Review

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Laser Powder Bed Fusion: Exploring Recent Technological Breakthroughs and Alloy Utilization

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Laser Powder Bed Fusion: Exploring Recent Technological Breakthroughs and Alloy Utilization

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Abstract: Laser Powder Bed Fusion (LPBF), as a transformative technology in the field of additive manufacturing, offers unprecedented design flexibility and material efficiency. This review paper delves into the latest advancements in LPBF technology and the various alloys used in the process, including titanium alloys, aluminum alloys, nickel-based superalloys, steel alloys, copper alloys, and high-entropy alloys. For each alloy category, we discuss their specific applications, performance characteristics, and challenges faced in LPBF usage. The paper discusses important technological breakthroughs, including innovations in laser systems, scanning strategies, and in-situ monitoring technologies, which have enhanced the precision and reliability of LPBF.

Keywords: laser powder bed fusion; alloy; advantage and limitation; laser parameters

1. Introduction

LPBF, also known as Selective Laser Melting (SLM), is a cutting-edge additive manufacturing technology capable of producing complex and high-performance components with exceptional precision and accuracy [1–7]. LPBF involves the layer-by-layer melting and solidification of metal powders using a high-energy laser beam, ultimately constructing intricate three-dimensional structures. This advanced manufacturing method has revolutionized component production across various industries, offering unparalleled design freedom and material flexibility. The historical development of LPBF technology can be traced back to the 1990s when researchers began exploring the potential of using lasers to selectively melt metal powders for additive manufacturing applications. Over the years, LPBF has evolved from a novel concept to a mature manufacturing technology, demonstrating its versatility and adaptability in producing functional parts with high dimensional accuracy and complex geometries. The importance of LPBF in the field of additive manufacturing lies in its ability to produce parts with customized material properties, complex internal structures, and reduced material waste compared to traditional manufacturing methods. LPBF also has potential advantages in zinc metal batteries[8,9]. This review aims to thoroughly investigate the advancements in LPBF technology, highlighting the progress and innovations driving this additive manufacturing method to the forefront of modern manufacturing. By examining the latest developments in LPBF technology, such as improved process parameters, enhanced scanning strategies, and optimized material compositions, this review will provide a comprehensive understanding of the evolving capabilities of LPBF technology. Additionally, this review will highlight the types of alloys [10–15] commonly used in LPBF, exploring various materials, including high-performance metals, superalloys, and specialized alloys tailored for specific applications. Focusing on the scope and objectives of this review, the exploration of LPBF technology will include a detailed analysis of alloy selection criteria, material properties, process parameters, and performance characteristics that influence the success of LPBF manufacturing. By elucidating the current trends and advancements in LPBF technology, this review aims to contribute to the growing body of knowledge in the field of additive manufacturing and provide valuable insights for researchers, engineers, and industry professionals involved in LPBF applications.

2. Fundamental Principles of LPBF

2.1. Working Mechanism

LPBF is an additive manufacturing process that involves selectively melting and solidifying layers of metal powder using a high-intensity laser beam under a controlled atmosphere. The LPBF process consists of several key components and mechanisms. These include the laser system, powder delivery system, build platform, recoating system, and control software. It uses high-power lasers to build components layer by layer, selectively melting powder material. The process begins by slicing the CAD model into thin layers. Powder is evenly spread on the build platform, and the laser scans each layer, melting and fusing the powder. After each layer is completed, the platform descends, repeating this process until the part is finished.

2.2. Process Parameters

Laser power, scanning speed, layer thickness, and other key parameters play crucial roles in determining the quality of the final product. Laser power directly affects the energy input into the powder bed, influencing the melting and solidification process [16]. Higher laser power can lead to faster melting and deeper penetration into the powder bed [17–20]. Scanning speed determines the rate at which the laser moves over the powder bed, impacting the cooling rate and microstructural characteristics of the manufactured parts. Layer thickness affects the resolution and surface finish of the printed parts. Optimizing process parameters is crucial for achieving high-quality parts with the desired mechanical properties. The interaction of laser power, scanning speed, and layer thickness affects the material microstructure, density, and mechanical properties of the manufactured parts.

