Proceedings of the 4th International Conference on Applied Physics and Mathematical Modeling
DOI: 10.54254/2753-8818/2026.39493

The Application of 3D-printing Technology in Engineering Manufacturing

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Abstract. Additive manufacturing, commonly known as 3D printing, has become an important manufacturing approach for producing complex geometries, customised components, prototypes, and low-volume parts directly from digital models. This paper reviews the basic principles, major process categories, engineering applications, and current limitations of 3D printing in modern manufacturing. Four representative technologies—Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Laser Powder Bed Fusion (LPBF, often referred to as SLM)—are compared in terms of material systems, forming mechanisms, accuracy, surface quality, support requirements, mechanical performance, post-processing, cost, and suitable applications. Their use in automotive engineering, aerospace manufacturing, mechanical equipment production, tooling, prototyping, and small-batch functional components is further discussed. The analysis shows that additive manufacturing provides clear advantages where geometric complexity, rapid iteration, customisation, and tooling reduction are important. However, equipment and material costs, limited printable material ranges, process-induced defects, anisotropic properties, quality-control challenges, and extensive post-processing continue to restrict broader industrial adoption. Therefore, additive manufacturing is more appropriately regarded as a complementary technology to conventional machining, casting, and mould-based manufacturing rather than a universal replacement.

Keywords: Additive manufacturing, 3D printing, engineering manufacturing, process comparison, industrial applications

1. Introduction

It is commely that referred to as additive manufacturing, 3D printing provides a viable industrial pathway to fabricate solid three-dimensional components based on digital geometric models. Its core mechanism relies on depositing materials layer by layer. Subtractive processes such as cutting, drilling and grinding work in the opposite way: they start from a solid blank and remove material until the target geometry remains. Mould-based manufacturing has its own drawbacks. It often produces considerable material waste, takes a long time to develop new products, and becomes less flexible when the required batch is small or the geometry is complex. At high production volumes, however, mould-based routes usually remain cheaper than additive routes [1].

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Additive manufacturing is usually chosen when customisation or geometric complexity matters more than unit cost. It is less competitive when speed, surface finish and material range are the main constraints. Printing speed is limited, equipment investment is high, and the material portfolio is narrower than in conventional manufacturing. Mechanical anisotropy, rough as-built surfaces and post-processing are common problems. Additive, subtractive and mould-based routes therefore serve different application spaces. None is universally better [2].

In mechanical production, automotive engineering, aerospace and mould development, 3D printing is now widely used for prototype validation and small-batch production. Its main advantages are mould-free forming, relatively low material consumption and flexible customisation. These features support the digital and refined transformation of manufacturing sectors worldwide [3].

2. Basic principles of 3D printing

Most industrial 3D printing processes follow the same underlying logic: a 3D digital model is sliced into numerous thin layers, and the physical component is built by stacking these sliced profiles. The operational details differ from process to process. Forming strategies, support removal, powder cleaning, heat treatment and post-processing all vary. The workflow described below is therefore a general one; it does not apply equally to every additive process. A typical job moves through four stages: digital modelling, slicing, automatic layer forming and post-processing [4].

The first step is to build an accurate 3D model of the target component in professional modelling software. This model provides the dimensional and structural data for printing. After inspection and repair, slicing software cuts the model into a series of continuous 2D horizontal layers. Layer thickness is a key parameter. It affects both dimensional accuracy and surface finish. Other factors also matter: laser spot or nozzle size, scanning settings, material shrinkage, machine hardware precision and post-treatment operations all contribute to the final result [5].

Once slicing is complete, the printer control system reads the path data and builds the part layer by layer. Fabrication usually starts from the bottom of the component. After one layer is formed and bonded, the build platform moves by a distance equal to the set layer thickness, and the next layer is deposited. This cycle repeats until the solid part is complete. From an industrial point of view, this material-deposition logic is the main feature that separates additive manufacturing from traditional subtractive machining [6].

Different materials need different consolidation mechanisms. Thermal melting, UV curing and laser-induced powder fusion are common examples. The purpose is the same: reliable interlayer bonding and sufficient structural density. Post-processing depends on the process. Vat photopolymerisation parts usually need support removal, surface polishing and secondary curing. Powder bed fusion parts need powder cleaning. Metal parts often require stress-relief heat treatment and secondary machining. FDM parts normally do not need secondary curing. These steps bring printed components closer to industrial assembly and service requirements. With this working principle, 3D printing is well suited to prototype research, personalised part manufacturing and components with complex internal cavities [7].

