SELECTIVE LASER MELTING FOR 3D PRINTING OF DIFFERENT MATERIALS AND THEIR APPLICATIONS: A REVIEW

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Selective Laser Melting (SLM) is a sophisticated form of additive manufacturing that allows the straightforward creation of complex, high-precision metal parts with a digital design. The paper will provide an in-depth examination of the SLM processing of various metals and alloys, including steels, titanium, aluminium, nickel, and metal matrix alloys and composites, in their applications and their suitability for critical applications such as aerospace, automotive, engineering, and biomedical fields. The paper focuses on material-related issues, including porosity, cracking, and residual stress, and the current state of the art in the optimization of the processes and the innovation of materials. The results highlight the increasing possibility of a reliable, efficient, and versatile solution for next-generation manufacturing by SLM.

KEYWORDS

Additive Manufacturing, SLM, Aluminium Alloy, Titanium alloy, Steel

1 INTRODUCTION

1.1 Background of Additive Manufacturing (AM)

One of the earliest methods to produce products in a layered way is rapid prototyping, which was invented in the 1980s. In this type, the three-dimensional CAD model is used to form the desired body. This process has significantly reduced material usage, shortened production time, and enabled the on-demand production or modification of products. Nowadays, this method is applicable not only in the industry but also in the medical, research, and creative fields. With rapid prototyping, researchers and scientists can develop models to analyse and compare with theoretical work. Healthcare experts will be able to use the technology to create replacement organs for damaged body parts. The pharmaceutical industry has recently followed suit to produce pills with specific shapes and uniform chemical makeup [Wong 2012]. Different types of additive manufacturing processes are represented in Fig. 1.

1.2 Powder Bed Fusion Techniques

Powder bed fusion is an additive manufacturing method that forms a finished product by layering powder one layer at a time. This process is applied in different industries such as the automotive industry, aerospace, and healthcare. In production, a laser beam scans a predetermined part of the powder bed at a set speed, fusing the powder onto the solid platform beneath. This may be done by totally melting the powder (Selective Laser Melting, SLM), or just partially melting it (Selective Laser Sintering, SLS). The significant distinction between the two is the melting, which in the former case, SLM, is completely done, and in the other case, SLS, is partially carried out.

After laser processing one layer, the thickness of the layer is changed, and new powder is sprinkled and flattened on the old one. It is this step-by-step process that happens layer by layer till the last component is developed. The direction in which the laser is made to scan also varies according to the layer; it is dependent on the geometry of the part at a given Z-height, and the chosen method of scanning the laser. This process is repeated until the last part is finished. This means that the laser scanning pattern will be different on each layer due to the geometry of the part at that Z-height and the Laser scanning method selected.

When considering powder bed fusion techniques, several key processing parameters are crucial to consider. These include layer thickness (t), laser power (P), scanning speed (v), hatch spacing (h), laser spot diameter (d), and the size and distribution of the particles. Additionally, the preheating temperature of the platform and the method for scanning the laser beam are also critical factors [Singh 2021; Vock 2019].

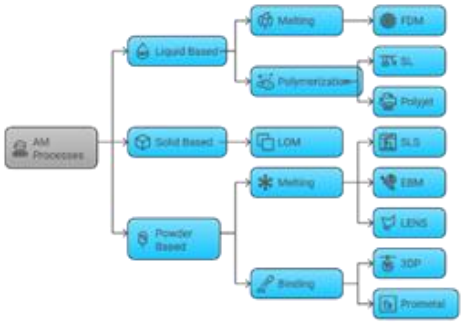

Figure 1. Classification of Additive Manufacturing Processes based on energy source, and deposition technique

Huo et al. used SLM technique to fabricate 91 W-6.3Ni-2.7Fe alloys. Experiments were performed with a different scanning speed which varies between 125 mm/s to 1000 mm/s. Other parameters such as hatch spacing, layer thickness, and laser power were 0.08 mm, 0.03 mm, and 200 W respectively [Huo 2025]. In a different study Deng et al. used SLM technique to fabricate AA6063 Al alloy. Variable parameters during the process were laser power (150 to 450 Watt), scanning speed (400 to 1000 mm/s), and hatch spacing (0.03 to 0.11 mm) [Deng 2025].

