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Introduction to Additive Manufacturing

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ADDITIVE MANUFACTURING (AM), popularly known as 3D printing, is a collection of manufacturing processes, each of which builds a part additively based on a digital solid model. The solid model-to-AM interface and material deposition are entirely computer controlled. According to the official terminology standard for AM, ISO-ASTM 52900 (Ref 1), *AM* is defined as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies." The standard further categorizes current commercially viable AM processes into seven categories, based largely on the broad binding mechanism for part creation. They are vat photopolymerization (vpp), material jetting (MJT), powder bed fusion (PBF), directed energy deposition (DED), material extrusion (MEX), binder jetting (BJT), and sheet lamination (SHL).

From a purely economic perspective, the traditional application space for AM has been for low-production runs of parts with complex shapes and geometric features. Examples include prototypes; tooling; jigs/fixtures; models for aerospace, automotive, biomedical, and other industrial sectors; mass customization; jewelry; and artwork. For low-cost AM systems such as some material extrusion and binder jetting equipment, part cost can be much lower than that of conventional manufacturing for small to medium quantities. At the other extreme, part production with stringent service requirements using PBF or DED can be expensive due to high feedstock cost and the large capital cost of the machine, supporting equipment, and postprocessing labor. Also, AM is advantageous economically where reduced part count and elimination of assembly requirements result in significant cost savings. This is shown in Fig. 1, where a 16-part assembly is replaced by a single AM part.

Performance-based applications of AM are notable. Certain parts have sufficiently complex shapes and geometric features where no other manufacturing routes are available. A common example is internal flow fields in parts, including conformal cooling channels in molds and dies, as well as gas/aerosol flow channels for optimally mixing and distributing fuel and oxidants. Figure 2 shows a conformal cooling channel implemented in an injection mold. The cooling time for injection-molded parts was reduced by 55%, enabling the manufacturer to improve molding cycle time by almost 25%.

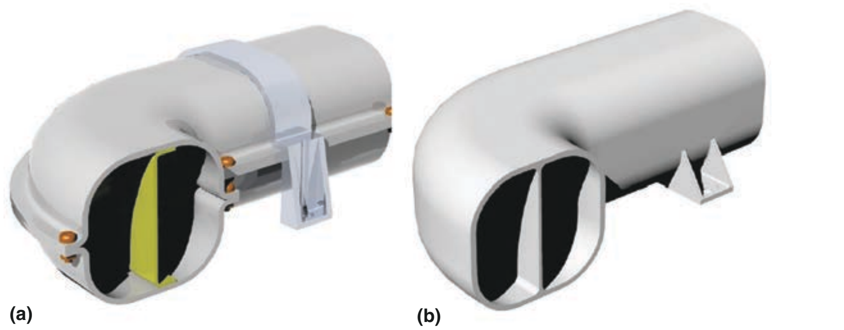

Fig. 1 Example of a multiple-part assembly (a) reduced to a single part (b) through additive manufacturing. Courtesy of 3D Systems

AM is also an enabling technology for topology optimization, an approach to design in which predictably loaded parts are analyzed using solid modeling/stress analysis software. This ensures that most or all elements of the part carry loads with an objective of reducing material to a minimum. Topology-optimized parts often have a biomimetic look that can be difficult or impossible to manufacture using conventional methods (Fig. 3). Another feature of AM is the ability to easily create designed lattice/truss and cellular structures in a part. Lightweighting applications for the biomedical industry involve hard-tissue scaffolding, for which engineered porosity facilitates adhesion to living material (Fig. 4).

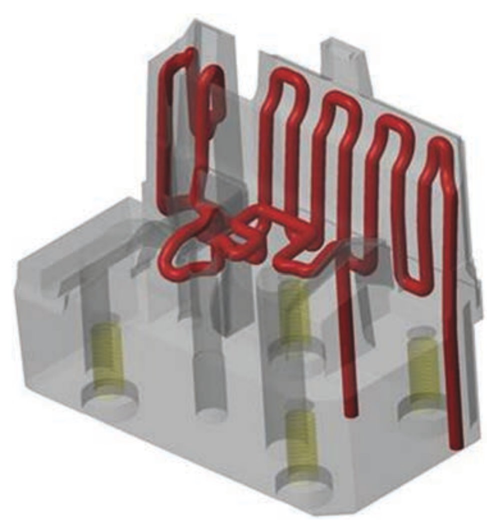

Fig. 2 Conformal cooling channel in an injection molding tool. Courtesy of Renishaw

Some AM applications are driven by materials issues, particularly for metal part production. Because the active build volume for AM is relatively small, parts tend to be chemically homogeneous without macrosegregation, as in powder methods. Certain AM processes, such as DED and material extrusion, facilitate creation of functionally graded compositions (Fig. 5). Here, various compositions of material are deposited during the build in specific locations. Gradation of porosity is also effected by AM. For AM processes involving fusion (PBF, DED, and material jetting of thermoplastics and metals),

Fig. 3 Nacelle hinge bracket for Airbus A320 (a) and topology-optimized design produced by additive manufacturing (b). Courtesy of EADS and Altair (Ref 2,3)

Fig. 4 Cellular bone scaffold for dental implantation. Courtesy of Nanyang Technological University

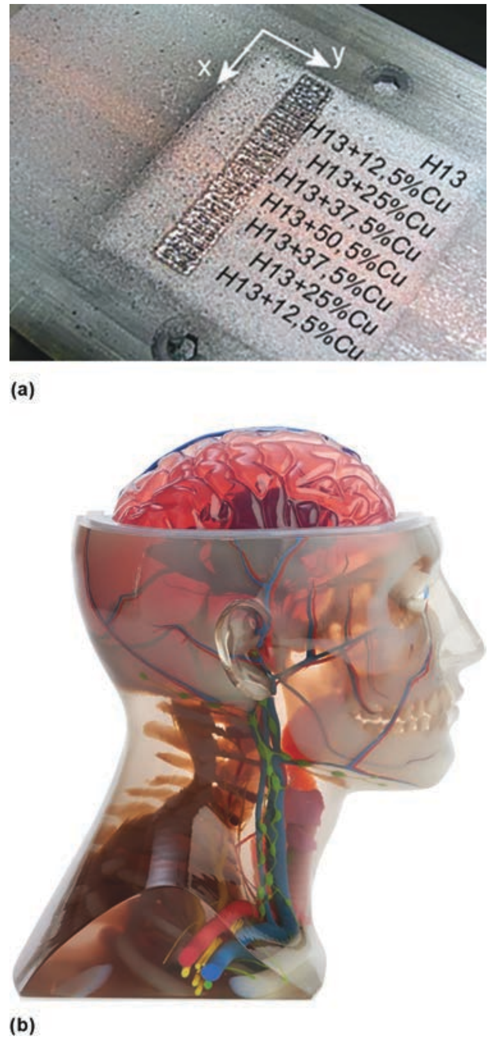

Fig. 5 (a) Functionally graded additive manufacturing cross section (Ref 4) and (b) a multimaterial photopolymer part (Stratasys J750 printer)

the energy input affects the heating and cooling rate locally, which can influence the microstructure. For example, it is possible to control the texture in a nickel-based alloy processed using electron beam PBF by altering the solidification kinetics via processing parameter adjustment (Fig. 6).

