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A Comprehensive Review of Additive Manufacturing Technologies: Processes, Materials, Applications, Design Optimization and Future Trends

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ABSTRACT :

Additive manufacturing (AM), also known as 3D printing, direct digital manufacturing or freeform fabrication, builds an object from three-dimensional model data by joining material, usually layer upon layer, in contrast to subtractive manufacturing in which material is removed from a solid block. The reviewed literature shows that AM has grown from a rapid-prototyping technique for visual models into a family of processes that can produce functional metal, polymer, ceramic-composite and biomedical parts, while its wider industrial use is still limited by accuracy, surface quality, material availability, process repeatability, qualification cost and build speed.This report reviews seven research papers published between 2012 and 2026. They cover a general review of AM processes and applications, a review of metal additive manufacturing, the role of AM in Industry 4.0, design for additive manufacturing through conformal cooling channels, AM and 3D bioprinting for biomedical use, recycling of waste metallic powder through cold spray additive manufacturing, and the deformation of carbon-fibre-reinforced PEEK parts that are converted into ceramic matrix composites. The literature shows a progression from process classification and metallurgy toward design optimisation, sustainable feedstock, biomedical applications and prediction of the complete process chain.Overall, the seven reviewed papers indicate that the quality of an additively manufactured part depends on materials, process, design and post-processing together. Powder-bed, powder-feed and wire-feed systems give different compromises between resolution, build volume and deposition rate; microstructure and defects control the mechanical and fatigue behaviour of metal parts; and design tools such as topology optimisation and conformal cooling allow geometries that conventional machining cannot produce.Across the studies, specific results are reported. Additively manufactured Ti-6Al-4V can reach static strength comparable to wrought material, and hot isostatic pressing raised the fatigue strength of ARCAM-produced material in the X-Y orientation by 27% over the as-fabricated condition. A serpentine conformal cooling channel brought the monitored temperature on a thermoforming mould base to 21.1 °C, against 30.3 °C for the original design. Recycled metallic powders produced cold spray deposits with porosity below 2%, deposition efficiency above 70% and an estimated cost reduction of about 30%. For carbon-fibre-reinforced PEEK, the total shrinkage from the printed polymer part to the final C/C-SiC component was 26.13% in the z-direction and 5.32% in the x-y direction, and a pre-oversized CAD model gave a final part of 75.28 mm × 7.79 mm against a 75 mm × 8 mm target.

Keywords: Additive Manufacturing (AM), 3D printing, powder bed fusion, directed energy deposition, metal AM, Industry 4.0, design for additive manufacturing, conformal cooling, bioprinting, cold spray, ceramic matrix composites.

1. INTRODUCTION

1.1 Background of Manufacturing and Additive Manufacturing

Most engineering components have traditionally been produced by subtractive processes such as machining, in which material is cut away from a solid block, or by forming and casting processes that need dedicated tooling. Subtractive methods are often time-consuming, generate waste material and restrict the shapes that can be designed [5]. Additive manufacturing (AM) reverses this approach. ASTM defines AM as a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, and the definition applies to metals, ceramics, polymers, composites and even biological systems [2].

The first layer-by-layer use of computer-aided design (CAD) was rapid prototyping, developed in the 1980s to create models and prototype parts [1]. Technologies now called 3D printing all originate from rapid prototyping, and with advances in plastic materials they have moved from models to finished products. Wohlers' 2011 report quoted in the literature gives an average growth rate of 26.2 percent for the industry from its beginning until 2010 [1]. Rapid manufacturing also became possible because of related technologies such as CAD, computer-aided manufacturing (CAM) and computer numerical control (CNC) [1].

1.2 Additive Manufacturing Technology

AM is a digital manufacturing route. A CAD model is converted into a file that describes the surface by small triangles, the file is sliced into thin layers, and a machine then deposits, cures, fuses or bonds material to form each layer. The reviewed papers show that this common principle is realised by many different processes. Dilberoglu et al. group the processes into material extrusion, vat photopolymerization, material jetting, binder jetting, powder bed fusion, direct energy deposition and sheet lamination, as shown in Figure 1 [3].

Frazier describes AM as a technology with the potential to change the global parts manufacturing and logistics landscape, because it enables distributed manufacturing and parts on demand while offering potential reductions in cost, energy consumption and carbon footprint [2]. In the context of Industry 4.0, AM is regarded as an essential physical technology for smart factories because it supports mass customisation and the production of sophisticated shapes and new material combinations [3].

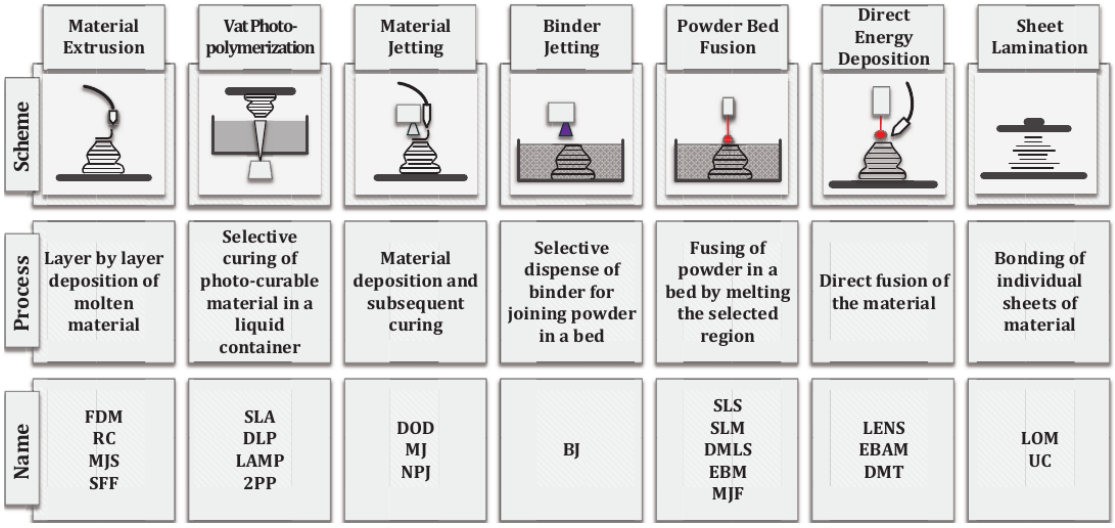


Figure 1. Categorisation of additive manufacturing processes [3]

1.3 Need for Additive Manufacturing

The literature identifies several reasons why AM is attractive compared with conventional manufacturing. These benefits are strongest for complex, customised or low-volume parts, and weaker for the mass production of simple parts.