2.3. Advantages and Limitations

LPBF offers several advantages over traditional manufacturing techniques. It can produce complex geometries with high precision and material efficiency [21–23]. The technology allows for rapid prototyping and customization, reducing lead times and tooling-related costs. LPBF is particularly suited for small-batch and high-value applications where design flexibility and material performance are critical. Despite its numerous advantages, LPBF also presents challenges and limitations. The process is sensitive to variations in material properties, powder quality, and environmental conditions. The process is sensitive to variations in material properties, powder quality, and environmental conditions. Post-processing steps, such as heat treatment and surface finishing, may be necessary to achieve the desired mechanical properties and surface quality. By understanding and optimizing process parameters, manufacturers can fully harness the potential of this technology to create innovative components for various industries. By understanding and optimizing process parameters, manufacturers can fully harness the potential of this technology to create innovative components for various industries.

3. Recent Progress in LPBF Technology

Technological advancements in LPBF primarily focus on addressing challenges such as material limitations, defects, and process optimization. Specifically, advancements in LPBF include exploring solutions[24,25] to overcome material limitations hindering the application of certain alloys in additive manufacturing processes. Efforts are made to enhance material compatibility and process parameters to broaden the range of materials applicable to LPBF technology. Recent investigations in machine learning have greatly contributed to research in LPBF [26–32]. In terms of material processing and powder characteristics, the focus is on optimizing powder properties, such as size distribution and morphology, to enhance the quality and reliability of parts manufactured through LPBF. Understanding the impact of material characteristics on manufacturing processes is crucial for achieving the mechanical performance and structural integrity required for the final manufactured parts. As emphasized in the document, these advancements aim to enhance the efficiency and effectiveness of LPBF processes. In terms of quality control and post-processing, recent advancements in LPBF technology include the development of advanced detection techniques and post-processing

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methods to ensure the quality and reliability of additive manufacturing components. Emphasis is placed on optimizing post-processing steps to reduce defects, improve surface finish, and enhance mechanical properties. The attention to quality control and post-processing marks a transition in LPBF manufacturing towards achieving higher precision, consistency, and repeatability.

4. Alloys Used in LPBF

4.1. Titanium Alloys

Titanium alloys play a crucial role in LPBF due to their excellent combination of properties , making them highly favored in various industries. Here, we delve into the applications, properties, specific types, and performance of titanium alloys in LPBF. Titanium alloys are widely utilized in LPBF across multiple industries such as aerospace, medical implants, and high-performance engineering. The key attributes driving their utilization include their outstanding strength-to-weight ratio, corrosion resistance, and biocompatibility. These characteristics make titanium alloys particularly suitable for applications requiring lightweight, durable, and biocompatible components. Ti-6Al-4V [33] (Grade 5 titanium): This is perhaps the most widely used titanium alloy in LPBF. It consists of 90% titanium, 6% aluminum, and 4% vanadium. Ti-6Al-4V ELI (Grade 23 titanium): Similar to Ti-6Al-4V, but with additional low interstitial elements, this alloy is specifically designed for biomedical applications. Its improved biocompatibility and reduced risk of inflammation make it suitable for medical implants such as dental and orthopedic implants. Ti-6Al-2Sn-4Zr-6Mo [34]: Known for its high strength and corrosion resistance, this alloy is particularly renowned in harsh environments like seawater. Ti-5553[35]: This emerging titanium alloy is designed for high-temperature applications, boasting excellent creep resistance and thermal stability.

4.2. Aluminum Alloys

Aluminum alloys [36] have various applications in LPBF, covering fields such as aerospace, automotive, and structural components. Its lightweight characteristics make it particularly suitable for weight reduction critical applications, such as aircraft structures, automotive body panels, and lightweight structural components. Additionally, its high thermal conductivity makes it suitable for applications like heat exchangers, electronic enclosures, and electrical connectors. AlSi10Mg [37,38]: This is one of the most commonly used aluminum alloys in LPBF. AlSi10Mg is composed of aluminum, silicon, and magnesium, and it has good strength, ductility, and corrosion resistance. In LPBF, it exhibits excellent processability with high build success rates and good surface finish. Parts made from AlSi10Mg have mechanical properties comparable to traditionally manufactured parts, making them suitable for a wide range of applications such as aerospace and automotive components. AlSi7Mg0.6: Similar to AlSi10Mg but with lower magnesium content, this alloy has better weldability and thermal conductivity. In LPBF, it exhibits excellent buildability and mechanical properties, making it suitable for applications such as heat exchangers, electronic enclosures, and lightweight structural components. AlSi12 [38]: This aluminum-silicon alloy has good castability and high wear resistance. In LPBF, it exhibits good processability and mechanical properties, making it suitable for applications requiring high wear resistance, such as pump components, hydraulic channels, and automotive engine parts. Al6061 [39]: This wrought aluminum alloy is known for its high strength and excellent machinability. n LPBF, Al6061 has good processability and mechanical properties, making it suitable for a wide range of applications, including tools, industrial components, and automotive parts.