Increasingly, AM is being employed in part repair. In preparing to fixture a part for computer numerical control (CNC) machining, DED is useful for building up the part, especially for expensive, high-end parts such as aerospace engine components.

Beyond the economies and performance of parts, AM technology also impacts the process and supply chain. Often, prototype part production was delayed until late in the product development cycle due to cost and time factors. With AM, it becomes feasible to manufacture much earlier in the process, and in many cases, create iterative *functional* prototypes in lieu of or in addition to form-and-feel prototypes. Having a prototype part early in the process facilitates final design. The notion here is exemplified by the adage, "If a picture is worth a thousand words, a physical part is worth a thousand pictures." The potential for distributed manufacturing enabled by AM also positively impacts the supply chain because customers are given more vendors and sources for subassemblies and products.

Another impact on the supply chain is the cost to transport parts. With a distributed manufacturing capability enabled by AM, it is possible to print the part at or near its final service location, resulting in savings in transportation costs. Corporate access to multiple certified manufacturing facilities and service providers positively affects the availability of parts and reduces risk associated with unforeseen changes in part provision from a single supplier.

A societal impact of AM is the transition partially from centralized manufacturing to distributed manufacturing, especially for low-cost fabricators. This occurred with computing in the late 1970s and 1980s, when microprocessors spawned the commercialization of desktop computing. Additive manufacturing effectively enables the same concept for manufacturing, in which the final user becomes equipped to manufacture with a reduction in assistance from other companies. The impact of distributed manufacturing is not yet fully realized, but its strength is demonstrated anecdotally almost every day in stories spanning the breadth of society where AM makes a difference.

Additive manufacturing processes share several broad, common characteristics. Typically, the build rate of ~0.5 to 5 cm^3/min is slow compared with conventional casting, molding, or forming. Exceptions are weld-head deposition approaches, large-scale material extrusion, and certain other AM approaches (e.g. binder jet) that rely on binding an entire layer simultaneously rather than using a point-to-point or raster mechanism such as a laser or nozzle, respectively. Surface finish is variable, with finishes on the order of 1 μm attainable for vat photopolymerization to tens to hundreds of micrometers for certain other AM processes. Most AM processes require support structures for all but the simplest shapes. Exceptions are sheet lamination, binder jetting, and polymeric PBF. Support structures are defined by ISO/ASTM 52900 as a "structure separate from the part geometry that is created to provide a base and anchor for the part during the building process." Removal of the support material and finishing the part, grouped with other activity and termed "postprocessing," may constitute a significant portion of the time, effort, and cost of manufacture.

Vat Photopolymerization

The surface of a photosensitive liquid thermoset polymer is exposed to a prescribed wavelength of "light," which chemically initiates the cross-linking reaction. This results in the formation of a solid in the liquid where the material is exposed to the light. Wavelengths often lie in the ultraviolet range. A typical schematic is shown in Fig. 7. In this embodiment, the photopolymer resides in a vat, and a low-power (milliwatt) laser scans the surface of a platform, inducing cross-linking and creating a solid layer. A recoater mechanism delivers a thin layer of liquid photopolymer to the surface, and the process is repeated. Because the laser scanning is computer controlled, the layers vary in shape, resulting in the ultimate creation of a fully three-dimensional part (Fig. 8).

The liquid polymer resin is typically an epoxy or acrylate mixed with a photoinitiator. Epoxies are more common because they are generally stronger and do not shrink as much as acrylates on cross-linking. Common photoinitiators are benzoin, acetophenone, benzyl ketal, and cyclohexyl phenyl ketone. When exposed to a specified wavelength, the photoinitiator reacts with the liquid monomer to form free radicals, thus initiating cross-linking. Termination of the polymeric long chains occurs by one of several mechanisms detailed in the article "Vat Photopolymerization" in this Volume. It is possible to mix additives, typically ceramic or metallic particulate, into the liquid photopolymer. In these cases, the refractive index of the particles should match that of the liquid photopolymer to prevent undue dispersion of the light.

Several variants of the vat photopolymerization process have been developed and commercialized. One builds the part upside down from the bottom of the vat. The light is transmitted through a window at the bottom of the vat onto the platform. Historically, an obstacle to this approach has been adhesion of the cross-linked polymer to the window. This has been mitigated in one instance by using oxygen-sensitive photopolymers and oxygen-permeable windows. The oxygen inhibits the cross-linking reaction at the surface of the window, which creates a thin layer of inactive liquid on the window surface. The advantage is continuous printing. Another variation is the use of a digital micromirror array, such as digital light processing technology from Texas Instruments, to project the entire layer simultaneously instead of using laser beam scanning. This results in a substantial increase in the build speed.

Parts produced by vat photopolymerization have excellent feature detail and surface finish

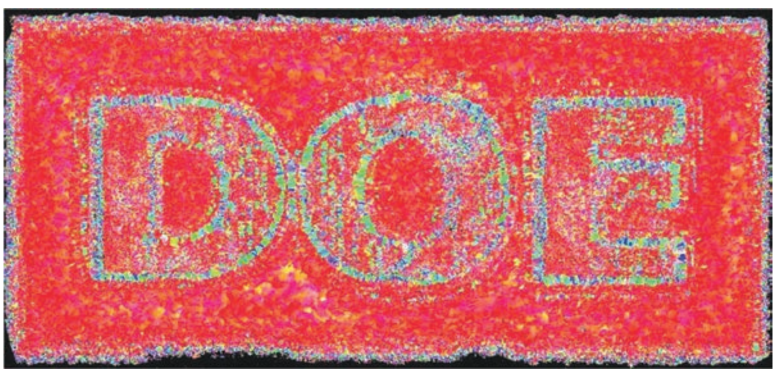

Fig. 6 Crystallographic texture control in additive manufacturing (Ref 5)

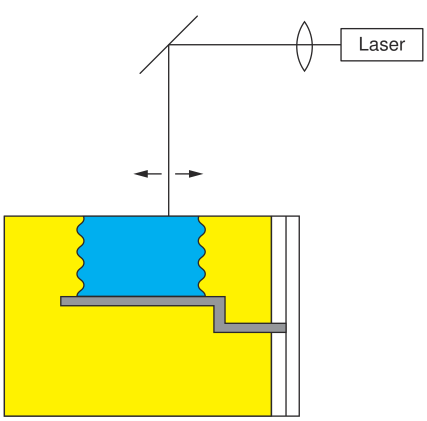

Fig. 7 Schematic of vat photopolymerization

Fig. 8 Stereolithography wind tunnel part designed for Lotus Formula 1. Courtesy of 3D Systems (Ref 6)

compared with those produced by other AM approaches, on the order of 1 μm for support-structure-free, non-bottom-facing surfaces. They may be postprocessed by blasting, sanding, polishing, and coating to produce transparency. Mechanical properties are consistent with the cured thermoset resin matrix, which is relatively low in strength and toughness and has low thermal deflection temperatures, compared with common thermoplastics. For these reasons, vat photopolymerization is very suitable for creation of quality prototypes and nonstructural parts. According to the *Wohlers Report 2019* (Ref 7), approximately one-third of all feedstock currently used in AM is thermosetting photopolymers for vat photopolymerization.

