A binder jetting system.

Introduction
to Additive Manufacturing

➤ **The idea of using a digital file to create a three-dimensional object is now a reality.**

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Additive manufacturing (AM) for ceramics has long been a dream, pursued in research labs and desired by industry. The idea of using a digital file to create a three-dimensional (3-D) object is now a reality, making the transition from rapid prototyping to part production. AM is a fairly new term adopted by the ASTM International Committee to encompass methods that build 3-D forms layer-by-layer using computer-driven technology.

AM is a completely different approach than traditional methods of subtracting materials from a larger workpiece (e.g., cutting, grinding) or conventional forming methods (e.g., pressing, casting, injection molding).[1] Terms such as 3-D printing, rapid prototyping, direct digital manufacturing, rapid manufacturing and solid freeform fabrication are often used to describe AM processes.

AM processes are driven by 3-D computer data, or stereolithography (STL) files, which contain information on the geometry of the object. STL files can be obtained from 3-D CAD software, medical scan data (e.g., CT, MRI), or from existing objects using point or laser scanners. The STL file, which breaks down the geometrical representation of the object into a simple mesh, can be manipulated into a suitable build orientation, and then digitally sliced into discreet 2-D layers. The process of layering is then conducted by the AM system through the deposition and bonding of 2-D layers.[2]

AM found its first market 25 years ago in the rapid prototyping of plastic mockup parts for product design.[3] As the technology developed, opportunities for tooling and direct part production followed, first in plastics, and more recently in metals and ceramics. Tooling examples include patterns built using 3-D printing of sand or wax for metal castings, and silicone rubber for urethane castings.

Direct part manufacturing of end-use parts is the fastest growing segment of the $1.3 billion market, increasing from 4% in 2003 to nearly 20% in 2010.[3] Examples include medical parts such as surgical implants, consumer products such as art ceramics and jewelry, and industrial parts such as impeller blades and aircraft ducting.

There is tremendous interest worldwide in evaluating the potential for AM as a useful and possibly disruptive technology. AM is generating excitement in many fields, from computer science and product design to new materials and lean engineering. AM has captured the imagination, but it is not always clear how ceramic materials fit into the picture.

General Advantages

One key benefit of using AM is the ability to easily fabricate complex shapes. Complexity adds cost to traditional processes. In general, the more complex the final shape, the more likely that AM will be of benefit.

AM also offers the freedom to redesign parts to decrease weight and more accurately serve their engineering purpose. For example, the shape of cooling channels can be optimized for fluid dynamics rather than restricted by the manufacturing method.[2]

Another important benefit is the ability to fabricate parts without expensive tooling or long lead times. Cost savings are associated with less production labor, material waste and energy consumption, as well as increased on-demand manufacturing. All of these factors provide varying degrees of impact depending on the specific product.

AM Technologies

As shown in Table 1, the seven AM categories offer more than 30 variations on the basic themes, each with its advantages and disadvantages. Binder jetting and material jetting are both considered 3-D printing methods using print heads with multiple nozzles. Material jetting is also called "direct printing," as the desired material is dispensed through the print head. This is in contrast to binder jetting, where only the binder is dispensed through the print head onto a flat powder bed of the desired material.

Table 1. Additive manufacturing categories as classified by ASTM.[4]

Category	Description
Binder jetting	Liquid bonding agent selectively deposited to join powder
Material jetting	Droplets of build material selectively deposited
Powder bed fusion	Thermal energy selectively fuses regions of powder bed
Directed energy deposition	Focused thermal energy melts materials as deposited
Sheet lamination	Sheets of material bonded together
Vat photopolymerization	Liquid photopolymer selectively cured by light activation
Material extrusion	Material selectively dispensed through nozzle or orifice

The binder jetting method was initially developed in the early 1990s at MIT and licensed to a number of companies.[2] It works by depositing a thin layer of powder onto a build platform or build box. The multiple array inkjet head, loaded with binder, is moved across the surface in the X-axis and indexed across in the Y-axis by a distance corresponding to the width of the print head array. The head is then traversed back in the X-axis, printing the layer in a series of stripes in the familiar manner of inkjet printers. The build platform is then lowered by 0.1-0.2 mm, and a second layer of powder is deposited.[2] The powder sticks together only where the binder has been printed.

