Journal of Science Research International (JSRI)
ISSN: 2456-6365 (Online)

OPEN ACCESS

ADDITIVE MANUFACTURING TECHNOLOGIES AND APPLICATIONS: A REVIEW

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Received: 17 June 2026	Revised: 17 July 2026	Accepted: 12 August 2026	Published: 30 August 2026

DOI: https://doi.org/10.5281/zenodo.22317550

Abstract:

Additive Manufacturing (AM) — widely known as 3D printing — has become one of the most important developments in modern manufacturing, allowing three-dimensional parts to be built layer by layer directly from computer-aided design (CAD) data. This paper reviews the core concepts of additive manufacturing, starting with how the technology grew out of early rapid-prototyping methods into the advanced manufacturing systems used today. It examines the connection between rapid prototyping and additive manufacturing, and how together they cut product-development time, lower manufacturing cost and material wastage, and give designers greater freedom to customize products. The paper further explains how additive manufacturing works, the digital workflow behind producing a printed part, and the principal additive manufacturing process families — binder jetting, directed energy deposition, material extrusion, powder bed fusion, sheet lamination, vat polymerization, and wire arc additive manufacturing. It then surveys how these processes are being applied across aerospace, automotive, healthcare, pharmaceuticals and other industries. The paper concludes that additive manufacturing is reshaping conventional manufacturing by making it possible to produce complex geometries, lightweight structures and customized products more efficiently, positioning it as a key enabling technology for future industrial innovation.

Keywords: *Additive Manufacturing, 3D Printing, Computer Aided Design.*

1. Introduction

Global competition has reshaped how new products are developed in recent years. To stay competitive in international manufacturing, a company must deliver products of high quality at a low cost, and do so quickly and safely. Engineering design sits at the heart of this process — it starts from an identified need and ends with a prototype that is ready to be manufactured.

Taking a product from concept to market quickly and cheaply has become the norm rather than the exception. This shift has pushed industry away from traditional, sequential product-development methods and toward rapid prototyping, which has repeatedly proven capable of shortening development cycles and cutting cost.

A popular saying in additive manufacturing captures this well: 'if you can sketch it, you can make it.' Rapid prototyping makes producing these physical prototypes faster, easier and more cost-effective, and it continues to open new ground for researchers, technology publishers and users of advanced manufacturing tools alike.

2. History

Manufacturing has historically relied on subtractive methods. Producing precise shapes — through filing, turning, milling or grinding — traditionally meant removing material from a larger block rather than adding it.

That began to change in the 1970s. At Bell Labs, Joseph Henry Condon and his colleagues built the Unix Circuit Design System (UCDS), which took over the slow, mistake-prone job of hand-converting circuit drawings into fabrication-ready designs for research and development work.

The origins of rapid prototyping actually lie outside manufacturing, in the older fields of topography and photosculpture. In topography, Blanther proposed in 1892 that raised-relief paper maps could be moulded by cutting a contour line into each of a series of plates and stacking the plates on top of one another. Nearly a century later, Matsubara of Mitsubishi (1974) adapted this layered thinking to a photo-hardening resin, building up thin cured layers to form a casting mould. Photosculpture, meanwhile, was a nineteenth-century technique for producing an accurate three-dimensional copy of an object.

Most famously, Francois Willeme's 1860 setup used 24 cameras arranged in a circle to photograph an object simultaneously; the silhouette from each photograph was then traced to carve a physical replica. Morioka (1935, 1944) later combined photosculpture with the topographic approach, using structured light to capture an object's contour lines, which could either be cut from sheet stock and stacked or projected onto raw material to guide carving. The Munz process (1956) took a different route, exposing a photographic emulsion layer by layer on a piston that lowered gradually, so that once the emulsion was fixed, a transparent solid cylinder held a complete three-dimensional image of the object [1].

What was then called Solid Freeform Fabrication is what we now know as rapid prototyping, 3D printing or additive manufacturing. Swainson (1977) and Schwerzel (1984) explored curing a photosensitive polymer at the point where two computer-controlled laser beams crossed, while Ciraud (1972) proposed depositing sintered cladding using magnetostatic or electrostatic forces combined with an electron beam, laser or plasma source. All of these were put forward as concepts, though it remains unclear whether any working machine was ever actually built from them [2].

Hideo Kodama in Japan and Charles Hull in the USA were the first to move beyond concept, describing working processes and actually building machines capable of printing in three dimensions — earning them recognition as the fathers of modern rapid prototyping. Their early machines set the direction for later techniques in topography and metallurgy that echo several of today's rapid-prototyping processes.