Material Jetting

One embodiment of material jetting uses a photopolymer akin to those used in vat photopolymerization. It employs an inkjetting approach to deposit the material in specific locations on a build platform or part that is bathed in the cross-linking electromagnetic radiation (Fig. 9). In broad terms, material jetting uses a localized material presence within indiscriminate cross-linking radiation, in contrast to vat photopolymerization, for which a localized energy source cross-links polymer within an indiscriminate material resin pool. It has been demonstrated that material jetting is possible using metallic feedstock. With multihead inkjets, multimaterial systems can be created, leveraging future optimization technology.

A second embodiment involves melting a polymer and atomizing it to create a fine particle stream for jetting. Feedstocks include polypropylene (PP), high-density polyethylene, polystyrene (conventional and high impact), poly(methyl methacrylate), polycarbonate, acrylonitrile butadiene styrene (ABS), and environmentally degradable polymers. Figure 10 shows a material-jetted polymer part. Limited work, primarily research, has explored the use of molten metal droplet AM. Early study of the physics of metal droplet formation in an AM context was performed in the early 1990s by Orme (Ref 8).

Material jetting presents several unique considerations. For polymers, the viscosity of the photopolymer must be sufficiently low to enable formation of a fine droplet stream. Droplet size and momentum define the degree of splat on the surface of the part, and these parameters must be controlled. The kinetics of the cross-linking reaction must also be sufficiently rapid to enable efficient, rapid deposition.

Powder Bed Fusion

Essential to PBF is the localized fusing of particulate in a bed using an energy source, typically a laser, electron beam, or light source (Fig. 11). Powder is spread over a build area in a thin layer on the order of 30–100 μm. Powder spreading is accomplished by a moving blade "recoater" or a counterrotating cylinder. The energy source selectively focuses energy on the surface, resulting in localized melting and fusion of the powder, both to adjacent particles in the layer and to the previous layer. Figure 12 shows a PBF part made of nylon.

Currently, three common energy sources are lasers, electron beams, and indiscriminate electromagnetic energy. Lasers are typically ~100 W neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers for polymer PBF. For metals, fiber lasers provide improved coupling and are 200–500 W. Electron beams use a 5–10 kW power source. Another approach such as multijet fusion from HP or rapid laser sintering deposits a fine, particulate coupling agent, such as fine carbon powder, by inkjetting after the spreading of each layer of powder. When exposed to light of proper wavelength and energy, the coupling agent is heated to an extent that adjacent powder particles melt and fuse. The process is faster than point-source PBF because

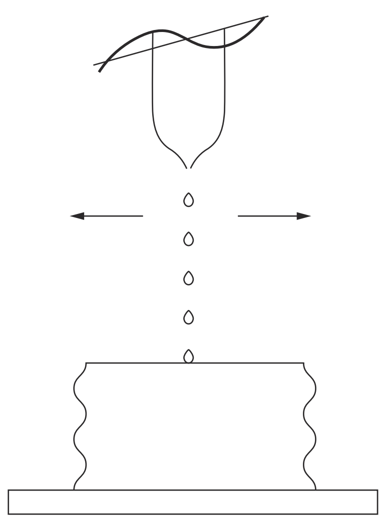

Fig. 9 Schematic of material jetting

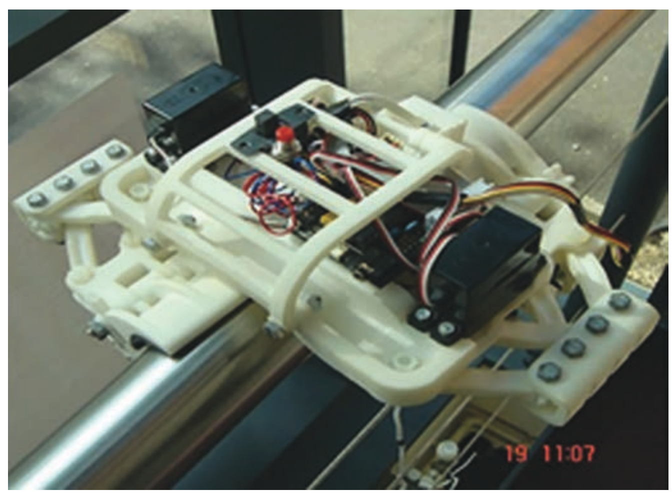

Fig. 10 Material jetting part. Courtesy of Loughborough University

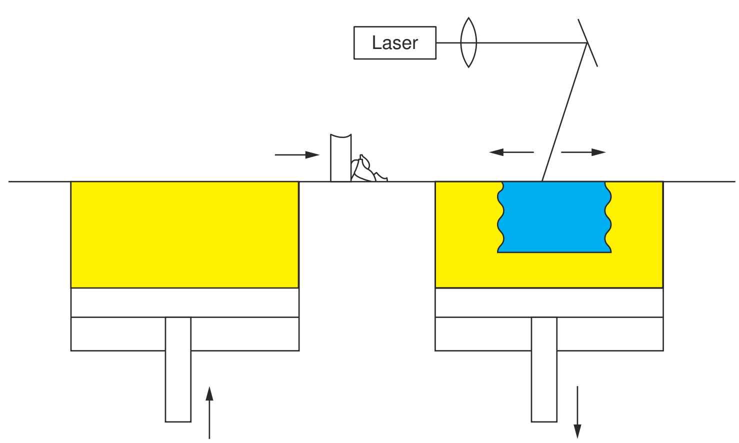

Fig. 11 Schematic of powder bed fusion

coupling agent deposition and entire surface binding is more rapid than raster scanning of a point energy source.

Polymeric parts are suitable for production using laser and light sources. Metal parts are produced using electron and laser beam approaches. Virtually any pulverized material can be used in PBF when a suitable transient or permanent binder is mixed with the primary feedstock. Postprocessing may be used in the case of metal and ceramic parts to either convert or burn off the binder, and can be followed by optional conventional sintering or infiltration to densify the part.

When residual stresses are controlled, as is the case for laser PBF of polymers, the loose, unfused powder supports the part, eliminating the need for support structures. For metal PBF, the part cake does not provide sufficient rigidity to prevent distortion from the heat, so parts are attached to a build plate using support structures, sometimes referred to as anchors.