The form is built layer by layer; at the end of the build cycle, the loose powder is removed by vacuum, revealing the part. The part is porous and, if desired, can be infiltrated or fired in a post-process step. This method is used for fine art ceramics, ceramic cores and large industrial sand molds for metal casting. The primary advantages for 3-D printing, especially binder jetting, are low cost,

AM Organizations and Events

- The National Additive Manufacturing Innovation Institute (NAMII) recently announced the location of its center in Youngstown, Ohio. NAMII was established as a pilot institute under the new National Network for Manufacturing Innovation (NNMI) infrastructure to help advance the U.S. manufacturing sector. NAMII is a public-private partnership with member organizations from industry, academia, government and workforce development resources. Visit www.namii.org to learn more.
- The RAPID conference, which will be held June 10-13, 2013, by the Society of Manufacturing Engineers (SME), is an industry-leading forum for the presentation and discussion of the latest development, trends, and techniques specific to additive manufacturing and 3-D imaging. Additional details are available at www.sme.org.
- The Additive Manufacturing Consortium (AMC) is a national group of industry, government, and research organizations engaged in the advancement of manufacturing readiness of additive manufacturing technologies. Instituted in 2010 by EWI and originally focused on metals, the consortium has since expanded to include ceramics. It has established a network to provide members with advice, development, performance testing and qualification of additive processes. For more information, visit http://ewi.org/additive-manufacturing-consortium.

high speed, scalability, ease of building parts in multiple materials, and versatility for use with ceramic materials.[1]

Originally evolved from systems that used thermoplastics, the material jetting method has been modified to accept ceramic slurries or ceramic powders in wax or liquid binder carriers. Material jetting has significant challenges, including getting materials to flow through nozzles at reasonable speeds without clogging. Work is ongoing to improve the rheology of material systems for ceramic materials such as alumina, zirconia and PZT. This method promises good surface finishes and high tolerances for parts that can be printed and then fired to high density.

Powder bed fusion originated with selective laser sintering (SLS). SLS uses a powder bed layer in a build box, similar to the binder jet method, but it is placed in a system that brings the powder to an elevated temperature and then exposes select areas to a laser beam. This causes localized sintering of the ceramic powder. The part has sufficient strength for handling, but requires a conventional post-process firing to achieve full density. All powder bed fusion methods share certain characteristics, including one or more thermal sources for inducing fusion or sintering between particles, a method for prescribing fusion in a region of each layer, and mechanisms for adding and smoothing powder layers.

Electron beam melting has become a popular approach to powder bed fusion as it is fast, efficient and can provide fully dense parts. The down side for ceramics is that the powder bed needs to be electrically conductive. Directed energy deposition is also a technique that is better suited to metals. Vat polymerization is used for polymers that can be loaded with ceramic powders.[4]

The sheet lamination method was an early rapid prototype method used for plastics and paper that has now been adapted for ceramic tapes. Green tapes are precision cut, stacked and fired. Extremely fine features with high tolerances can be obtained. This method is being used to form microfluidic devices with thousands of channels.

Material extrusion, including fused deposition modeling, melt extrusion, and gel formation, can easily be envisioned as play dough or icing being squeezed from a nozzle and then bonding to itself in the next layer. Most of the applications have focused on plastic systems, but the technique lends itself to ceramics. Examples of industrial ceramic parts include specialty crucibles and filters.

A water jacket core for an engine produced by binder jetting.

A pump impeller core produced by binder jetting.

System Vendors and Fabricators

Many of the major system vendors are listed in Table 2. Table 3 includes companies that use AM to fabricate parts for their customers, with a focus on ceramics. The landscape is changing rapidly, with several of the larger companies acquiring others. 3D-Systems is a fast-growing AM company that offers software and equipment for all of the basic AM categories. Its systems readily produce wax and polymer forms that can be used as molds for ceramics (e.g., in the dental industry), but the company doesn't have a strong presence in direct fabrication of ceramics.

ExOne has developed the largest volume, fastest systems for handling ceramic materials, driven by the success of 3-D printing for sand casting molds. A build chamber of 400 x 250 x 250 mm is available, with speeds of 30 seconds per layer. Viridis 3D uses modified Voxelijet equipment to produce sand molds and cores. Both of these companies sell special ceramic blends and other supplies for 3-D printers. AM of ceramic molds and cores has been a game changer for the metal casting industry. Binder jetting is best suited due to its low cost and speed. The as-printed product is porous, exactly what is needed for casting.