1.3 Overview of Selective Laser Melting (SLM)

Selective Laser Melting (SLM) is a versatile technique that can be applied to almost any metal. However, the ease of processing these metals and the optimal settings—often referred to as processing windows—can vary significantly. This variation is influenced by factors such as the chemical composition of the materials, their absorption of laser energy, melt viscosity, surface tension, and thermal conductivity. Anyone can process these metals, and the ideal settings can vary significantly.

1.4 Importance of material selection in SLM

Choosing the right material is vital for ensuring the quality and performance of the final product. Different materials come with their unique properties, like thermal conductivity, laser absorptivity, and melting behaviour, all of which can significantly impact how stable the process is. By selecting the right material, we can make sure it works well with the laser energy input, helping to reduce issues like porosity and cracking. This choice also plays a significant role in the mechanical properties of the printed part, including its strength, hardness, and resistance to fatigue. Additionally, material selection influences how the microstructure develops during the solidification and cooling stages. It even affects what kind of post-processing will be needed and how cost-effective the whole process will be. So, picking the right material is key to achieving the best functionality and reliability in SLM [Gu 2020].

2 WORKING PRINCIPLE OF SELECTIVE LASER MELTING

2.1 Process Description

An additive manufacturing process where layers of powder are added to give a final product is called powder bed fusion. It is a new, innovative method of additive manufacturing called SLM that can offer opportunities to different industries. It is especially trendy in manufacturing complex metal components that do not require much post-production. This is achieved through scanning of metal powders with a high-energy laser along a given path to melt the powders layer by layer. The technique forms complex 3D objects bit by bit. Every new layer partially remelts the layer beneath it, as they are added, thus reducing such defects as porosity, segregation, and impurities. It also aids in the development of a more even microstructure. The cooling rates are relatively fast, varying between 10^3 and 10^8 K/s, which results in delicate grain structures and high supersaturation levels in the parts, ultimately improving the mechanical strength of the end product. Among the essential benefits associated with the use of SLM is that it does not necessitate the use of moulds or fixtures, thus making it possible to achieve high dimensional accuracy. It also allows for the integration of the functionally graded materials into one part.

Moreover, recycled metal powder optimizes the efficiency of the material and brings down the cost of production. This is done by depositing a new layer of powder on the build platform and melting it selectively using a laser beam. This process continues until the completion of the whole component. By modifying the laser parameters, the size and behaviour of the melt pool, typically about 100 µm, can be optimised. SLM is credited with making parts that have superior mechanical properties and complex geometries. Nonetheless, some obstacles are yet to be solved, and they include the creation of a smooth surface finish and increasing dimensional accuracy [Zhang 2019].

Besides the above advantages, this technique has found its application for various metals and powders. The process can be used to process a low strength aluminium to a very hard tungsten carbide/Inconel carbide. Deng et al. used the SLM technique to fabricate AA6063, which has high laser reflectivity, poor powder flowability, and a wide solidification temperature range. The above characteristics make it prone to the defects formation. The authors observed a crack of 300 to 500 micrometres, parallel to the build direction, and a maximum local stress of 418 MPa [Deng 2025]. Shi et al. fabricated tungsten carbide reinforced Inconel 718 composites and observed a maximum tensile strength and micro-hardness of 1203 MPa and 403 HV [Shi 2025]. Ding et al. used the SLM technique to process Ti6Al4V alloy and applied hot stamping on the manufactured parts. The hot stamping improved the corrosion resistance by 2.38 times compared to the untreated samples [Ding 2025]. In a similar study, Huo et al. employed the SLM method for the 91 W-6.3Ni-2.7Fe alloys, examining the densification and microstructural properties, and achieved a satisfactory density at a speed of 175 mm/s [Huo 2025]. In a different study, Fang Ma et al. employed the SLM method to fabricate Fa-Ga alloy and obtained a porosity-free and defect-free product [Ma 2025].

2.2 Machine Setup and Components

The main components of the machine are the laser source, beam steering mechanism, inert gas enclosure, cylinder, and powder delivery system (Figure 2). Nowadays, fibre lasers operating at a wavelength of 1064 nm are typically used to process high-entropy alloys (HEAs) . Lasers that produce green or blue light with high intensity are, however, promising for future use, as they have shorter wavelengths and can absorb more energy through metals [Yang 2024]. The most commonly used system for moving the beam is the galvanometer scanner, which has a rapid working process, enabling the melt pool to heat up and solidify quickly. The X-Y motor system is slower and a more affordable alternative. Older models used a powder-feeding cylinder, whereas the most recent models have a powder-dropping mechanism, which improves the quality of powder distribution and reduces wastage [Shaheen 2021]. The shielding atmosphere is usually argon gas. There is also an option to preheat the components of the substrate used, as well as the powder, to reduce stresses in the residue and improve the quality of the final parts [Gu 2020].

