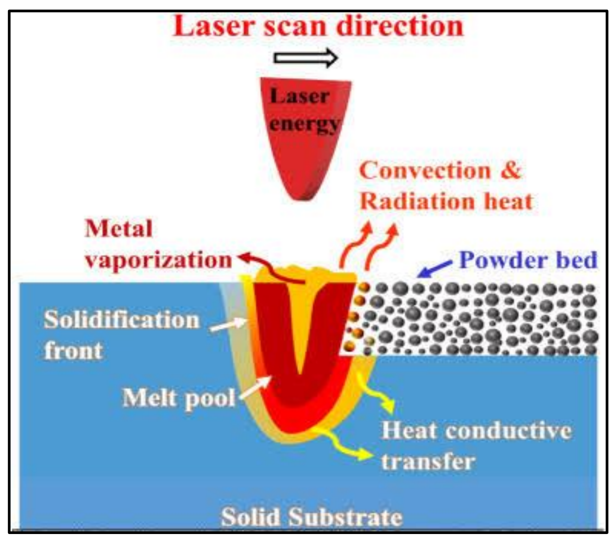

Figure 2: Schematic diagram of the melting mechanism of both processes (adapted from Jincheng Wang 2023).

Figure 2 illustrates the laser-induced melting mechanism during LPBF, showing the interaction between the moving laser beam and powder bed. The schematic highlights melt-pool formation, solidification, heat transfer, metal vaporization, and associated convection and radiation losses, collectively governing material consolidation and microstructural development.

Table 2: Influence of Laser Power on LPBF Components.

Laser Power Condition	Influence on Component Quality
Low Laser Power	Incomplete melting, lack of fusion, high porosity, reduced density
Optimum Laser Power	Stable melt pool, high density, improved surface finish, superior mechanical properties
Excessive Laser Power	Keyhole porosity, metal evaporation, spatter formation, residual stress, and distortion

Table 2 presents the relationship between laser power and the resulting quality of LPBF-fabricated components. Insufficient power leads to incomplete melting and porosity, whereas an appropriate power level produces a stable melt pool and a dense structure. Excessive power can induce keyhole defects, evaporation, spatter, residual stresses, and dimensional distortion.

3.2 Laser Scanning Speed

Laser scanning speed is another critical process parameter that significantly influences the quality, dimensional accuracy, and mechanical performance of LPBF-manufactured components. It determines the duration of laser interaction with the metallic powder and directly affects the energy delivered to the melt pool. The balance between laser power and scanning speed governs the melting behavior, cooling rate, solidification characteristics, and bonding between adjacent layers. Consequently, selecting an appropriate scanning speed is essential for producing dense components with minimum defects.

Table 3: Influence of Laser Scanning Speed on LPBF Components.

Scanning Speed	Influence on Part Quality
Low Speed	Better melting, high density, increased heat accumulation
Optimum Speed	Stable melt pool, uniform microstructure, improved mechanical properties
High Speed	Incomplete melting, lack of fusion, increased porosity, poor bonding

A relatively low scanning speed increases the interaction time between the laser beam and powder particles, allowing sufficient heat transfer and complete melting of the material. This generally produces a stable melt pool, improved metallurgical bonding, and higher relative density. However, excessively slow scanning speeds may lead to overheating, excessive melt pool expansion, metal vaporization, and residual stress accumulation due to prolonged heat exposure.

On the other hand, very high scanning speeds reduce the laser beam's residence time, thereby limiting the energy absorbed by the powder bed. Insufficient melting causes discontinuous scan tracks, poor interlayer bonding, and lack-of-fusion defects, ultimately reducing mechanical strength and dimensional accuracy. Furthermore, rapid scanning increases cooling rates, producing finer microstructures but also increasing thermal gradients and residual stresses. Table 3 summarizes the effect of laser scanning speed on the quality of LPBF components. Lower speeds increase energy input and heat accumulation, while an appropriate speed supports stable melt-pool behavior, a uniform microstructure, and improved properties. Excessively high speeds can cause insufficient melting, weak interlayer bonding, and increased porosity.