3. Common types of 3D printing technologies in engineering manufacturing

Additive manufacturing has mature standard classification systems. This section compares four widely used representative technologies: FDM, SLA, SLS and SLM. FDM belongs to material extrusion. SLA belongs to vat photopolymerisation. SLS and SLM both belong to powder bed

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fusion. In current metal additive manufacturing literature, Laser Powder Bed Fusion (LPBF) is the general term for metal powder bed fusion, while SLM remains a common engineering synonym for the same metal process [8].

Each process has its own preferred materials, forming mechanism and application range. The comparison below uses consistent criteria: material system, forming accuracy, as-built surface finish, support requirements, mechanical properties, production speed, post-processing workload, cost and typical application scenarios [9].

FDM is the cheapest of the four. A heated nozzle pushes a thermoplastic filament onto the build plate, and the material hardens as it cools. PLA and ABS are the usual choices. Nothing about the setup is complicated: desktop machines are common, operating cost is low, and the working environment does not need special control. That is why FDM is widely used for concept models, jigs and structural checks [10]. The trade-off is surface quality. Layer lines are visible, and the Z-direction strength is usually lower than the in-plane strength. Machine grade, nozzle size and parameter settings all affect the final result, so quality can vary a lot between setups.

SLA is the opposite case. It is chosen for accuracy, not cost. A UV laser scans the surface of a liquid resin bath, and the exposed areas cure into thin solid layers. The build platform moves relative to the exposure plane to set the layer thickness; this can be arranged top-down or bottom-up. Dimensional accuracy and surface finish are both better than FDM, and small features can be reproduced reliably. Precision mould prototypes and micro-mechanical samples are typical uses. The weak point is the resin itself [9]. General-purpose resins give moderate strength and limited heat resistance, so they are mainly used for model validation. Engineering-grade, heat-resistant or toughened resins can produce functional parts, but the mechanical and thermal performance depends heavily on the formulation.

SLS behaves differently because of the powder bed. A laser scans across a spread layer of polymer powder, and local energy causes partial melting, particle coalescence and solidification. Un-melted powder around the part stays in place and acts as support, so no separate sacrificial structure is needed. This is the key advantage. Hollow features, nested geometries and closed internal cavities can be built as one piece. Ceramic and composite powders are also used, but they need separate process optimisation. Under tuned parameters, SLS polymer parts have good toughness and stable mechanical performance, which makes them suitable for automotive sub-components, transmission parts and functional prototypes [10].

LPBF, often called SLM, is the metal version of powder bed fusion. The mechanism is not partial melting. A higher-power laser fully melts metal powder such as stainless steel, aluminium alloy or titanium alloy, and the molten metal solidifies into a metallic matrix. Full melting does not remove all defects. Internal pores, residual stress, microstructure anisotropy and rough as-built surfaces can still appear, and post-printing heat treatment is often required. Whether the final part meets service standards depends on material selection, parameter optimisation, in-situ monitoring and post-processing strategy. Aerospace and precision machinery are the main application areas, because the process can produce complex metal components that are difficult to make by cutting or casting.

In short, FDM, SLA, SLS and LPBF (often called SLM) cover plastic prototypes, high-precision resin models, functional polymer parts and high-strength metal components. Each process fits a specific application scenario. Their complementary performance expands the application boundary of additive manufacturing in modern engineering and drives the continuous upgrade of manufacturing paradigms.

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4. Applications of 3D printing in engineering manufacturing

Growing market demand for low-volume customised parts, intricate structural workpieces and accelerated product iteration has pushed 3D printing into wider industrial adoption. In most cases, it acts as a supplement to conventional manufacturing rather than a full replacement. Four application categories should be distinguished: prototypes, tooling fixtures, non-critical functional parts and certified load-bearing components [11]. Each category has different requirements for material performance, process stability, quality assurance and formal certification.

In the automotive industry, additive manufacturing is commonly used for custom jigs, fixtures, test prototypes and a small number of non-critical functional subcomponents. Certified load-bearing parts are still mainly produced by traditional forming methods. During new vehicle R&D, engineers can print lightweight intake prototypes, cooling system test samples and interior structural specimens using FDM, SLS or LPBF(SLM). These are mostly prototypes and non-critical demonstrators. They help with assembly fitting and preliminary performance testing, and they can shorten component iteration cycles to some degree [12]. For small-batch special vehicles, polymer SLS can produce non-critical parts with complicated hollow structures. Most certified core load-bearing automotive components still rely on casting and forging. Production cost, mass production efficiency, long-term reliability and strict automotive certification standards are the main reasons.