From a niche field that few people had even heard of, rapid prototyping has since grown into a technology applied to an extraordinary range of problems — from constructing bridges to printing human organs.

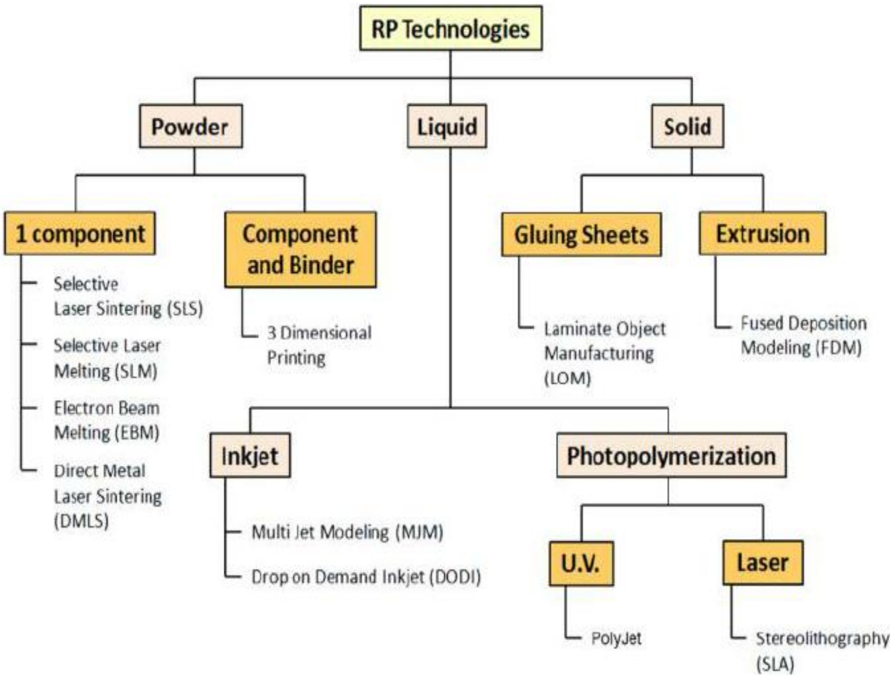
3. Rapid prototyping

Rapid prototyping first appeared in the late 1980s. It can be defined as a family of techniques for quickly building a working physical model or component, layer by layer, straight from 3-D CAD data — in other words, a way of producing scaled or full-size models of parts and assemblies quickly enough to check whether a design actually works. Because it saves both money and time, it is widely used to verify fit within an assembly. Additive manufacturing (3D printing) and laser cutting are the most common forms of rapid prototyping used today.

This raises a natural question: why choose rapid prototyping when conventional, subtractive manufacturing is still available? The answer lies in what rapid prototyping adds — clearer communication among teams, shorter development time, fewer costly mistakes, fewer engineering changes once production has started, and the chance to add useful features (and drop unnecessary ones) early, while doing so is still cheap.

Development time falls because corrections can be made early rather than after tooling is committed. When engineering, manufacturing, marketing and purchasing teams can all examine the product early in the design process, errors are caught and changes made while they still cost relatively little. Recognising this advantage, developers have since created a large number of rapid-prototyping processes covering materials as different as plastics and metals, each aimed at producing better prototypes.

a. Characterization of Rapid Prototyping Techniques



b. Additive manufacturing

Additive manufacturing — more commonly called 3D printing — is changing industrial production by making it possible to build parts and systems that are lighter and stronger than their conventionally made equivalents. It helps to think of the two terms this way: 3D printing/additive manufacturing is the process, while rapid prototyping describes one of its outcomes.

Like communications, imaging, architecture and engineering before it, manufacturing is now going through its own shift from analogue to digital processes, and additive manufacturing is a large part of that shift — bringing the flexibility and efficiency of digital workflows into the factory [6].

Figure 1: Additive manufacturing

Formally, additive manufacturing joins or solidifies material under computer control to build up a three-dimensional object, adding material rather than removing it [9]. This modern fabrication approach draws on a wide range of materials to make products as different as medical implants and aircraft wings. Because parts are built up from two-dimensional layers as thin as 0.05 mm, the process gives designers considerable freedom to create new products at low cost and with little material wasted.