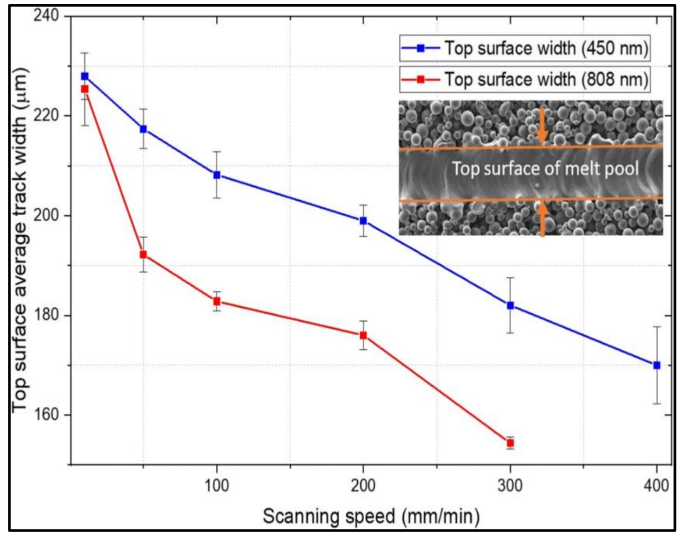

Figure 3: Effect of Laser Scanning Speed on Melt Pool Formation Mohammed (adapted from Alsaddah).

Figure 3 demonstrates the effect of laser scanning speed on melt-pool dimensions during LPBF. Increasing the scanning speed progressively reduces the measured surface track width, indicating lower thermal input and reduced melt-pool size. The observed trend highlights the importance of scanning speed in controlling melt-pool geometry and process stability.

3.3 Hatch Spacing

Hatch spacing is the distance between adjacent laser scan tracks in the LPBF process. It determines the overlap between neighboring melt pools and plays an essential role in achieving complete fusion throughout the fabricated component. Proper overlap ensures strong metallurgical bonding, minimizes porosity, and improves dimensional accuracy. When the hatch spacing is too small, excessive overlap between adjacent tracks causes repeated remelting and heat accumulation. Although this may improve interlayer bonding, excessive remelting increases thermal stresses, distortion, and manufacturing time. Conversely, excessively large hatch spacing leaves unmolten regions between adjacent tracks, producing lack-of-fusion defects and reducing component density. The optimization of hatch spacing depends on laser power, scanning speed, and melt pool dimensions. Maintaining an appropriate overlap ratio produces continuous scan tracks, improved density, and better mechanical performance. Table 4 summarizes the influence of hatch spacing on the quality of LPBF components. Excessively small spacing can cause heat accumulation and repeated melting, whereas an appropriate spacing promotes consistent track overlap and higher density. Conversely, excessive spacing may leave insufficiently fused regions, increasing porosity and compromising structural integrity.

Table 4. Effect of Hatch Spacing.

Hatch Spacing	Effect
Small	Heat accumulation, remelting
Optimum	Uniform overlap, high density
Large	Lack of fusion, porosity

3.4 Laser Scanning Strategy

The laser scanning strategy defines the sequence and orientation of the laser beam as it melts each powder layer. Common strategies include unidirectional, bidirectional, island, chessboard, and rotational scanning. The selected scanning pattern significantly influences thermal distribution, residual stress development, grain orientation, and distortion. Alternating or rotational scanning strategies are commonly adopted because they reduce heat accumulation in a single direction, leading to more uniform thermal distribution and lower residual stresses. Island scanning further minimizes distortion by dividing the build area into smaller sections, allowing localized heat dissipation before subsequent scanning. The selection of an appropriate scanning strategy depends on component geometry, material characteristics, and desired mechanical performance. Ongoing research focuses on developing adaptive scanning strategies to improve productivity while reducing residual stress and manufacturing defects.