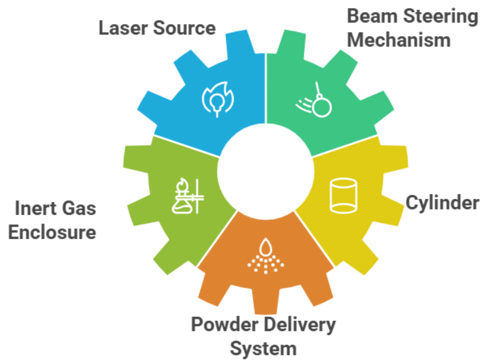

Figure 2 Different parts and components of the Selective Laser Melting (SLM) machine

2.3 Laser Parameters (power, speed, scan strategy)

A range of significant process parameters influences the SLM process. Laser power, scanning speed, hatch spacing, layer thickness, and scan strategy are among the most studied ones. The higher the energy transferred to the substrate, the greater the laser power. To obtain comprehensive information on the solidification process during the melting of powder particles, the appropriate amount of power should be chosen, depending on the material's characteristics. If the power is too low, partial melting will occur, which can contribute to defects. Melting and solidification rates, however, are influenced by the scanning speed. Hatch spacing regulates the overlapping between scan tracks spaced next to each other, through which good metallurgical bonding occurs. Layer thickness refers to the thickness of the layered powder; excessive thickness can cause incomplete melting and lead to problems such as balling. To evaluate the overall impact of these parameters, the volumetric energy density (in Joules/mm³) is commonly used [Gao 2023].

2.4 Powder Characteristics (size, shape, flowability)

SLS and SLM are processes where powder properties are the key to employ the most efficient method and to prepare the final product of high quality. Powder particle size is one of the most influential parameters that impact physical and chemical stability, content uniformity, solubility, and bioavailability because it alters the surface area. Larger particles are more flowable and decrease the packing density, but raise energy requirements in sintering. Anchor, on the contrary, smaller particles improve the uniformity of the content and mechanical strength of particles, yet are more prone to the aggregation process, so spreading powder becomes complicated. In commercially applicable SLS polymer powders, the desired particle size is 20-60 µm. There must also be optimal flow characteristics of the powders to ensure even spreading of the powder and a high packing density. Flow enhancers (colloidal silicon dioxide, talc, and calcium or magnesium silicates) can be added, as well as antistatic agents, to enhance flow. Further, the shape of particles greatly influences the powder properties: worldwide, it is contemplated to have a low contact area and increased flow properties, whereas the particles may have a more spherical shape (e.g., flake or acicular), and thus, they are more likely to become tangled and inhibit motion. When using metallic powders, as in SLM, gas atomized powders have the advantage over water atomized powders due to their more spherical shape, producing good flow and bed packing density. The powder is evenly spread in the powder spreading mechanism, which spreads the layer of powder across the substrate through the scraper. This layer needs to be uniform in thickness; otherwise, it causes irregular absorption of the laser and melt instability. The particle size is, therefore, a crucial aspect of uniform layer formation and the best interaction of the laser. The thickness of the powder layers, which may range between 100 and 500 µm, is another factor that determines the amount of laser power and build time, and the quality of bonding between consecutive layers, where thicker layers need a higher amount of power to prevent defects such as delamination. In addition, other powder characteristics that affect the laser parameters and, ultimately, the mechanical and surface properties of the metal parts produced include composition, melting point, optical character, and thermal conductivity. Hence, applying powder property control about particle size, shape, distribution, etc. is an essential element when it comes to successful SLS and SLM processing [Charoo 2020, Trevisan 2017].

2.5 Material Properties (thermal conductivity and laser absorptivity)

The physical properties, e.g., thermal conductivity and laser absorptivity, have a significant impact on defect formation during Selective Laser Melting (SLM). When the material involved has high thermal conductivity and low laser absorptivity as is the case with aluminium, the process will tend to have accelerated heat dissipation, culminate into incomplete melting, development of porosity and poor adhesion among the successive layers. In contrast, materials with relatively low thermal conductivity, which have higher absorptivity, including stainless steel and titanium have better melt-pool stability, with an increased tendency to form keyhole porosity and residual stresses due to localized overheating. Therefore, the rational control over the nanofabrication process parameters such as laser power and scan rate as determined by the thermal and optical properties of the material is urgent to reduce defect formation and the maintenance of a uniform microstructure [Yang 2022, Zhang 2022].