- Design freedom: complex shapes, internal passages, hollow and lightweight structures can be built that are difficult or impossible to machine [1][2][3].
- Customisation: patient-specific implants, prosthetics and one-off products can be produced directly from digital data [3][5].
- Parts on demand: distributed manufacturing can shorten supply chains and reduce logistics and inventory costs [2].
- Material efficiency: material is added only where required, and waste powder can be recycled or reused [1][6].
- Rapid development: physical models and functional prototypes shorten the product development cycle [1].
- Repair and refurbishment: directed-energy processes can add material to worn or damaged components [1][2].

1.4 Working Principle and Process Chain

The AM process chain starts with a 3D CAD model, which is converted to the STL (Standard Tessellation Language) format created in 1987 for stereolithography. The STL file approximates the continuous geometry with triangles, and the smaller the triangles the closer the file is to the real surface [1]. The model is then sliced into layers. Slicing replaces the continuous contour with discrete stair steps, so layer thickness directly influences accuracy and surface finish, and Wong and Hernandez recommend designing z-dimensions as multiples of the layer thickness [1].

After building, most parts need post-processing. Metal parts may require stress relief, hot isostatic pressing (HIP), machining or surface finishing [2], resin parts need draining and curing [1], and ceramic-matrix composites made from printed polymer preforms require crosslinking, pyrolysis and silicon infiltration [7]. The final quality of the part therefore depends on the whole chain: design, file preparation, process parameters, feedstock, build orientation and post-processing.

2. LITERATURE REVIEW

2.1 Review of Selected Research Papers

1. A Review of Additive Manufacturing — Wong and Hernandez (2012)

This review explains how a CAD drawing is converted to an STL file and sliced into layers, and then discusses the main AM processes: stereolithography (SL), Polyjet, fused deposition modelling (FDM), laminated object manufacturing (LOM), three-dimensional printing (3DP), Prometal, selective laser sintering (SLS), laser engineered net shaping (LENS) and electron beam melting (EBM). It reports applications in the aerospace industry, where lighter structures reduce weight, in architecture, in medicine and dentistry, in fuel-cell manufacture, in art and for hobbyists. The paper concludes that not every commonly used manufacturing material can be handled and that accuracy must improve to remove the need for finishing.

2. Metal Additive Manufacturing: A Review — Frazier (2014)

Frazier reviews metal AM from the viewpoint of material science, processes and business considerations. Equipment is classified as powder bed, powder feed and wire feed systems. The paper discusses rapid solidification, columnar grain growth and repeated thermal cycling in Ti-6Al-4V, the static and fatigue properties of Ti-6Al-4V, Inconel 625 and Inconel 718, the effect of porosity and surface roughness on fatigue, the need for process control, standards, qualification and certification, and the cost comparison of AM with conventional fabrication. It concludes that a paradigm shift is required to exploit AM fully.

3. The Role of Additive Manufacturing in the Era of Industry 4.0 — Dilberoglu et al. (2017)

This paper reviews AM within the framework of Industry 4.0 and focuses on materials, processes and design. It discusses metal AM, smart (4D printing) materials such as shape-memory alloys and polymers, printable hydraulics and electronics, and special materials such as concrete, textile, food and lunar dust. Among processes it covers powder bed fusion, direct energy deposition, wire and arc additive manufacturing (WAAM), nanoparticle jetting, atomic diffusion additive manufacturing and single pass jetting, as well as hybrid additive-subtractive manufacturing. In design, it reviews design for additive manufacturing (DfAM), topology optimisation and file formats.

The first three papers establish the basic principle, the metallurgical behaviour and the industrial context of additive manufacturing. The following four papers extend this progression toward design optimisation, biomedical use, sustainable feedstock and the prediction of deformation in a complete process chain.

4. Design for Additive Manufacturing: Thermoforming Mold Optimization via Conformal Cooling Channel — Tomasoni et al. (2020)

Tomasoni et al. study the cooling system of a thermoforming mould made of an aluminium base, an ABS cooler and an aluminium matrix. Three new cooling-channel geometries (serpentine, rectangular and tank) are compared with the traditional channel in virtual experiments using the CFD software Altair AcuSolve. The serpentine channel with a circular section of 7 mm diameter gave the best and most uniform cooling and was selected for comparison with the original design, together with a redesigned channel in the base.

5. Additive Manufacturing (AM) and 3D Bioprinting for Biomedical Application: Understanding the Drivers, Barriers and Technology Trends — Onu et al. (2025)

Onu et al. compare AM and 3D bioprinting for biomedical applications. AM techniques such as stereolithography, selective laser sintering and fused deposition modelling are used for patient-specific implants, prosthetics and surgical models, while bioprinting deposits bioinks containing living cells for tissue engineering, disease modelling and drug testing. The paper identifies drivers such as customisation and rapid prototyping and barriers such as limited biomaterials, regulation, high investment, scalability, sterilisation, vascularisation and cell viability.

6. Sustainable Recycling of Waste Metallic Powder Particles via Cold Spray Additive Manufacturing Technology — Singh et al. (2026)

Singh et al. propose recycling cold spray overspray powder and grinding swarf into feedstock for cold spray deposition. A multi-stage process of screening, segregation, blending and milling was applied to powders of stainless steel 316L, titanium, copper and aluminium. Three coatings and two thick deposits of about 7–8 mm were produced on an Al-6061 substrate and characterised by microscopy, microhardness and scratch testing. The coatings had porosity below 2%, deposition efficiency above 70%, higher hardness than the substrate and lower wear rates.