Polymer feedstocks for PBF are generally semicrystalline thermoplastics, including polyamide 11 (PA11), PA12, PP, polyether ether ketone, and polyaryletherketone. For laser-based PBF, the feedstock is preheated to a temperature near but less than the melting point. Once the material is melted by the laser, the bed temperature should remain above the crystallization temperature to minimize residual stresses and distortion. Therefore, a large temperature difference between the melting and crystallization temperatures is desirable. For PA, this temperature difference is ~20 °C (~36 °F). Cooling prior to part removal generally requires the same amount of time it takes to build the parts. For example, if building the parts takes 10 h, the parts in the powder bed should cool for 10 h. If the parts are removed too quickly, they will distort and possibly oxidize. Feedstock particle size is on the order of 50–80 μm.

Metallic feedstock for PBF is typically weldable and castable and includes aluminum alloys, cobalt-chromium alloys, nickel alloys, gold, silver, stainless steel, tool steel, and titanium alloys. Typical power sources for fusion are lasers and electron beams. Powder particle size is in the range of 20 to 40 μm for laser PBF and 45 to 100 μm for electron-beam PBF.

Directed Energy Deposition

Directed energy deposition feeds material into an energy beam, typically a laser, electron beam, or plasma arc weld head (Fig. 13). Feedstock is typically in the form of metal powder or wire. Compared with other AM process categories, DED offers unique features. First, it is possible to deposit large amounts of material, particularly with wire-fed processes, up to 200 to 400 in^3/min (508 to 1016 cm^3/min). Directed energy deposition is suited for multiple-material deposition, because the various feedstocks can be fed into the energy beam using separate nozzles/feeders. Since the part is fully exposed during the metal additive process, DED is well suited to creating large-volume parts as well as repairing or adding features to existing parts. For electron beam and welding heat sources, the coupling and thermal efficiency can be high. Representative parts are shown in Fig. 14.

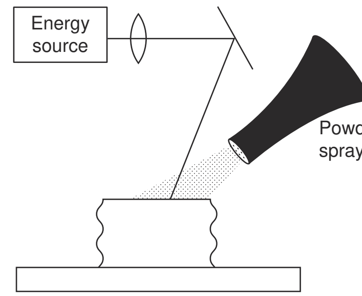

Fig. 13 Schematic of directed energy deposition

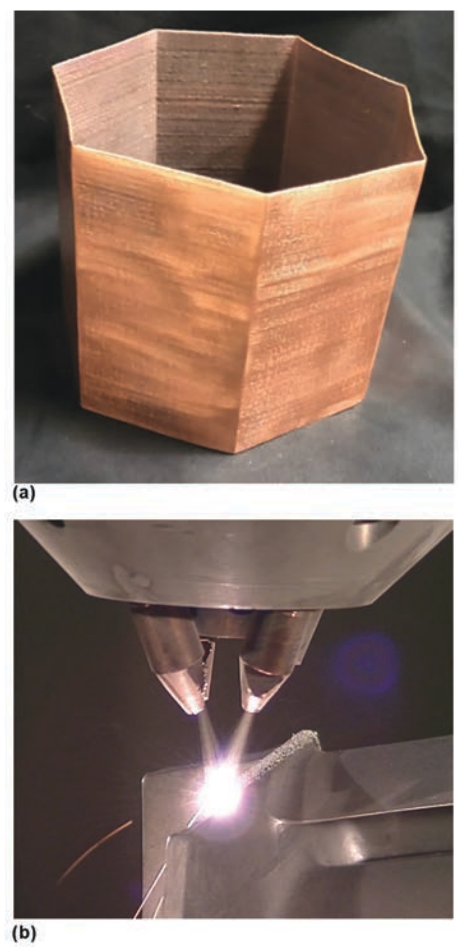

Fig. 14 Representative directed energy deposition parts. (a) Pure copper septagon structure 175 mm in diameter and 200 mm tall with 1 mm wall thickness. (b) Repairing a titanium turbine compressor vane. Courtesy of Optomec, Inc.

Fig. 12 Powder bed fusion part, nylon. Courtesy of 3D Systems

One issue related to DED processes is that nearly all parts require postmachining, and it can be significant, time consuming, and costly. Also, DED limits the geometric complexity of a part. It is extremely difficult to use DED to produce internal channels, cavities, or other features that are typically easy, even trivial, for PBF.

Lasers are usually CO_2, Nd:YAG, fiber, disk, or diode. Laser power varies between 400 and 4000 W, with spot sizes ranging widely between about 50 μm and 25 mm. The plasma arc approach uses either gas tungsten arc, gas metal arc, or plasma-transferred arc welding heads. Heat sources range in power from less than 1 kW to 60 kW or more. Working distance from the power source is large for laser and electron beam approaches, and usually on the order of 300 mm (11.8 in.). For welding approaches, the working distance is about 25 mm (0.98 in.). Atmosphere control is maintained using either an inert build chamber, common for laser-based processes; vacuum in the case of electron beam processes; and a localized shielding gas for arc welding approaches.

For DED with powder feedstock, the powder size and shape are dictated by the feeder specifications. The size is in the range of 5 to 150 μm. The capture efficiency in the energy beam is typically 40 to 80%. Powder mass flow rates are typically 1 to 50 g/min. Wire-feed systems can deposit material on the order of 300 g/min.

Hybrid AM generally refers to a combination of AM, particularly DED, and other processes, such as CNC milling, that alternates after 1 to 20 layers of the build. Most often, the secondary process is subtractive (i.e., material removal) and involves machining of some sort during the build for the purpose of creating a precision surface finish and tight tolerances, compared with AM only.

Material Extrusion

Material extrusion is accomplished by forcing feedstock through a nozzle that moves relative to a build platform. The typical approach involves melting a polymer or polymer matrix, but methods for extruding slurries are also available. The latter approach is most popular for creating large concrete structures and is popular for printing food such as icing, cookie dough, and blended vegetables. Optimal feedstocks are those that are shear thinning. Shear thinning results in feedstock low in viscosity during extrusion, but maintains a firm, high viscosity after placement, which minimizes distortion and sagging. Robocasting is an early example of shear-thinning material extrusion.

A schematic diagram of material extrusion is shown in Fig. 15. The material is deposited crudely as a cylindrical shape with a circular or oval cross section, the axis of which as-deposited is termed the road path. The road-path pattern is typically varied between layers to improve structural integrity. Characteristic of the road-path pattern is inter-road-path porosity, which can be as high as 25%. This porosity may be controlled to some extent by adjusting the rate and amount of fill deposited.

Material extrusion nozzle size is largely dictated by the desired surface characteristics as well as the force needed to extrude the feedstock. These considerations conflict, as the surface is improved by small diameter nozzles while the force required for extrusion increases with decreasing nozzle diameter. The amount of material deposited, and thus the speed of the process, increases as the size of the nozzle diameter increases. Typical nozzle diameters for polymer material extrusion are in the range of 0.2 to 1.0 mm.

Material extrusion, due in part to the simplicity of the process, includes the lowest-cost AM machines, on the order of 200 to 1500 USD. As such, by far the most fabricators in service are from this group. According to the *Wohlers Report 2019*, sales of material extrusion machines were more than 590,000 units annually worldwide.