4. Defect Mechanisms

The performance of Laser Powder Bed Fusion (LPBF) components is strongly influenced by process-induced defects that develop during rapid melting and solidification. The most common defects include lack of fusion, porosity, residual stress, and balling, which primarily result from improper combinations of laser power, scanning speed, hatch spacing, and layer thickness. These defects reduce component density, dimensional accuracy, fatigue life, and mechanical performance. Lack of fusion results from insufficient energy input, while excessive laser energy may lead to keyhole porosity and unstable melt pool behavior. Rapid thermal cycling also generates residual stresses that may cause distortion or cracking. Therefore, selecting optimized processing parameters and effective process monitoring are essential for minimizing defects and improving the reliability of LPBF-manufactured components.

Table 5: Common LPBF Defects

Defect	Cause	Effect
Lack of Fusion	Low energy input	Poor bonding
Porosity	Gas entrapment or excessive energy	Reduced density
Residual Stress	Rapid heating and cooling	Distortion
Balling	Melt pool instability	Poor surface quality

Table 5 outlines the principal defects encountered in LPBF components, together with their underlying causes and effects. Insufficient energy input can lead to a lack of fusion, while gas entrapment and excessive energy may promote porosity. Rapid thermal cycling causes residual stress and distortion, whereas melt-pool instability can lead to balling and poor surface quality.

5. Future Research Directions

Laser Powder Bed Fusion technology continues to evolve with advancements in materials, process optimization, and intelligent manufacturing systems. Future research should focus on improving process stability through real-time monitoring, closed-loop process control, and advanced sensing technologies. The integration of artificial intelligence, machine learning, and digital twin frameworks can significantly enhance defect prediction, process optimization, and quality assurance, as shown in Figure 4. Furthermore, the development of sustainable powder recycling techniques, multi-material fabrication, and standardized qualification procedures will contribute to wider industrial adoption. Continued research on microstructure control, residual stress reduction, and productivity improvement will further strengthen the reliability and commercial viability of LPBF technology across aerospace, biomedical, automotive, and energy sectors.

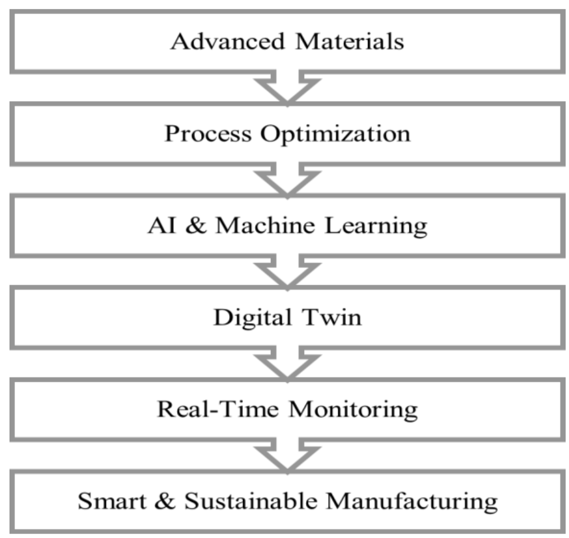

Figure 4: Future research directions for LPBF.

6. Conclusion

Laser Powder Bed Fusion has become one of the most promising metal additive manufacturing technologies due to its capability to fabricate complex components with excellent dimensional accuracy and mechanical performance. This review presented the fundamental principles of LPBF, discussed the influence of critical process parameters, and summarized common manufacturing defects that affect component quality. The study highlights that optimized processing conditions are essential for achieving dense components with improved mechanical properties and reduced defects. Recent developments in intelligent process monitoring and data-driven optimization provide new opportunities for enhancing manufacturing reliability and productivity. As research continues to address current technical challenges, LPBF is expected to play an increasingly important role in the future of advanced manufacturing.

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