7. Additive Manufacturing of Ceramic Matrix Composites Based on Carbon Fiber Reinforced PEEK by Material Extrusion Technology: Design Based Deformation Mechanisms — Freudenberg et al. (2026)

Freudenberg et al. follow a gear wheel from material extrusion of carbon-fibre-reinforced PEEK (CF-PEEK) through thermal crosslinking, pyrolysis and liquid silicon infiltration to a C/C-SiC ceramic matrix composite. Four shape-stability criteria are defined and three deformation categories are identified: unavoidable shrinkage-induced deformation, distortion caused by internal stress, and severe shape loss due to insufficient gas release during pyrolysis. Finite element simulation qualitatively predicted the deformation, and an optimised slicing strategy with a pre-oversized CAD model gave a final part close to the target dimensions.

2.2 Comparative Literature Table

Paper	Main focus	Method / system	Key outcome
Wong & Hernandez (2012)	General AM review	SL, FDM, 3DP, SLS, EBM, LENS, LOM, Polyjet	Wide applications; materials and accuracy still limited
Frazier (2014)	Metal AM	Powder bed, powder feed and wire feed systems; Ti-6Al-4V, IN625, IN718	Static properties comparable to wrought; defects control fatigue; qualification is a barrier
Dilberoglu et al. (2017)	AM in Industry 4.0	Materials, metal and hybrid processes, DfAM	AM is a key physical technology for smart factories
Tomasoni et al. (2020)	Conformal cooling design	CFD of four mould cooling geometries	Serpentine channel gave 21.1 °C vs 30.3 °C at the monitored point
Onu et al. (2025)	Biomedical AM and bioprinting	SLA, SLS, FDM, inkjet, extrusion, laser-assisted bioprinting	Drivers, barriers and trends identified
Singh et al. (2026)	Powder recycling	Cold spray of recycled SS316L, Ti, Cu, Al powders	Porosity < 2%; DE > 70%; about 30% lower cost
Freudenberg et al. (2026)	CMC from printed CF-PEEK	Material extrusion, pyrolysis, liquid silicon infiltration, FEM	Shrinkage 26.13% (z) and 5.32% (x-y); near-net-shape part

2.3 Problem Statement

Additive manufacturing offers freedom of design, customisation and reduced material use, but a part produced by AM is not automatically equal to a part produced by a mature conventional process. Layer-by-layer processing introduces stair-step surfaces, porosity, anisotropy, residual stress and deformation, and the properties depend on the machine, the feedstock and the thermal history of the build. For safety-critical use, qualification and certification are costly and time-consuming.

The engineering problem is therefore to select a suitable process, material and design so that the benefits of AM are obtained while accuracy, mechanical performance, cost and sustainability requirements are met. The literature moves from the description of processes toward metallurgical understanding, design optimisation, sustainable feedstock and prediction of process-induced deformation.

2.4 Research Objectives

- Explain the working principle and process chain of additive manufacturing.
- Identify and compare the major AM processes and equipment types.
- Examine the materials, microstructure and mechanical properties reported for AM parts.
- Study design-for-additive-manufacturing and process-planning approaches reported in the literature.
- Compare measured and simulated evidence of performance improvement from the reviewed case studies.
- Identify practical limitations and future directions for additive manufacturing.

2.5 Research Gap

The reviewed papers address different layers of the same problem. The early reviews classify processes and applications, while later studies investigate metallurgy, optimise a specific design, extend AM to biomedical devices, make powder feedstock sustainable and predict deformation through a multi-step process chain. A continuing gap is the need for process control and qualification methods that give consistent quality from machine to machine, together with design rules that are available to engineers who have limited AM experience. Frazier identifies in-process sensing and closed-loop control as a priority, and Dilberoglu et al. note the lack of design knowledge and standards [2][3].

The more recent papers strengthen this gap by showing that AM performance is not only a machine problem. Cooling-channel geometry [4], feedstock quality and reuse [6], slicing strategy and infill [7] and regulatory and biomaterial constraints [5] must all be considered together. A useful future direction is therefore a coordinated approach in which design, material, process parameters and post-processing are planned together rather than optimised independently.

3. ADDITIVE MANUFACTURING TECHNOLOGY

3.1 Basic Working Principle

In every AM process the part is built by adding material in successive layers according to the sliced CAD model. The processes differ in the form of the feedstock (liquid resin, powder, wire, filament or sheet) and in the way the layer is formed, such as photopolymerisation, melting, sintering, binding or bonding. Wong and Hernandez classify the processes as liquid-based, solid-based or powder-based, and consider liquid-based and powder-based processes the most promising for the future [1].

3.2 Main Process Categories

- Material extrusion: a heated filament is extruded through a nozzle and deposited layer by layer, as in fused deposition modelling (FDM).
- Vat photopolymerisation: a laser or light source selectively cures photosensitive liquid resin, as in stereolithography (SL/SLA).
- Material jetting: droplets of photopolymer are deposited and cured, as in Polyjet and nanoparticle jetting.
- Binder jetting: a liquid binder is jetted onto a powder bed, as in 3DP and Prometal.
- Powder bed fusion: a laser or electron beam melts or sinters selected regions of a powder bed, as in SLS, SLM and EBM.
- Directed energy deposition: material is fed to a focused energy source and fused as it is deposited, as in LENS and WAAM.
- Sheet lamination: sheets of material are bonded and cut to the layer contour, as in laminated object manufacturing (LOM).

3.3 Metal Additive Manufacturing Equipment

Frazier classifies commercial metal AM systems as powder bed, powder feed and wire feed systems, according to the feedstock; the energy source can be an electron beam, a laser or an arc [2]. In a powder bed system, powder is raked across the work area and the beam melts or sinters it into the desired shape, after which another powder layer is added. These systems produce high-resolution features and internal passages and maintain dimensional control, but their build volumes are limited (Figure 2) [2].