Feedstock for material extrusion typically is from the class of amorphous thermoplastics, most popularly polylactic acid and ABS. Amorphous polymers are suitable for forming slurries with a rather continuous range of viscosity, as opposed to semicrystalline polymers, which have a sharp transition from solid to melt characteristics. This feature of amorphous polymers makes them generally more suitable for material extrusion. Low melt viscosity is desirable from the perspective of the force required to extrude the feedstock. This is particularly an issue when neat polymer is loaded with fillers or particulate. As in metal and ceramic injection molding, the amount of added nonpolymeric material is limited to less than about 60% by volume for material flow considerations.

Due largely to residual porosity, parts made using material extrusion are typically not used in structural applications. Ongoing developments are underway to improve structural integrity of parts, motivated by the relatively low cost of parts produced by material extrusion compared with some other AM methods. They include development of materials such as polyetherimide, control of porosity through process parameter optimization, and structural design using the porous structure, such as use of Weibull statistical methods. Concrete printing is an example of large-scale material extrusion and has been used for demonstration building construction as well as transportation-related concrete structures, such as bridges. Large-scale material extrusion is a high-volume rate deposition technique usually based on a gantry system, as shown in Fig. 16.

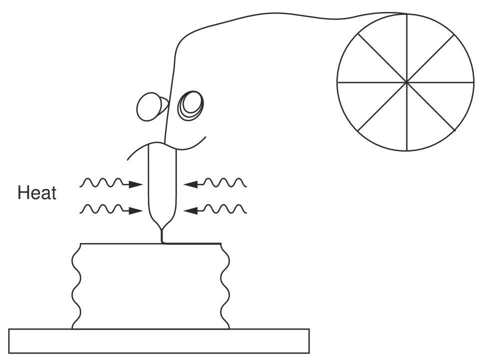

Fig. 15 Schematic of material extrusion

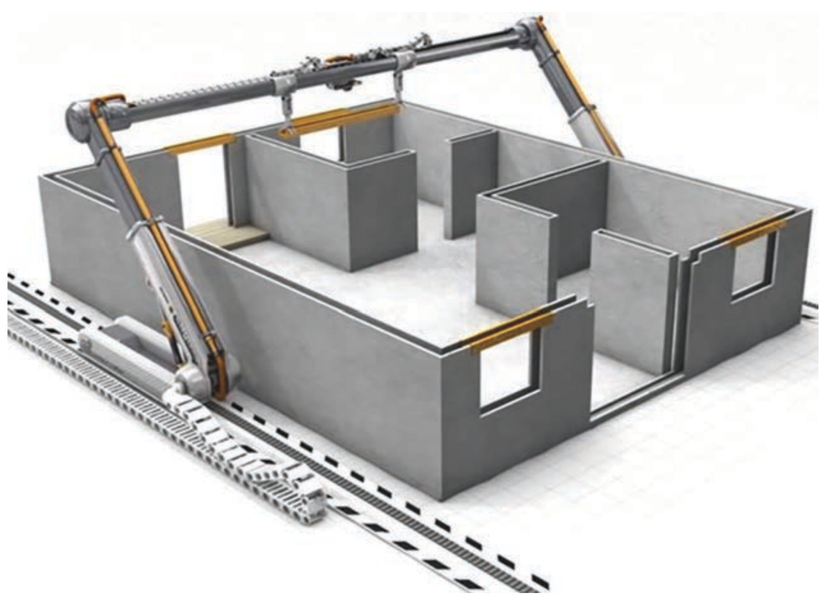

Fig. 16 Schematic of large-area material extrusion (contour crafting). Courtesy of Behrokh Khoshnvis, University of Southern California

Material extrusion of parts of general shape requires the use of support structures. They are typically generated automatically by the system or other special software. Material extrusion is amenable to multimaterial part construction, enabled generally by multiple extrusion heads or by multiple feedstock feeds into a single extrusion head, which serves a mixing/blending function. A common multimaterial embodiment involves use of a different material from the part material to build the support structure. This facilitates support structure removal after the build is complete, for example, by using a dissolvable support material.

Binder Jetting

Binder jetting is a powder bed process in which an adhesive is sprayed selectively onto the surface of the powder bed (Fig. 17). Historically, inkjet printing technology has been used with low-viscosity adhesive inks. Traditional binder jetting for prototypes and figures is amenable to the creation of color parts by employing standard color inkjet technology using multiple print heads. This facilitates the use of binder jetting for visual prototypes and nonstructural parts requiring aesthetic qualities. The quality of the part is dependent on the interaction mechanism of the adhesive with the powder bed. The goal is for the droplet to wet and bind powder particles rapidly and locally without splatting or otherwise dispersing on impact. The deposition rate, adhesive droplet size, droplet velocity, and binding mechanism all impact part quality.

As long as the powder feedstock is wet by the adhesive, almost any pulverized or atomized material (e.g., carbides, oxides, and any metal) may be used. Immediately after the build, parts are "green" or loosely bound and are brought to full density via infiltration or postprocess sintering. For metallic and ceramic powder beds, postprocessing for structural part creation is similar to metal or ceramic injection molding. The advantage is that much higher metal/ceramic loading is possible compared with flowing a polymer/feedstock mixture into a mold. The surface quality of as-built binder jet parts is defined largely by the powder bed particle size and the inkjet droplet size. The density of as-built binder jet parts is largely defined by the powder bed density during the build, which is on the order of 65% or less, so the amount of infiltrant used or the amount of shrinkage needed to reach full density is largely dictated by this powder bed density.

A unique property of binder jetting is that because the powder bed can completely support parts as they print, parts can be nested over and around each other in the build box. This ability to pack large batches of parts into a single build box makes for a very high-productivity printing scenario. Further, because postprocessing steps such as depowdering and sintering/infiltration can also be completed in large batches, binder jetting is well suited for large-volume production.

Recent developments in binder jetting have focused on densifying steels and nickel alloys through printing and sintering of fine powder feedstocks. Fine powders on the order of 10 μm have significant drive for sintering and can reach upwards of 99% density using solid state sintering. This combined with the high productivity and material flexibility of the binder jetting process cycle has spurred recent market growth around the technology for metal induction molding replacement manufacturing for the automotive industry.