3 MATERIALS USED IN SLM

3.1 Stainless Steel

The wide use of alloy steels in structures, high-temperature parts, and in medical and dental applications can be mainly attributed to their high level of biocompatibility. These are usually steels with high density, strength, hardness, and surface roughness. Nonetheless, obtaining desired and uniform part density is one of the key challenges in manufacturing metals via the SLM approach. Alloy steel SLM processing is more costly than conventional production techniques; however, the added value it creates in producing complex and custom parts makes it a necessary aspect of production, especially in areas requiring delicate touches, such as the medical industry.

Other forms of steel have also been considered in their processing using SLM. They are made of Inox904L stainless steel, AISI Maraging 300 steel, precipitation hardening steel, tool steel H20, and tool steel X110CrMoVAl. Other than steels, alloys of iron and intermetallics like Fe-Ni, Fe-Ni-Cu-P, Fe-Ni-Cr, Fe-Al, and Fe-Cr-Al have also found application in SLM, though much less is published on them. Until now, the primary focus of such research work has been on the determination of the appropriate processing parameters to obtain such fully dense components using these materials and their associated microstructural forms [Gunasekaran 2020]. Application of different materials in SLM is represented in Figure 3.

3.2 Titanium and its Alloys

In the last ten years, titanium has become one of the most researched materials in SLM, as it is closely followed by steel in terms of the number of publications. Commercially pure titanium (cpTi) and the Ti-6Al-4V alloy (Ti64) are the two alloys that a majority of the research has focused on. The liquid phase of titanium poses problems to conventional production processes such as melting, casting, and moulding, because titanium is highly active and reacts with elements like oxygen, nitrogen, hydrogen, and carbon, among others. Nevertheless, the SLM process has a benefit in this aspect. It includes local heating and fast cooling, which contributes to the minimization of the uptake of interstitial components such as hydrogen, carbon, and oxygen. Also, the work is done in a protective environment, usually an inert gas like argon, to displace the atmospheric air and reduce contamination. In addition to two popular titanium-based alloys, cpTi and Ti64, other alloys such as Ti-6Al-7Nb, Ti-24Nb-4Zr-8Sn, Ti-13Zr-Nb, and Ti-13Nb-13Zr alloys are also candidates for hosting due to their adequacy in SLM processing [Lu 2023].

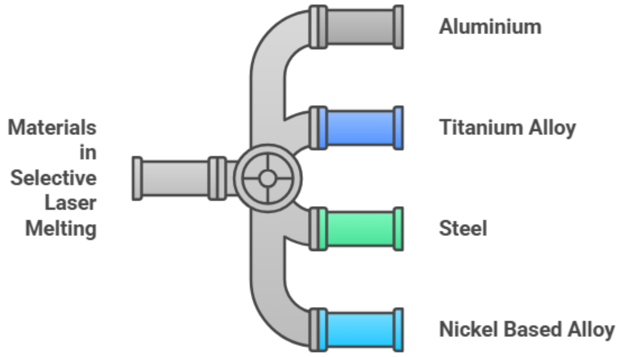

Figure 3 Different metals and alloys commonly used in SLM

3.3 Aluminium Alloys

Aluminium (Al) alloy is said to be especially challenging to process because of the following intrinsic material properties. Al powders are light, exhibiting high reflectivity, high thermal conductivity, and low laser absorption at the typical power of a fiber laser (1.06 µm, 1000 nm) commonly used in SLM. The above features result in ineffective energy absorption of the laser exposure, leading to difficult melting and consolidation of the process. Nevertheless, certain cast Al alloys have shown moderately good processability of SLM, especially AlSi10Mg and AlSi12. These types of alloys are used because they have good castability and low shrinkage; in addition, the high constituent of Al-Si eutectic contributes to the development of low stresses during solidification.