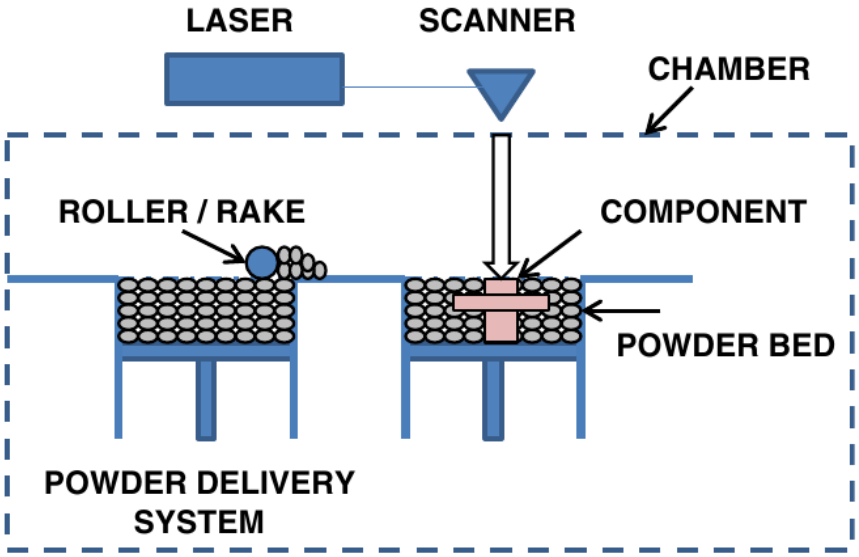


Figure 2. Generic illustration of an AM powder bed system. Source: Frazier [2], Fig. 1.

In powder feed systems, powder is conveyed through a nozzle onto the build surface and melted by a laser (Figure 3). Their build volumes are generally larger than those of powder bed units (more than 1.2 m^3 is quoted for one LENS unit), they scale up more easily, and they can be used to refurbish worn or damaged components. Wire feed systems use wire as feedstock with an electron beam, laser or plasma arc; they have a high deposition rate and large build volumes, but the fabricated product usually requires more extensive machining [2].

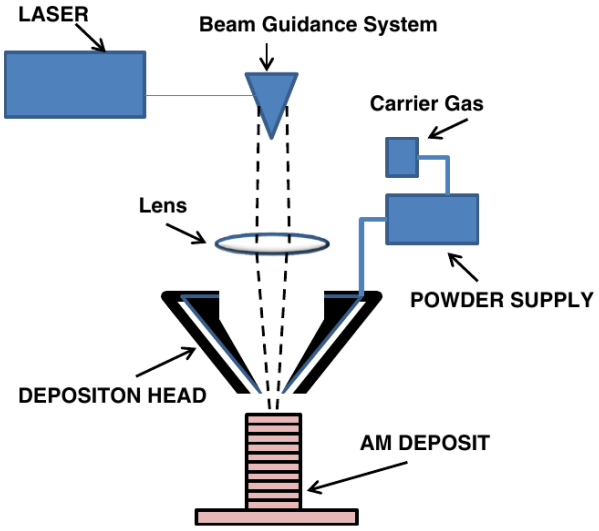


Figure 3. Generic illustration of an AM powder feed system. Source: Frazier [2], Fig. 2.

3.4 Stereolithography

Stereolithography was developed by 3D Systems and was the first and most widely used rapid-prototyping process. It is a liquid-based process in which an ultraviolet laser cures a photosensitive polymer; the platform is lowered after each layer and, when the part is finished, the excess resin is drained and can be reused (Figure 4) [1]. The basic principle is photopolymerisation, in which a liquid monomer or polymer is converted to a solid polymer by ultraviolet light. A newer microstereolithography version achieves layer thicknesses below 10 μm [1].

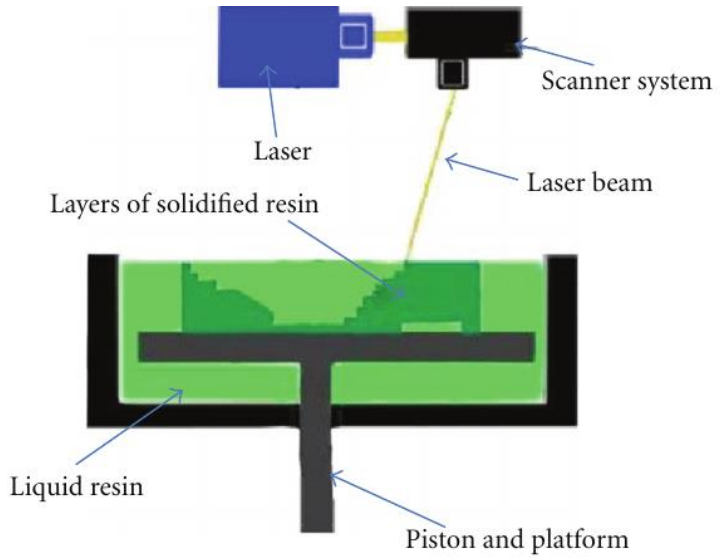


Figure 4. Stereolithography process. Source: Wong and Hernandez [1]

Typical errors in the process include overcuring of overhanging parts, the scanned line shape, and variable layer thickness because the resin is viscous. Several materials can be printed in one part (multiple-material stereolithography), but the resin must be drained and replaced when the material changes [1].

3.5 Other Polymer, Powder and Sheet Processes

- Fused deposition modelling: a thin plastic filament is melted and extruded at a typical thickness of 0.25 mm. It needs no chemical post-processing or resin curing and the machine is less expensive, but the z-resolution is low and large complex parts may take days [1].
- 3DP and Prometal: a binder is jetted onto a powder bed. Prometal builds injection tools and dies from stainless steel powder, followed by sintering and bronze infiltration to obtain a functional part [1].
- Selective laser sintering: a laser fuses powder layer by layer; plastics, metals and their combinations can be used and unused powder can be recycled, but accuracy is limited by particle size and the process needs an inert atmosphere [1].
- Electron beam melting: a high-voltage electron beam (typically 30 to 60 kV) melts metal powder in a vacuum chamber and is suited to metal parts [1].

- Laser engineered net shaping: metal powder is injected into a laser melt pool; it can also repair parts, but residual stress from uneven heating and cooling can be significant [1].
- Laminated object manufacturing: sheets are bonded and cut by laser. It has low cost and needs no supports, but material is wasted and complex internal cavities are difficult to build [1].
- Polyjet: inkjet heads deposit photopolymer cured by ultraviolet lamps, with a layer thickness of 16 μm and multi-colour capability, although the parts are weaker than SL or SLS parts [1].