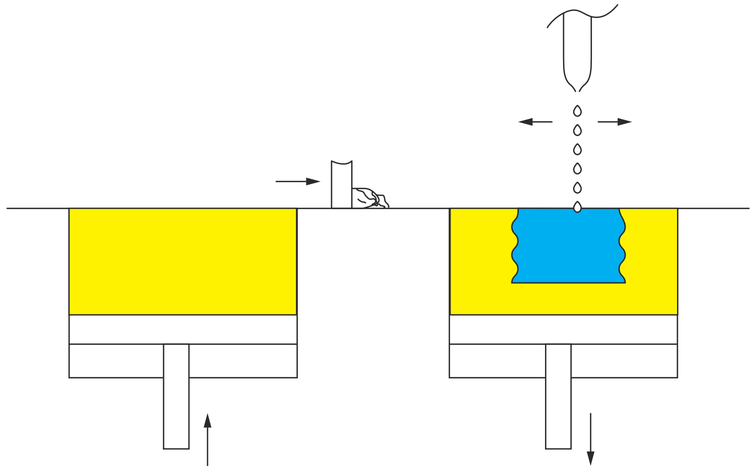

Fig. 17 Schematic of binder jetting

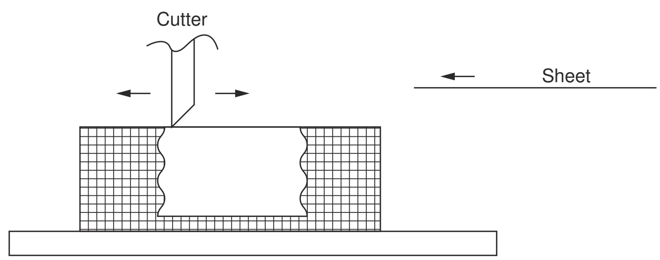

Fig. 18 Schematic of sheet lamination

Sheet Lamination

Sheet lamination AM processes involve binding and shaping of sheet feedstock. The earliest sheet lamination processes used continuous roll paper, which was adhered to the previous layer and then cut to create the shape. Cutting sources include mechanical cutters such as knife blades, lasers, and milling machine tools. Most processes involve placement of the sheet, followed by cutting (see Fig. 18), although it is possible to cut the sheet before stacking. Each approach offers advantages. Stack-and-cut approaches are simpler to implement and do not require precise registration of each new layer relative to those already processed. Specifically designed support structures are not needed for stack-and-cut processes because the processed sheet material serves to support what is above it. Depending on the features of the part being produced, specially designed supports may be needed to complete a cut-and-stack part. For stack-and-cut technologies, the part at the end of the build is completely encased in a block of bound feedstock, which must be removed, usually by hand. This poses limits on the degree of fine detail obtained using this approach. In each layer during the cutting process, the cutter not only differentiates the part from the rest of the sheet but also cuts a grid array in the unused region of the sheet to facilitate part removal. Material waste is usually inherent to sheet lamination processes. Sheet feedstock not used in the part typically cannot be reused in the process and is discarded.

A principal advantage of sheet lamination, like binder jetting, is that the build process takes place at room temperature. This facilitates use of dissimilar metals with large differences in melting point and insertion of polymeric devices and sensors into metal parts.

Feedstock material for commercial sheet lamination is either paper or metal foil. For the former, sheets are bound with an adhesive. The primary feedstock constraints are creating the sheet morphology and ensuring that the adhesive is effective in binding layers. Paper-based sheet lamination parts may be colored during the build by inkjet printing part surfaces in each layer during the build. Such color parts are useful for visual models and prototypes. For the process, ultrasonic AM, metal foil is used, and sheets are bound by solid-state ultrasonic welding using a rolling sonotrode. Sheets are machined using a CNC milling process that is a part of the system. Common feedstocks include aluminum, copper, stainless steel, and titanium.

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History of Additive Manufacturing

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Additive Manufacturing Terminology

The group of technologies today (2020) termed additive manufacturing (AM) began commercialization in 1988. The original term was *rapid prototyping*, indicative of the original use in accelerating the modeling and prototyping of new designs, mostly in the automotive industry. Also in 1988, J. Beaman at the University of Texas at Austin, appreciating that the potential application of the technology was broader than just prototyping, coined the term *solid freeform fabrication*. These two terms perpetuated until the early 2000s, when a large number of terms came into use, some with greater popularity than others. Examples from the period include *additive fabrication*, *additive processes*, *additive techniques*, *layer manufacturing*, *freeform fabrication*, *rapid tooling*, *additive layer manufacturing*, *rapid manufacturing*, *direct digital manufacturing*, *additive manufacturing*, and *three-dimensional (3-D) printing*.

The term *3D printing* was clearly applied to modern AM processes in the 1980s, according to multiple independent sources. (Information dissemination in the 1980s was much different from today. By way of example, the worldwide web was not released to the general public until 1991, and in the 1980s, typical background literature was obtained by manually searching local library shelves and by networking at conferences.) The earliest known use of the term *3-D printing* as applied to AM was in an article by Wohlers in 1988 that reviewed the then-new stereolithography machine recently commercialized by Hull (Ref 1). The concept of printing an object was in use at least as early as 1984, when Hull filed his famous stereolithography patent, which said, "'Stereolithography' is a method and apparatus for making solid objects by successively 'printing' thin layers of a curable material···" (Ref 2).

The term *3D printing* was popularized by Emanuel Sachs from the Massachusetts Institute of Technology (MIT), and was used in 1989 in a patent on a binder jetting process that he co-invented (Ref 3). Sachs chose the name *3D printing* from a list of names that he and a student created, despite the fact that many of those interviewed for their opinions did not react positively to it. "But printing is 2D!" was a typical response. In addition to its descriptive appeal, Sachs' affinity for the name stemmed from the fact that his father was a publisher and had taken him to tour commercial printing presses. The name caught on. By the early 2000s, media outlets around the world were using 3D printing as a common vernacular to refer to AM. By the end of the 2000s, the term was entrenched for multiple uses: reference to the MIT binder jetting process, to AM in general, and, specifically, to low-cost AM machines. This is still the case today.

The term *additive manufacturing* was formally adopted on January 14, 2009, at the charter meeting of an ASTM International technical committee meeting in West Conshohocken, PA. Near the end of the meeting and leading to a motion to form a technical committee for standards development, there was a detailed discussion of what to call the technology. The term *3D printing* was discussed but abandoned, due to its association with the MIT binder jetting process, among other reasons. A motion was made and adopted to form the ASTM International Committee on Additive Manufacturing Technologies, which resulted in the formation of ASTM Committee F42. Within two years, the International Organization for Standardization (ISO) formed a comparable committee, ISO/TC 261 on Additive Manufacturing, which further advanced adoption of the term.

One of the most persistent aspects of AM is the standard triangle language (STL) file format used to transfer computer-aided design (CAD) model data to AM systems. This file format was developed by Dave Albert of the Albert Consulting Group for 3D Systems in or around 1987, preliminarily for the commercialization of the first modern AM machine, the 3D Systems SLA-1. While the limitations and shortcomings of the format have been widely discussed, and alternative formats have been proposed, STL remains the de facto standard for AM.