Conversely, 2xxx, 5xxx, 6xxx, and 7xxx series Al alloys are superior in strength and ductile properties to the LM 2A alloys and are widely applied in the aerospace and automotive industries. However, these alloys have not been effectively used with SLM since there is a high propensity of these alloys to crack microscopically with rapid thermal processes and steep cooling velocities that occur in the process. These micro-cracks negate the structural capabilities of the manufactured pieces, rendering these alloys inapplicable in load-bearing processes unless further optimization of the methods is done.

Moreover, SLM-produced pure aluminium components often exhibit defects. Typical problems arise with irregularly shaped or spherical gas pores and fine oxide particles in an aluminium matrix. Laser energy density plays a critical role in terms of relative density and quality of SLM parts. The lack of energy density results in incomplete melting of powder particles and an uneven pore shape, whereas excessively high energy density leads to metal sputtering and the formation of sphere-like pores containing gas. Such pores usually have gases like nitrogen (N2) or argon (Ar) that are employed in the processing of an inert atmosphere, and the hydrogen gas that is trapped inside the powder. Also, the aluminium powders are generally in the atomized form and already have pre-existing surface oxides, which might break into smaller oxide particles during the processing process that are usually less than 0.3 µm, and end up being trapped within the final product. Such fine inclusions of oxides may cause adverse effects on the mechanical properties and finishing quality of the SLM components.

Conclusively, although Al alloys are very promising as it pertains to SLM because of its common usage and desirable strength-to-weight ratio, the underlying material drawback on the one hand and issues with processing on the other hand demands significant consideration in choice of alloy, optimization of laser conditions, and even powder treatments that may be required to print defect-free and structurally efficient modules [Wang 2020].

3.4 Nickel-based Superalloys

Nickel-based alloys rank among the most investigated materials to be used in the SLM process and are ranked after steel and titanium. The best feature of these materials is their good performance at high temperatures. The most studied alloys among them are the Inconel alloys, including Inconel 625 and Inconel 718, since these alloys enjoy widespread industrial applications. Chromel, Hastelloy X, Nimonic 263, IN738LC, and MAR-M 247 are other nickel-based alloys that have been investigated in SLM.

A significant amount of research has been conducted on these alloys, with process parameter optimization being of paramount importance to ensure that stable melt tracks can be formed, thereby obtaining fully dense and structurally sound 3D components. Besides these high-temperature alloys, a temperature-sensitive shape memory alloy (SMA), NiTi, has also come into the spotlight with respect to SLM processing. Clare et al. were successful early practitioners in the NiTi component production by SLM and achieved a two-way trained alloy that showed a gradual transition to the phase. Their findings revealed the occurrence of martensitic transformations in the range 32-59 and the austenitic transformations in the range 59-90.

Later, Meier et al. conducted investigations on the SLM processing of NiTi and found that the fabricated components exhibited excellent cyclic stability. However, the SLM components exhibited slightly lower fracture strength and strain compared to conventionally manufactured NiTi. This indicates the potential and the difficulties in processing advanced nickel-based alloys via SLM to be used in structural and functional applications [Korkmaz 2022].

4 APPLICATIONS OF SLM IN VARIOUS FIELDS

4.1 Aerospace Industry

SLM is a high-quality, near-net-shape manufacturing process that has saved time and cost, producing strong and high-performance components. This is what makes it very appealing to the aerospace industry, where there is always a steady demand for innovative materials. Due to the nature of performance demands that are continuously increasing within the aerospace industry, lightweight materials are needed to provide high mechanical properties and durability

Metal Matrix Composites (MMCs) are potential engineering materials because their properties can be tailored, as in the case of composites (since they have both reinforcing and matrix phases). Of all the MMCs, the aluminium and titanium matrix composites (AMCs and TMCs) in particular are well suited to the aerospace industry due to their superior strength to weight properties. Nevertheless, numerous challenges remain in integrating SLM-manufactured composites into aerospace systems; therefore, feasibility and reliability factors should be considered in further research. Application of SLM in different area is shown in Figure 4.

4.2 Biomedical Applications

Selective Laser Melting has received massive attention in the manufacture of complex-shaped, customizable implants with favourable mechanical properties. The idea is to revolutionize the production of medical instruments, especially in the production of artificial organs, including those of the heart, such as heart stents, drug delivery, scaffolds, and orthopaedic implants fabricated by AM. Despite limitations, the high Young moduli, better mechanical properties, low surface integration, high level of corrosion resistance, and antibacterial properties make them unparallel for use in anatomical structures [Zhang 2016].