3.6 Emerging Metal Processes

Dilberoglu et al. describe several recent metal AM processes. Wire and arc additive manufacturing (WAAM) combines arc welding with wire feeding and can produce very large components from weldable metals, which makes it attractive for the aerospace industry. Nanoparticle jetting (NPJ) jets metal nanoparticles in a liquid medium to form thin layers and is claimed to give the best surface finish among metal AM processes. Atomic diffusion additive manufacturing (ADAM) prints metal powder held in a plastic binder, after which the binder is removed and the whole part is sintered. Single pass jetting (SPJ) combines powder deposition, compaction and binder jetting in a bidirectional pass and is claimed to be about one hundred times faster than regular laser-based processes [3].

4. MATERIALS, DESIGN AND PROCESS PLANNING

4.1 Materials for Additive Manufacturing

Materials are central to the development of AM. Dilberoglu et al. group current research materials into metals (stainless steel, aluminium alloys, cobalt-base alloys, titanium and nickel-base alloys), smart materials, printable hydraulics and electronics, and special materials [3]. Metals are the most common engineering materials, and most commercial metal printers employ metal powders. Remaining issues include cost, production speed, tensile, fatigue and hardness behaviour, surface quality and homogeneous microstructure.

- Smart materials: shape-memory alloys, shape-memory polymers and piezoelectric materials allow 4D printing, in which the printed structure changes shape or properties with time or under a stimulus such as heat, light or water [3].
- Printable hydraulics and electronics: multi-material printing can deposit solid and liquid materials together or embed conductive circuits, so that working mechanisms such as soft grippers are produced in one stage [3].
- Special materials: concrete for construction, textiles, edible materials and lunar dust have been investigated for AM [3].
- Biocompatible materials: titanium, Ti-6Al-4V, CoCrMo and 316L stainless steel, polymers such as PEEK, PLA, PGA, PCL and PEG, and hydroxyapatite composites are used in implants and bioprinting [5].
- Composites: carbon-fibre-reinforced PEEK can be printed by material extrusion and converted to a C/C-SiC ceramic matrix composite [7].

4.2 Microstructure and Defects in Metal AM

AM is a layer-by-layer process in which a single layer is effectively cast on the previous one, giving complex, time-dependent temperature profiles. The alloy may experience repeated solid-state and liquid-solid transformations; for Ti-6Al-4V a notional thermal profile of one layer shows two liquid-solid and two alpha-beta transformations [2]. Cooling rates reported for the LENS process are 10^3 to 10^4 K/s, and about 10^4 K/s for selective laser melting [2].

The combination of rapid solidification, directional heat extraction and repeated thermal cycles produces columnar grains growing in the build direction, microstructural banding and anisotropy. Typical defects are micro-porosity (10–50 μm and below 1 vol.% in SLM Ti-6Al-4V) attributed to gas entrapment, and lack of fusion [2]. Because the microstructure depends on equipment, time between passes and part size, machine-to-machine variability must be understood and controlled.

4.3 Design for Additive Manufacturing

Design for additive manufacturing (DfAM) helps designers select process parameters such as cost, time, quality and CAD constraints. Dilberoglu et al. divide DfAM into general design frameworks, which guide inexperienced designers in choosing materials and processes, and objective-specific methods, mainly based on topology optimisation, which give the best shape for a requirement such as minimum weight at a given stiffness [3]. Other work optimises slice thickness, build orientation and support structures, and new file formats such as AMF and 3MF address the limitations of the STL format [3].

Conformal cooling is a good example of design freedom in AM. Cooling channels that follow the shape of the mould are difficult to machine but can be built directly by AM. Earlier studies cited by Tomasoni et al. report that conformal channels reduced mould temperature by 9 °C and cycle time by 20% in injection moulding, and that lattice structures combined with conformal cooling reduced cooling time by 26% [4]. Because specific design rules for cooling channels do not yet exist, the authors compared the cooling performance of new channel geometries for a thermoforming mould (Figure 5) [4].

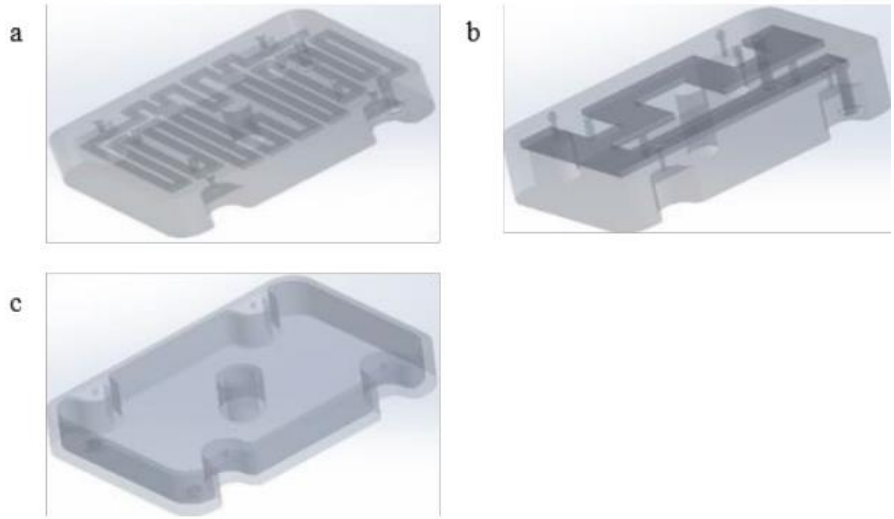


Figure 5. Redesigned cooler geometries: (a) serpentine, (b) rectangular and (c) tank. Source: Tomasoni et al. [4]

4.4 Hybrid Manufacturing and Industry 4.0

Hybrid manufacturing combines additive and subtractive processes, applied sequentially or in an integrated way, to improve dimensional accuracy and surface quality and to make features that a single process cannot produce. Reported examples include FDM followed by CNC machining, selective laser melting combined with precision milling, EBM combined with rapid CNC machining, and hybrid deposition with micro-rolling for metal aircraft parts [3].

Industry 4.0 links cyber-physical systems, the Internet of Things, big data and cloud computing to production. Dilberoglu et al. expect AM to benefit through real-time process control and inspection, decentralised production using cloud services, reduced waste through just-in-time production and a wider role for designers and users in manufacturing [3]. They also stress the need for standardisation and certification of AM processes.