Historical Overview

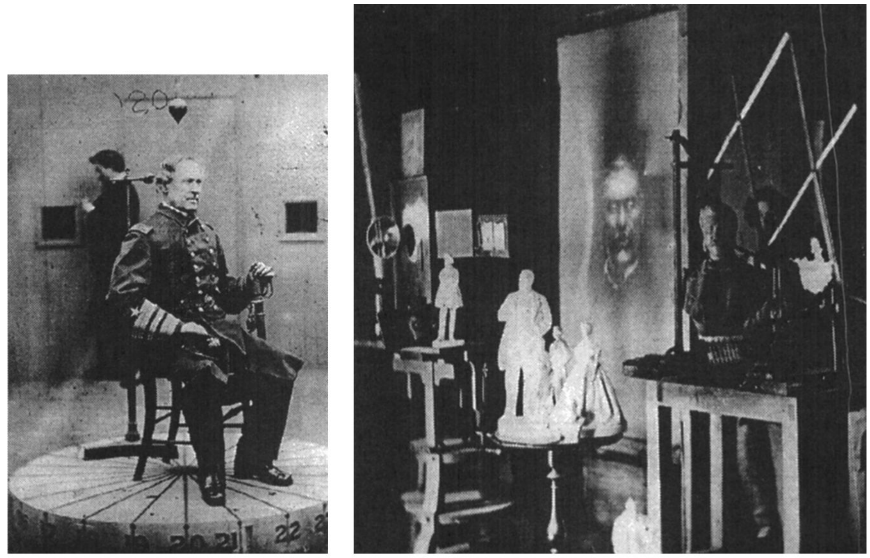
The history of AM may be split into three segments. The earliest, called AM prehistory, is characterized by additive part creation without the use of a computer. These approaches involved hand lay-up and date back to at least 1860. A second segment of AM process development occurred in the period from ~1968 to 1984. Called AM precursors, the AM machines here relied on the use of a dedicated computer. In this period, distributed computational capacity was growing and available. However, programming the computer was difficult and required a significant skill set. This skill set was known to the inventors of the processes in this period, but none of the inventions were successfully commercialized. This was in part due to the fact that an AM fabricator owner must have computer knowledge to use the machine, and few in society or technical fields had this knowledge or the interest in gaining it. Paramount was the requirement for a user/consumer to describe their AM part digitally by using design software such as CAD software. The landscape of distributed computing changed remarkably in 1984 with Apple Computer's release of the Macintosh computer. With its graphical user interface facilitated by a mouse, learning how to access the capabilities of a computer moved from learning a cryptic text-based screen and commands to "point and click" and "plug and play." Over a few years, societal knowledge of the use of and access to distributed computing exploded. This development created a foundation for commercialization of AM technologies, moving into the third segment of AM historical development, modern AM.

Additive Manufacturing Prehistory (~1860–1965)

This period of AM development is characterized by AM without the use of a computer. The oldest of the three main areas of AM development is photosculpture. Figure 1 shows the photosculpture studio of François Willème in Paris (Ref 4). A subject was positioned on a platform. Twenty-four cameras, each behind a small window, simultaneously took a photo of the subject from all sides. Two such small windows are shown in Fig. 1(a). Willème then used a pantograph apparatus to create 24 sectors of the sculpture by tracing the silhouettes of the photos. The pantograph linkage mechanisms shown in Fig. 1(b) are part of this technology. The assembled sculpture was then hand-finished by artisans. A photographic technique was invented by Baese (Ref 6) in which multiple cameras situated around a subject simultaneously took images. Photo plates consisted of a photosensitive gel that expanded upon exposure when treated with water, reproducing the surface contour of the subject. Monteath (Ref 7) used silhouettes and photoexpanding gelatin plates to create bas-reliefs of subjects. Morioka took multiple photographs of a subject illuminated by a banded light pattern of parallel light and dark lines (Ref 8). The approach allowed layered sections to be fabricated, which then were stacked to create an actual object representing the subject. Munz invented a vat polymerization process in the mid-1950s (Ref 9). The schematic of the device is shown in Fig. 2. The surface of a photosensitive resin based on silver halide or bichromated gelatin was exposed to light, which resulted in forming a solid, with the help of stopping/fixing agents. A piston was lowered to allow infill of more photosensitive resin, followed by re-exposure by the light source.

The second area of AM prehistory involves sheet lamination approaches using a hand cut-and-stack method. Blanther patented a method for creating 3-D paper contour maps from aerial topographical maps (Fig. 3, Ref 10). A thin wax sheet was placed over the map, and lines of constant elevation were cut into the sheet. The pieces were separated and stacked before repeating the process with different elevations. The end product was a set of molds, which, after smoothing and backing, was used as a die set for pressing the paper sheets into 3-D contour maps. The general concept was advanced by Perera, who used cardboard sheets (Ref 11), and Concordet (Ref 12), Zang (Ref 13), and Gaskin (Ref 14), who used glass or clear plastic sheets.

The third area of AM prehistory involved the use of weld deposition. The earliest known example of this is a patent by Baker that was issued in 1925 (Ref 15). Referred to as a class of ornamental welding, a weld head was used as a deposition tool and moved by hand to create a part, in similar fashion to modern-day polymer "doodlers." Figure 4 shows several illustrations from the Baker patent. A series of patents in the 1960s to 1980s dealt with weld deposition on a rotating mandrel. These included Garver (Ref 16), White (Ref 17), Ujiie (Ref 18), Brandi and Luckow (Ref 19), Gale and Fair (Ref 20), and Brown, Breinan, and Kear (Ref 21). All include the buildup of metal around a rotating cylinder, as shown in Fig. 5.



(a) (b)

Fig. 1 (a) Willème's photo apparatus (Admiral Farragut, seated). (b) View of Willème's studio in Paris, ~1865. Source: Ref 5

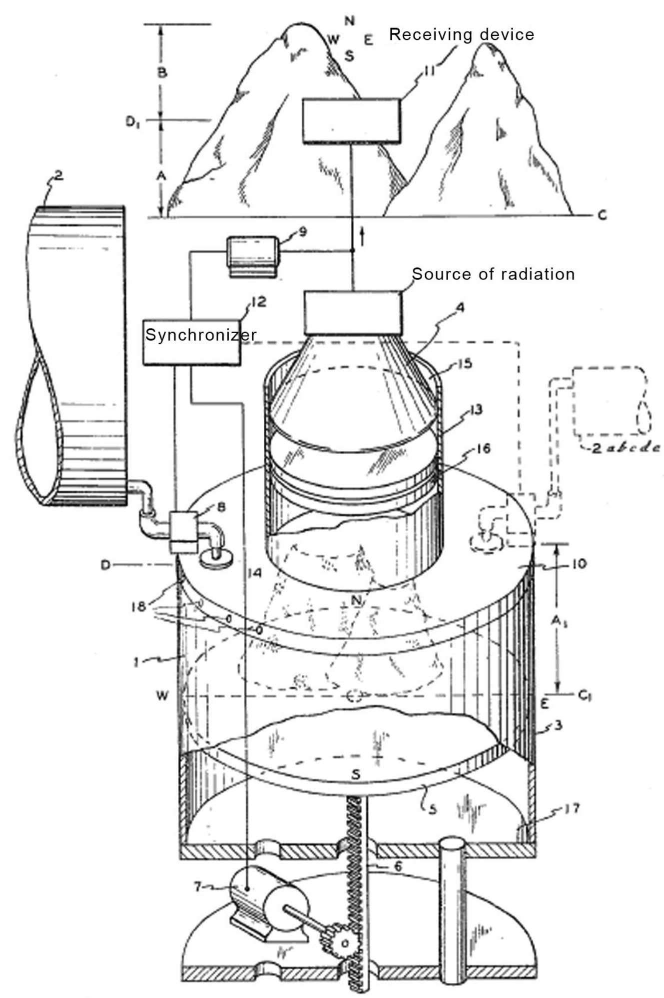


Fig. 2 Munz' photosensitive resin printer. The build platform (5) is lowered during the build. The light source (4) travels through optics (16) and into the vat of feedstock A, exposing the resin at level D. The mountain image at the top of the sketch is a radar-based recording device that sends an image to the light source (4). The part is shown by dotted lines in the build chamber and is built on the platform (5). Source: Ref 9