4.3. Nickel-Based Superalloys

Nickel-based superalloys hold a significant position in LPBF due to their excellent strength [40–42], oxidation resistance, and corrosion resistance, as well as their ability to maintain mechanical properties at high temperatures. These alloys are widely used in high-temperature and high-stress environments, such as turbine blades, jet engine components, and rocket engines in aerospace, gas turbines and nuclear reactor components in power generation, high-pressure and corrosive environment parts in the oil and gas industry, and turbocharger impellers and high-performance engine components in automobiles. Specifically, Inconel 718 is widely used in the aerospace and power generation fields due to its excellent tensile, fatigue, creep, and fracture strength, along with its high corrosion and oxidation resistance. Inconel 625, with its excellent fatigue and thermal fatigue strength, oxidation resistance, and corrosion resistance, is suitable for chemical processing, marine, and aerospace applications. Hastelloy X performs excellently in high-temperature industrial applications, with good oxidation resistance and high-temperature strength. René 41 is suitable for high-stress aerospace components; despite its machining difficulties, LPBF technology can achieve the production of complex geometries. Through continuous technological advancements and innovations, LPBF technology has not only improved the functionality and durability of these alloy components but also promoted the development of various industries, further enhancing its importance in modern manufacturing.

4.4. Steel Alloys

Steel alloys hold a fundamental position in LPBF due to their versatility, excellent mechanical properties [43–45], and wide range of applications. These alloys are renowned for their exceptional strength, durability, and machinability, making them suitable for various industrial applications, including molds, dies, and cutting tools that require high wear resistance and toughness, structural components, engine parts, and exhaust systems in automobiles, load-bearing components and fatigue-resistant parts in aerospace, surgical instruments and implants in medical use, as well as gears, bearings, and other components in industrial applications that must withstand high stress and wear. Specific types include maraging steel (such as 18Ni-300), which demonstrates excellent performance in LPBF with its high strength and toughness, superior dimensional stability, and good machinability, making it suitable for tool manufacturing, aerospace components, and high-performance industrial applications. Stainless steels (such as 316L and 17-4 PH), are widely used in medical devices, marine applications, and food processing equipment due to their excellent corrosion resistance and mechanical properties. Tool steels (such as H13 and D2) are suitable for hot-working and cold-working tool applications due to their high hardness and wear resistance. Additionally, AISI 4140, with its high fatigue strength and wear resistance, is suitable for automotive parts, industrial machinery, and tool manufacturing. Through continuous technological advancements and innovations, LPBF technology has not only enhanced the functionality and durability of these steel alloy components but also propelled the development of multiple industries, further elevating its significance in modern manufacturing.

4.5. Copper Alloys

Copper alloys are highly favored for their excellent performance in LPBF, including outstanding thermal conductivity, electrical conductivity, corrosion resistance, and antibacterial properties [46–48]. Currently, there is active development of new alloys customized for LPBF, involving the addition of elements, high-strength alloys, and alloys with antibacterial properties, such as copper-based alloys with added nickel, aluminum, silicon, etc., as well as high-strength copper alloys. These include copper-based alloys (such as copper-nickel alloys, copper-aluminum alloys, copper-silicon alloys), and high-strength copper alloys. Meanwhile, researchers are also striving to optimize process parameters, control microstructures, and explore multi-material printing technologies. These research trends and innovations will further drive the application of copper alloys in LPBF, providing new development opportunities for industrial applications in fields such as electronics, automotive, aerospace, and medical equipment.

5. Conclusions

LPBF technology offers a revolutionary additive manufacturing method with high precision, efficiency, and multifunctionality. Its ability to produce high-precision, complex geometric components makes it indispensable in the aerospace, medical, and engineering fields. LPBF minimizes material waste and production cycles, enhancing resource utilization and operational efficiency. Various alloys including titanium alloys, nickel-based superalloys, stainless steel, and copper alloys are utilized in LPBF, meeting the demands of various industries. However, LPBF faces challenges such as high initial costs, size limitations, and complex post-processing requirements. Despite these drawbacks, LPBF continues to evolve, with ongoing research focusing mainly on process optimization, development of tailor-made new alloys, and exploration of new application areas. The future of LPBF lies in overcoming these challenges, leveraging its advantages, and utilizing technological advancements to drive innovation, efficiency, and sustainable development in additive manufacturing.

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