4.5 Sustainable Feedstock: Recycling of Waste Powder

Powder production and overspray loss add to the carbon footprint of powder-based processes. Singh et al. recycle two waste streams, cold spray overspray with leftover powder in the feeder, and grinding swarf, into feedstock for cold spray deposition. The recovered powders are pre-sieved through a 120 µm mesh, ball milled, heat treated at 100 °C for 30 minutes to remove moisture, sieved again through a 53 µm mesh, heat treated once more and then loaded into the powder feeder (Figure 6) [6].

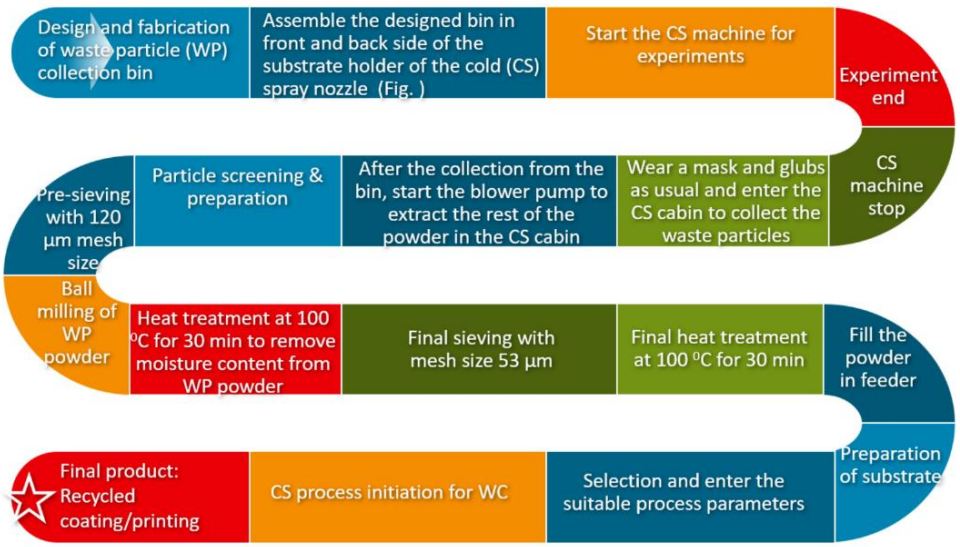


Figure 6. Process for recycling waste metallic particles through cold spray. Source: Singh et al. [6]

The approach converts waste into coatings and thick deposits, supports circular-economy principles and addresses a gap in earlier work, which mostly focused on a single waste source. The study notes that conventional gas- and water-atomised powders are costly, so powder derived from waste offers a low-cost alternative [6].

5. PERFORMANCE, RESULTS AND APPLICATIONS

5.1 Mechanical Properties of Metal AM Parts

Frazier concludes that, when properly processed, the static mechanical properties of AM metals are comparable to those of conventionally fabricated components. For Ti-6Al-4V, the yield and ultimate tensile strengths of AM material exceed typical wrought values, although ductility is slightly lower and there is anisotropy with respect to the build direction, the Z-direction generally being the weakest [2]. For Inconel 625, the as-fabricated ductility was equivalent to wrought and annealed material while the yield strength was 9% lower [2].

- The AMS 4999 specification for Ti-6Al-4V calls for post-AM thermal processing: HIP at nominally 100 MPa, or an anneal at about 913 °C for 2–4 h followed by furnace cooling [2].
- HIP removed residual porosity (pores below 50 µm attributed to argon entrapment) and improved properties; the fatigue strength of HIPed material in the X-Y orientation was 27% greater than as-fabricated [2].
- Surface finish affects fatigue: the sides of a build can be 2–3 times rougher than the top, and fatigue life decreased as surface roughness increased [2].
- Dynamic properties are dominated by defect structures, namely micro-porosity and surface finish, so properly HIPed and machined AM alloys can reach good fatigue performance [2].

Qualification is a major barrier. A conventional statistically substantiated database for aircraft structures can cost 8–15 million dollars, require 5,000 to 100,000 specimens and take more than two years, so accelerated qualification methods and in-process monitoring are needed [2].

5.2 Conformal Cooling Case Study

The thermoforming mould was simulated for 600 s with an initial temperature of 30 °C, coolant at 20 °C and velocity 0.15 m/s, and a heat flux of 100 W/m² applied as a step function of 30 s on and 30 s off. Among the three new geometries, the serpentine channel (7 mm circular section) gave the lowest temperatures, between 21.3 °C and 22.6 °C, and more than 80% of the cooler surface fell below 30 °C. The rectangular and tank geometries reached only 27.5–28.6 °C, and the tank design had filling problems [4].

The serpentine design with a redesigned base channel was then compared with the original cooling system (Table 1). At the monitored point on the base frame the temperature after 600 s was 21.1 °C, a reduction of 29.7% from 30 °C, whereas the original system stayed at 30.3 °C [4]. The authors point out that the mould worked for only ten minutes in the simulation while real use lasts eight consecutive hours, so the benefit is expected to be larger in practice.

Parameter	Original cooling	Serpentine cooling	Remark
Point 1 (base frame), temperature range	29.9–31.5 °C	20.8–30.3 °C	Strong cooling on heated frame
Point 1, temperature after 600 s	30.3 °C	21.1 °C	29.7% reduction from 30 °C
Point 2 (matrix), minimum temperature	28.6 °C	27.3 °C	4.5% lower
Point 2, slope of temperature curve	0.003	0.007	Faster cooling rate

Table 1. Comparison of original and serpentine cooling systems. Source: Tomasoni et al. [4].

5.3 Recycled Powder Coatings by Cold Spray

Coatings made from the recycled powders were dense, with porosity below 2%, and a deposition efficiency of more than 70% was achieved for the multi-material system. Thick deposits of about 7–8 mm were built from two powder sets, showing that recycled powder can build full-scale parts because of the high deposition rate of cold spray. The reuse approach could reduce cost by about 30% [6].