Aerospace is one of the fields with high application potential for metal additive manufacturing. LPBF (SLM) can produce metal parts with intricate internal flow channels, topology-optimised shapes, lattice structures and integrated multi-feature components. Weight reduction is not an inherent advantage of LPBF itself. The lightweight effect comes from greater design freedom: topology optimisation, lattice filling, part consolidation and integrated internal flow channel design. Material and structural performance must still be maintained. Typical examples include partial auxiliary turbine engine demonstrators, bracket prototypes and custom connector samples for spacecraft. Almost no as-printed parts can be directly used as certified airborne load-bearing hardware. Aerospace components face strict quality verification. Even if geometry conforms to design drawings, printed workpieces usually need multiple rounds of non-destructive testing, stress-relief heat treatment and surface modification before formal service evaluation. Parts can only be used in real airborne equipment after passing full reliability assessment and aerospace certification. Many current aerospace applications remain limited to prototypes, tooling and secondary non-flight-critical components.

For general mechanical equipment production, 3D printing offers practical solutions for special-shaped parts, spare part reproduction and low-volume non-standard components. For ageing equipment whose original moulds are lost, additive manufacturing can produce replacement spare parts from reverse-engineered digital models. This reduces inventory pressure for rarely used accessories. Light-curing technologies such as SLA are widely used to make precision test parts for mechanical assemblies to verify gap matching. When production orders grow to large batch sizes, traditional moulding and machining usually achieve better economic benefit.

5. Conclusion

Equipment and consumable costs remain the first barrier. High-performance LPBF metal printers require large upfront investment. Special polymer powders, photosensitive resins and alloy powders also cost more per kilogram than common casting and machining stock. For mass production, the unit cost of additively manufactured parts usually cannot compete with conventional processes.

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Desktop printers are cheap to buy, but their output quality is not enough for most heavy-duty industrial work. The gap between low-cost hardware and real engineering demands is still wide.

Material availability is the second barrier. The range of printable materials is narrower than the range available for subtractive and formative manufacturing. Many high-strength, high-temperature-resistant and corrosion-resistant engineering materials are not yet fully compatible with mainstream additive workflows. Even for materials that can be printed, batch fluctuations in powder quality, resin stability and filament uniformity can cause inconsistent final part performance. In most cases, users can only choose from commercially mature grades rather than customising a material system for a specific working condition.

Quality control in metal LPBF is the third barrier, and it is the hardest to solve. Process parameters, transient melt pool stability, pore generation, residual stress evolution and microstructure are tightly coupled. A small change in scanning strategy, laser power, powder quality or chamber environment can shift defect density and microstructural features, which then changes mechanical properties. This coupling makes stable batch-to-batch performance and formal engineering certification difficult. Hardware upgrades or post-processing optimisation alone cannot fully address it.

Uncertainty in as-printed part performance is the fourth barrier. Different processes produce different defect types. FDM parts may suffer weak interlayer bonding and mechanical anisotropy. SLA resin components tend to degrade under long-term light and thermal exposure. SLS and LPBF parts may contain internal pores, unfused zones and residual stress. These defects are not always visible from the outer surface. Mechanical properties vary by direction, and batch performance can drift with slight changes in machine status and process parameters. Applications that need stable, predictable long-term service performance are therefore difficult to serv.

Post-processing is the fifth barrier, and it adds both labour and uncertainty. Most printed parts cannot meet assembly requirements right after printing. Support removal, surface polishing, stress-relief heat treatment and chemical surface modification are common steps. Some metal parts also need secondary machining to reach the required dimensional tolerance. Post-processing consumes extra time and labour, and improper handling can introduce new damage or dimensional error. Automation in this area remains limited in many manufacturing sites.

In practice, additive manufacturing is likely to stay a complement rather than a general replacement. Its strongest position is where geometry is complex, batch size is small, tooling cost is high or customisation is essential. Injection moulding, casting and subtractive machining still dominate when volumes are large and unit cost is the main concern. Advances in equipment, materials, process parameter optimisation, in-situ quality monitoring and post-processing automation may widen the application window, but they will not remove all current constraints.

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