Additive Manufacturing Precursors (1968–1984)

Modern computers may date to the work of Turing in the mid-1930s. Early portable, that is, distributed, computers appeared in the mid-1970s. It is against this framework that precursor AM processes appeared. The inventors knew how to operate a computer and how to use it to drive a process. However, the operation of a computer was largely unknown to the general public. Therefore, it was not feasible for a computer-based machine to enter the market, because there essentially was no customer base. Common to the precursor AM processes were:

- A computer was used to drive the process.
- None were successfully commercialized.
- Most were forgotten.
- A number were rediscovered and successfully commercialized 10 to 20 years later.

Perhaps the earliest known use of a computer was in a laser crossed-beam approach proposed by Swainson in 1968 (Ref 22). Figure 6 shows a nontactile laser arrangement used to capture the geometric image. It is processed by a computer (item 66), and information is sent to a process chamber, where crossed lasers reproduce the object by solidifying material from liquid at the point of intersection of the two process lasers. A number of mechanisms were proposed for solidification, including use of photosensitive gelatins and "photoreversible photochromic material."

The use of a computer to control weld metal deposition was described by Ciraud in 1972 in a German patent application (Ref 23). As shown in Fig. 7, powder (item 9) is fed through a dispenser (item 8), where it is deposited into one or more energy beams (items 7 and 7a). The part (item 1) is formed in a layerwise fashion. In 1984, Masters filed a patent that described one or more computer-controlled "energy beams" that were used to create a freeformed object based on a computer solid model (Ref 24). Bronowski in 1985 patented a moveable weld head freeform approach (Ref 25). As shown in Fig. 8, a computer solid image of a part is created (item 1^1). It is processed through a computer (item 3), which sends build information to both a robotic weld head (item 11) as well as weld dams or "shoes" (items 14 and 15), which control the molten deposition at the part edges.

Matsubara (Ref 26) proposed a technique whereby photopolymer resin sheets containing refractory particles were selectively exposed to light. The unhardened portions were dissolved away, leaving a part that eventually could serve as a casting mold. Several inventors machined sheets of metal using a milling cutter followed by stacking and fixing the sheets. These included DiMatteo (Ref 27), Nakagawa et al. (Ref 28), and Kunieda and Nakagawa (Ref 29).

In 1979, Housholder filed a U.S. patent on what today (2019) would be described as powder-bed fusion. His intent was to create sand casting molds (Ref 30). One embodiment used a scanning laser beam and a powder bed, complete with laser scanners and recoating blade (Fig. 9). A computer was used to control the process. An early sand part produced by Housholder is shown in Fig. 10.

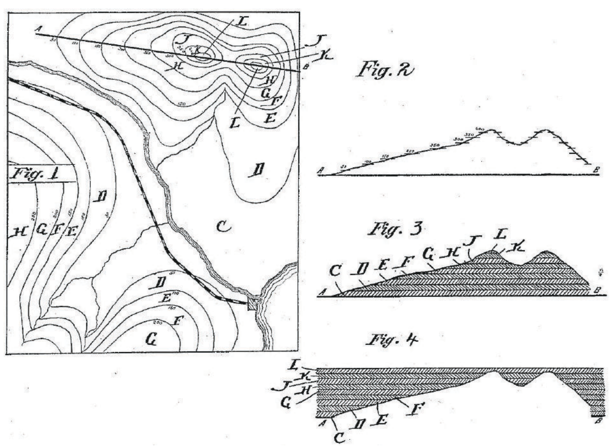


Fig. 3 Blanther's image showing a cut-and-stack approach for creation of a die set from a topographical map, 1892. Source: Ref 10

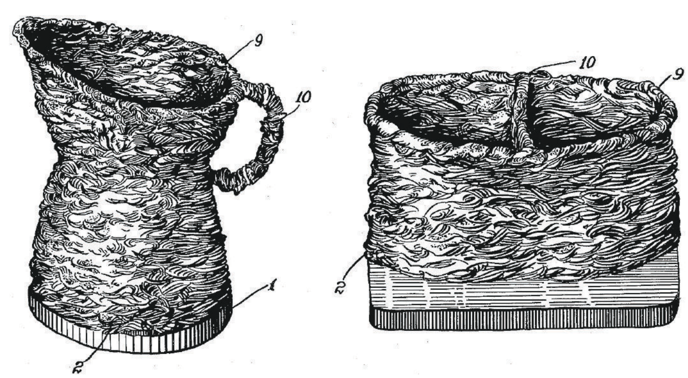


Fig. 4 Several objects made by using weld deposition. Source: Ref 15

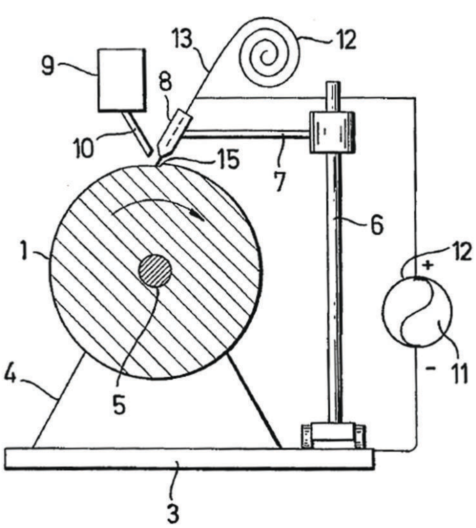


Fig. 5 Illustration of weld metal buildup around a rotating mandrel. Source: Ref 19

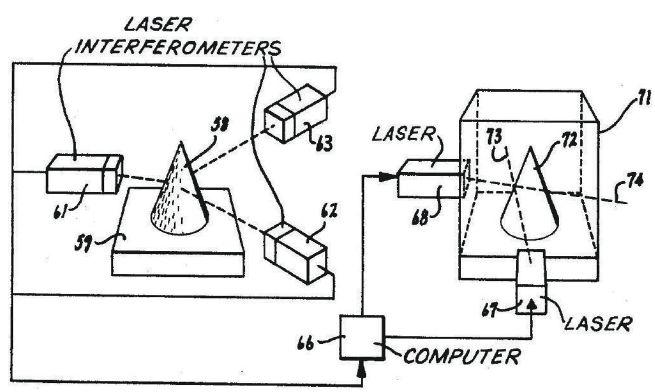


Fig. 6 First use of a modern computer to form a freeformed object. Source: Ref 22