All coatings were harder than the Al-6061 substrate (110.92 ± 2.2 HV), and the coating containing grinding waste (Vacuum waste 1 + Grinding waste) was the hardest, which the authors attribute to hard oxide phases and the tamping effect of unbonded particles. Scratch tests at 20 N over 4 mm showed lower penetration depth and wear rate for every coating than for the substrate (Table 2) [6].

Sample	Hardness (HV)	Scratch depth (µm)	Wear rate ($mm^3/N \cdot m$)
Al-6061 substrate	110.92 ± 2.2	32.163	2.373×10^{-1}
Vacuum waste 1	200.6 ± 42.42	9.346	3.783×10^{-2}

Vacuum waste 1 + Grinding waste	254.44 ± 51.89	7.823	2.900×10^{-2}
Vacuum waste 1 + Vacuum waste 2	132.33 ± 8.8	18.662	1.060×10^{-1}

Table 2. Hardness and scratch-wear results. Source: Singh et al. [6].

5.4 Deformation in the CF-PEEK to Ceramic Composite Process Chain

Freudenberg et al. used a gear wheel to follow the modified liquid silicon infiltration (LSI) process shown in Figure 7: slicing, additive manufacturing by material extrusion, thermally induced crosslinking, ceramisation and characterisation. The motivation is that machining can account for up to 25% of the total cost of ceramic matrix composites, so near-net-shape production is desirable [7].

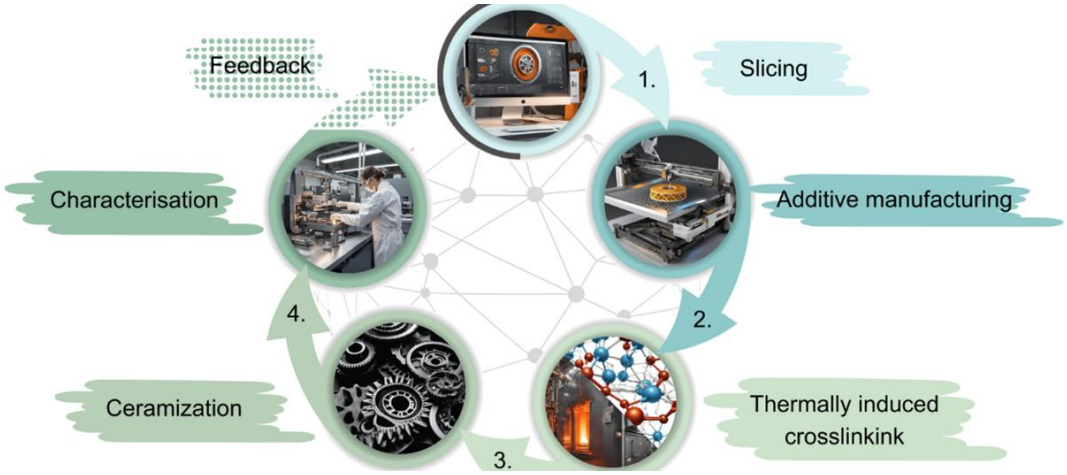


Figure 7. Modified liquid silicon infiltration (LSI) process chain. Source: Freudenberg et al. [7]

The fixed printing parameters were a layer height of 0.15 mm, two wall lines, a printing temperature of 410 °C, a build plate temperature of 50 °C and a printing speed of 25 mm/s, while infill and printing direction were varied (80% infill and a quasi-isotropic layer structure by default). Fibres hinder shrinkage in the printing plane, so shrinkage is anisotropic and highest in the z-direction. The highest shrinkage occurred during pyrolysis, and the total shrinkage from CFRP to the final C/C-SiC part was 26.13% in z and 5.32% in x-y [7].

Using these values, the CAD model was pre-oversized to a height of 10.83 mm (135% of the target) and a diameter of 79.21 mm (105% of the target). The final siliconised part measured 75.28 mm in diameter and 7.79 mm in height against the targets of 75 mm and 8 mm, demonstrating the efficacy of the reverse calculation method [7].

5.5 Biomedical Additive Manufacturing and Bioprinting

In biomedical use, SLA gives precise parts with smooth surfaces suited to dental and cranial implants, SLS fuses titanium powder into durable implants with porous structures that promote tissue ingrowth, and FDM produces patient-specific models for surgical planning [5]. Selective laser melting and electron beam melting were used with 3D-scanned data to make customised prosthetic components, for example a titanium alloy acetabular cup made by SLM [5].

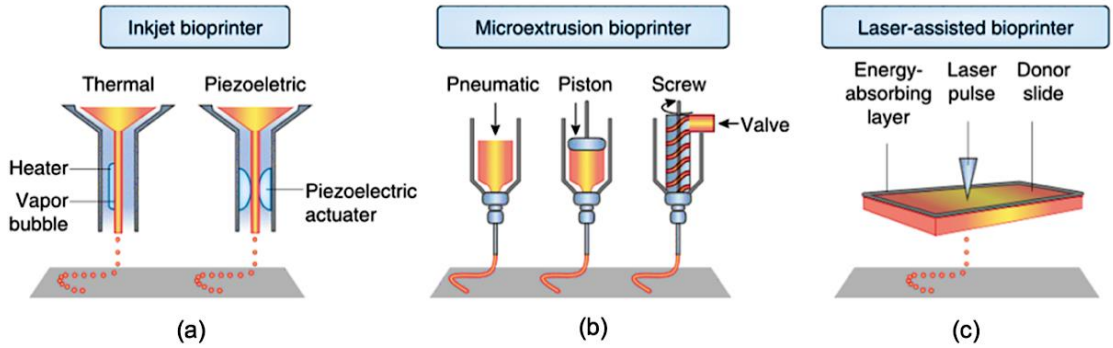


Figure 8. Types of bioprinters: (a) inkjet, (b) microextrusion and (c) laser-assisted. Source: Onu et al. [5]

Bioprinting begins with imaging by MRI or CT, followed by design, selection of bioink and cells, and printing by inkjet, microextrusion or laser-assisted

printers (Figure 8). It supports disease modelling, drug testing and tissue engineering, and 4D bioprinting is emerging to make constructs that respond to stimuli [5]. The main barriers are limited suitable biomaterials, complex regulation, equipment cost, scalability, sterilisation, vascularisation and maintaining cell viability during printing.