The workflow begins with a part defined digitally in computer-aided-design (CAD) software, which is then converted into an .stl file that effectively slices the model into a stack of ultra-thin layers. A nozzle or print head follows this layer information, depositing material precisely on top of the layer before it; alternatively, a laser or electron beam selectively melts (or partially melts) regions within a bed of powdered material. Either way, the material cools or cures and fuses into a single three-dimensional object. This has changed both manufacturing itself and the engineering design process built around it, and 3D printing is now finding growing use across automotive, aerospace, pharmaceutical and healthcare, fashion, retail and sports applications. How good the final printed object turns out to be depends on the composition of the feedstock material, the process used, the type and speed of the printer, and the size of the object being printed [3].

Industry has been adopting 3D printing gradually, moving beyond simple prototyping into the manufacture of low-volume, customized parts. The life sciences sector was an early adopter, driven by demand for patient-specific items such as dental crowns, hearing aids and orthopaedic implants, while the automotive industry has found it useful for producing low-volume spare parts for older and vintage vehicles. The range of printable materials is already broad — thermoplastics, thermoplastic composites, pure metals, metal alloys and ceramics — even though 3D printing as an end-use manufacturing method is still relatively young. Over the coming decades, particularly as it converges with synthetic biology and nanotechnology, it could reshape design, production and logistics far more broadly than it does today. The many additive manufacturing technologies that fall under the 3D-printing umbrella typically build objects in successive layers around 0.1 mm thick, and can be grouped into four broad categories: printers that extrude a molten or semi-liquid material; printers that cure a photosensitive resin; printers that bind or fuse powder granules together; and printers that laminate and cut sheets of paper, plastic or metal [4].

4. Additive manufacturing processes

i. Binder jetting

In binder jetting, a print head similar to that in desktop 3D printers moves along the x, y and z axes, laying down alternating layers of powdered material and a liquid binder that holds the powder together [5].

ii. Directed energy deposition

Directed energy deposition can process a wide variety of feedstocks, including ceramics, metals and polymers. A laser, electric-arc or electron-beam source mounted on a moving arm travels horizontally, melting wire, filament or powder feedstock, while the build platform lowers vertically to accommodate each new layer [7].

iii. Material extrusion

Material extrusion is one of the most common AM processes: a spooled polymer is fed or drawn through a heated nozzle mounted on a movable arm, which deposits melted material layer by layer as it moves horizontally while the build platform moves vertically. Successive layers bond to one another through careful temperature control or, in some systems, chemical bonding agents [10].

iv. Powder bed fusion

Powder bed fusion is really an umbrella term for several related techniques — direct metal laser melting (DMLM), direct metal laser sintering (DMLS), electron beam melting (EBM), selective laser sintering (SLS) and selective heat sintering (SHS) — that all use an electron beam, laser or thermal print head to melt or partially melt thin layers of powder, with any unfused powder removed once the build is complete [8].

v. Sheet lamination

Sheet lamination covers two related technologies: laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM). LOM is generally used for parts where visual or aesthetic appeal matters, building them up from alternating layers of paper and adhesive. UAM instead uses ultrasonic welding to bond thin metal sheets together — a low-energy, low-temperature process that works with metals such as aluminium, stainless steel and titanium [9].

vi. Vat polymerisation

Vat polymerization builds an object layer by layer from a vat of liquid photopolymer resin. Mirrors steer ultraviolet light onto the resin surface, curing each successive layer through photopolymerization [10].

vii. Wire arc additive manufacturing (also known as directed energy deposition-arc, or DED-Arc)

This process builds three-dimensional shapes through arc deposition, using conventional arc-welding power sources together with a manipulator to guide the weld. Wire is the usual feedstock, deposited along a predetermined path to form the desired geometry — work that is typically carried out using robotic welding equipment, most often under automated control [7].

5. Conclusion

Additive manufacturing has changed the traditional approach to product design and manufacturing by making it possible to fabricate complex three-dimensional components directly from a digital model. As this paper has shown, the technology has grown from a rapid-prototyping tool into a dependable manufacturing process in its own right, capable of producing functional parts with high accuracy, less wasted material and shorter production cycles. Because the different additive manufacturing processes each suit particular materials and industrial requirements, the technology now serves applications across healthcare, aerospace, automotive and consumer products. Challenges remain — build speed, the range of usable materials, and cost among them — but continued progress in materials, machine capability and process control keeps widening what additive manufacturing can do. Given its capacity to support mass customization, lightweight design and more sustainable production, additive manufacturing is set to play a growing role in smart, digital manufacturing, and stands out as one of the more promising technologies of Industry 4.0.

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