Companies such as EOS and Phenix Systems sell equipment based on the selective laser sintering method that can be used for ceramics. Materials Solutions uses EOS equipment to make parts and develop processes for customers. This method is taking off for metals, but information on ceramic products is scarce. The laser method is more costly and slower than binder jetting. Current research efforts at several universities and government labs may yet discover the best fit for this method in ceramic applications.

AM offers significant materials challenges (especially for ceramics) that present a large barrier for entry. Ceralink has recently become involved in AM through client requests, both from the equipment side and from parts manufacturers. Ceralink specializes in ceramics, composites, and metals contract R&D, as well as fast manufacturing methods such as microwave heating and radio frequency lamination. Ceralink is currently developing methods and procedures for ExOne to expand the range of printed metal and ceramic parts.

Two methods that have quietly proved their value in ceramic part fabrication are material extrusion and sheet lamination. Developed at Sandia National Laboratories in the 1990s, robocasting was specifically designed to extrude ceramics such as alumina through a nozzle using a robotic arm. Robocasting Enterprises licensed the technology and offers fully dense specialty parts in a variety of ceramic materials. CAM-LEM can also fabricate fully dense ceramics (e.g., in alumina, AlN and silicon nitride) by laminating tapes, exactly aligned, that have precisions features cut into them.

Challenges and Industry Needs

Though significant progress and technological advancements have been made by the emerging AM industry, many challenges still lie ahead related to materials development and adoption beyond niche applications. Post processing to achieve high densities is a main challenge for the AM methods that produce porous parts. Early industrial adopters (e.g., ceramic molds and cores) don't require further densification. A next step is to produce integrally cored molds for investment casting. AM has also been successful in fine art ceramics, where densification is assisted by a liquid phase and tolerances are not as stringent.

Materials considerations such as rheology, powder flow, powder packing, particle shape and size distribution can impact product quality factors, including surface finish, density, uniformity, and dimensional integrity. AM offers possibilities to make structures that are difficult or even impossible with traditional methods, but strategies must be developed to achieve success. Many applications will require hands-on experimentation by ceramic engineers and material scientists. For example, there is a strong interest in making graded structures similar to bone, where a more porous inner region is formed within a dense outer structure.

It will be important to identify and better understand the processing-structure-property relationships with the different AM methods to ensure predictability of produced parts.[5] Standardized mechanical and physical property data, for instance, must be determined on the many material and processing combinations offered by the AM industry to allow for comparison to traditionally produced counterparts. ⊕

Editor's note: All of the photos included are courtesy of ExOne.

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Table 2. Major additive manufacturing system vendors.

System Vendor	Method/ Specialty	Material
3D-Systems* (US,AUS,NED, ITA)	Binder jetting, material jetting, vat photopolymerization, powder bed fusion, material extrusion	Metal, polymer
Arcam (SVE)	Powder bed fusion	Metal
Envisiontec (GER, US)	Vat photopolymerization	Polymer
EOS (GER)	Powder bed fusion	Ceramic, metal, polymer
ExOne* (US, GER, JPN)	Binder jetting	Ceramic, metal, polymer
Fabrisonic (US)	Sheet lamination	Metal
Objet (ISR, US, GER, Asia)	Material jetting	Polymer
Optomec (US)	Directed energy deposition	Metal
Phenix Systems (FRA)	Powder bed fusion	Ceramic, metal
POM* (US)	Directed energy deposition	Metal
RepRap (UK)	Material extrusion	Polymer
Stratasys* (US, GER, IND)	Material extrusion, material jetting	Polymer
Voxelijet* (GER)	Binder jetting	Ceramic, metal, polymer

**also part fabrication*

Table 3. Companies that fabricate custom or production ceramic parts using additive manufacturing.

Part Fabrication	Method/ Specialty	Material
3D Ceram (FRA)	Vat photopolymerization	Ceramics
3D Printsmith (US)	Prototyping, consulting	Ceramics, metals
CAM-LEM (US)	Sheet lamination, prototyping	Ceramics, metals
Ceralink Inc. (US)	Binder jetting, R&D, consulting, materials development	Ceramics, metals
Materials Solutions (UK)	Powder bed fusion, R&D, consulting	Ceramics, metals
Robocasting Enterprises (US)	Material extrusion	Ceramics
Shapeways (US)	Binder jetting	Ceramics, metals
Viridis 3D (US)	Binder jetting, R&D, consulting	Ceramics, metals

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