5.6 Applications and Practical Benefits

- Aerospace and automotive: lightweight structures, honeycomb cells and hollow parts that reduce weight while maintaining strength [1].
- Tooling and moulds: conformal cooling channels that improve cooling uniformity and reduce cycle time [4].
- Medical and dental: patient-specific implants, prostheses, surgical models and bioprinted tissues [1][5].
- Architecture and construction: physical models of complex designs, and printing of concrete for buildings [1][3].
- Energy: precise thin-film deposition for polymer electrolyte membrane fuel cells, with inkjet printing 4 to 5 times faster than screen printing [1].
- Repair, coating and recycling: directed-energy and cold spray processes can refurbish components and reuse waste powder [1][2][6].
- Advanced composites and ceramics: near-net-shape ceramic matrix composite parts for high-temperature use [7].

6. RESULTS AND DISCUSSION

6.1 Comparative Findings

Study	Control / method	Evidence reported	Main implication
Wong & Hernandez [1]	Process review (SL, FDM, SLS, EBM, LENS)	Applications and process characteristics described	AM suits complex, customised parts but needs better accuracy
Frazier [2]	Powder bed, powder feed and wire feed metal AM	HIP raised X-Y fatigue strength by 27%; qualification can cost $8–15 million	Process control and qualification limit adoption
Dilberoglu et al. [3]	Materials, hybrid processes, DfAM	Smart materials, WAAM, NPJ, ADAM, SPJ reviewed	AM supports customisation in smart factories
Tomasoni et al. [4]	CFD of conformal cooling channels	21.1 °C vs 30.3 °C; 29.7% reduction	Channel geometry strongly affects cooling
Onu et al. [5]	Biomedical AM and bioprinting review	Drivers, barriers and trends identified	Regulation and biomaterials limit use
Singh et al. [6]	Cold spray with recycled powder	Porosity < 2%; DE > 70%; about 30% cost saving	Waste powder can be a feedstock
Freudenberg et al. [7]	CF-PEEK extrusion to C/C-SiC	26.13% (z), 5.32% (x-y) shrinkage; 75.28 × 7.79 mm part	Deformation can be predicted and compensated

6.2 Advantages and Limitations

- Advantages: design freedom and internal features; customisation; reduced material waste; parts on demand; repair of damaged parts; ability to use recycled feedstock [1][2][6].
- Limitations: limited build volume in powder bed systems; anisotropy and defects; rough as-built surfaces; need for post-processing; limited materials; high equipment and qualification cost; slow build speed for mass production [1][2][3].

The literature consistently indicates that AM should be selected where its strengths in complexity, customisation and material efficiency matter. It is not yet a universal replacement for conventional manufacturing, particularly for large-volume production of regular parts [3].

6.3 Key Engineering Challenges

- Process control: real-time sensing and closed-loop control are needed to reduce machine-to-machine variability [2].
- Qualification and standards: certification of structural parts is costly, and standards for AM are still developing [2][3].

- Surface quality and accuracy: stair-step effects, rough surfaces and the need for finishing limit direct use of parts [1][2].
- Process-induced deformation: shrinkage, internal stress and gas release must be predicted and compensated in the design [7].
- Biomedical constraints: biomaterials, regulation, sterilisation, vascularisation and cell viability [5].
- Design knowledge: engineers need design rules and tools to exploit AM, as cooling-channel design shows [3][4].

6.4 Overall Discussion

The seven papers show a clear development path. Early work describes the processes and applications of rapid prototyping and 3D printing [1]. Metal AM studies then clarify how rapid solidification and repeated thermal cycles control microstructure, defects and fatigue behaviour [2]. The Industry 4.0 review places AM among digital technologies and highlights smart materials, hybrid processes and design tools [3].

The later papers demonstrate specific engineering benefits. Conformal cooling shows that a geometry that is difficult to machine can give a large reduction in mould temperature [4]. Biomedical AM shows the value of customisation, together with regulatory and biological barriers [5]. Cold spray with recycled powder shows how AM-related processes can be made more sustainable and economical [6], and the CF-PEEK study shows that process-induced deformation can be quantified and compensated in the CAD model [7].

A high-performing AM part therefore requires a suitable process, controlled feedstock, an appropriate design and correct post-processing. Better machines can improve resolution and speed, but design optimisation, process monitoring and compensation of shrinkage can improve the use of existing equipment.

7. CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

Additive manufacturing builds parts directly from digital models by adding material layer upon layer. The reviewed literature shows that it has developed from rapid prototyping into a set of processes capable of producing metallic, polymeric, composite and biomedical components, and that its greatest advantages are design freedom, customisation and efficient use of material.

The metal AM studies show that mechanical properties comparable to wrought material can be reached, but that defects, anisotropy, surface roughness and the cost of qualification still limit structural use. Powder bed, powder feed and wire feed systems offer different compromises between resolution, build volume and deposition rate.

The case studies demonstrate the value of design and process planning. A serpentine conformal cooling channel reduced the monitored mould temperature from 30.3 °C to 21.1 °C, recycled powders produced dense, wear-resistant cold spray deposits at an estimated 30% lower cost, and a pre-oversized CAD model compensated the 26.13% z-shrinkage of a CF-PEEK to C/C-SiC process chain to give a near-net-shape gear wheel.

The biomedical and Industry 4.0 papers further show that AM must be treated as part of a wider system that includes digital design, materials, regulation, sustainability and quality assurance. Its future depends on solving process-control, standardisation and material challenges together.

7.2 Future Scope

- Develop in-process sensing and closed-loop control to reduce machine-to-machine variability and support faster qualification.
- Create design rules and software tools that make DfAM and topology optimisation accessible to engineers with little AM experience.
- Extend conformal cooling studies to other moulds and processes and validate simulations experimentally.
- Expand recycled and waste-derived feedstocks and assess their environmental benefit through life-cycle analysis.
- Develop new biomaterials, vascularised bioprinted tissues and point-of-care AM within clear regulatory frameworks.
- Improve prediction of shrinkage and deformation for composites and ceramics by combining simulation and experimental data.
- Combine AM with subtractive processes and digital technologies for hybrid, cloud-connected production in smart factories.

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