4.3 Automotive Sector

It is understood that the SLM method has the potential to make an impact in the development of materials and design flexibility in the automotive industry. Recent research on soft magnetic alloys has focused on using SLM to produce these alloys for electric motor powering in gas-electric hybrid and fully electric cars. The method is a possible alternative to traditional production, as it allows for new motor shapes and better magnetic and thermal properties.

In one such examination, the metal powders that were used as raw materials were gas-atomized with a range of sizes of 15 µm to 45 µm. Three soft magnetic alloys, such as 430L stainless steel, Fe50Ni, and Fe6Si, were chosen and examined with respect to their density, microstructure, and magnetic and electrical characteristics. Although it has advantages, It has specific challenges like porosity, cracking of material, vaporization of alloying, and generation of residual stresses. To overcome these problems, the study was able to identify the optimal parameters involved in each of the alloys to minimize the number of defects during fabrication [Yakout 2019].

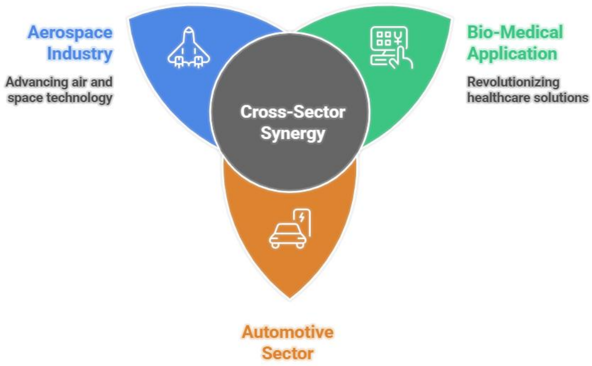

Figure 4 Applications of Selective Laser Melting (SLM) technology across various industries

5 ADVANTAGES AND LIMITATIONS OF SLM

SLM, also known as Selective Laser Melting, is an advanced additive manufacturing process that enables the production of complex and high-performance metal parts directly from digital models. Among the most substantial benefits of SLM is that it achieves very intricate geometries with very high precision, which makes it ideal to be used in aerospace, medical, and automotive sectors. It has excellent material use with minimal wastage, and it is fast to prototype and customize. Also, SLM can have very close to full density metallic components, which are at times comparable to or superior to more conventionally made components.

Nevertheless, SLM is also constrained. It may prove costly and time-consuming, especially when equipment and materials used are expensive. SLM is parameter-sensitive; any incorrect combination of the parameters can cause defects such as porosity, residual stresses, or micro-cracks. Heat treatment and surface finishing may be necessary as post-processing. Materials suitable for SLM are limited, although their range has expanded over the years. Additionally, the powder requires rigorous safety precautions due to its potential to contaminate and burn. Common defects in aluminium, stainless steel and titanium alloys are porosity, cracking and residual stress. Aluminum is often porous due to poor laser absorption; stainless steel can develop keyhole pores; and titanium due to its low level of thermal conductivity has a high level of residual stress and cracking because of rapid solidification and high thermal gradients.

6 FUTURE TRENDS AND RESEARCH DIRECTIONS

The main research directions in Selective Laser Melting (SLM) include enhancing process stability, developing new alloy systems, and achieving superior mechanical properties through optimized scanning strategies and post-processing methods. Another area of research involves multi-material printing, real-time process monitoring, and AI-based parameter optimization to achieve higher reliability and efficiency. SLM will significantly spill over to wider industrial applications in the coming years, with increased adoption in aerospace, medical implants, and even automobiles. The focus will be on sustainability, cost savings, and coupling with digital manufacturing systems that would facilitate smarter, faster, and more custom metal part production.

7 CONCLUSION

It has proved to be a revolutionary manufacturing process that can make complex and multi-functional high-performance components in diverse industries. This study focuses on the (SLM) of aluminium, stainless steel, titanium, and nickel alloys offers high design flexibility, excellent mechanical properties, and near-net-shape fabrication. Aluminium shows poor laser absorption, stainless steel may develop keyhole pores, titanium suffers from high residual stress, and nickel alloys require precise process control to prevent microstructural inhomogeneity and surface roughness. Even though issues such as residual stress, porosity, and poor material compatibility exist, there are still ways to streamline the process and develop new materials to increase the capabilities of SLM. The next generation of work must also focus on enhancing material quality, process reliability, and cost-efficient processing to achieve wider industry acceptance of SLM technology.

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