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Applications

Once reserved for concept modeling and rapid prototyping, additive manufacturing has expanded in recent years to include applications for metal casting, as well as jigs, fixtures, drill and cutting guides, and other types of tooling. Every day, new and innovative applications are emerging for the production of end-use parts and final products. More and more, production challenges involving three-dimensional objects can be solved faster, better, and in many instances, at lower cost, using AM technology.

Prototyping

Prototyping was among the earliest applications of AM technologies and remains one of the most popular tools for product development. As material properties, surface finish, and dimensional accuracy have improved, AM models have been increasingly used for functional prototyping and for fit and assembly testing. AM parts are also being used as patterns for tooling and metal-casting processes.

Visual aids and presentation models

If a picture is worth a thousand words, then surely a physical model is worth a thousand pictures. The value of a tangible model for communicating design intent was the driver for the earliest successes of additive manufacturing. Models can help clarify ambiguities in engineering drawings and design specifications and can mitigate project overages in terms of lead times and cost.

Models can be used to protect priceless originals. One example is the classic James Bond Aston Martin DB5, which appeared in the movie *Skyfall*. Three 18-piece scaled plastic replicas were used as "body doubles" on the set. The pieces were printed on Voxeljet equipment. The models were exquisitely finished, lacquered, chromed, and assembled at UK-based Propshop Modelmakers Ltd. The finishing touch on one of these detailed models included bullet holes. One of the replicas was auctioned by Christie's for $100,000.

3D-printed Aston Martin DB5 replica, courtesy of Propshop Modelmakers Ltd. (now Voxeljet UK Ltd.)

Another example is when urban designers and architects need topographic models that communicate accurate terrain, 3D printing affords quick and precise representation. Trust System Corp. in Japan is able to provide its clients with easy-to-understand, value-added 3D terrain models.

Multi-color 3D print of Mount Usu volcano, courtesy Trust System Corp.

Prototyping is a critical tool for industrial designers, and is an especially pivotal phase for students of the discipline. Having the opportunity to prototype is crucial to these students for learning about complex surfaces, assembly design, machine constraints, and the characteristics and real-world applications of materials.

Student transportation design project, designed by Titus Liu, courtesy of Art Center College of Design

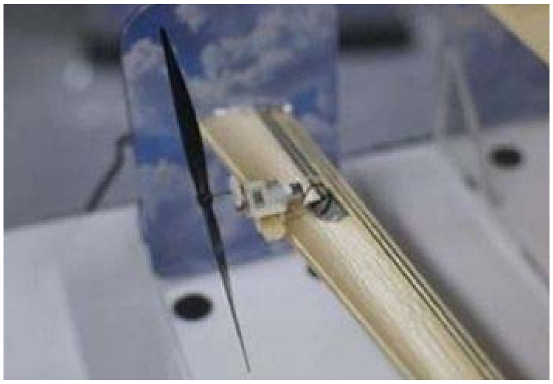
Fit, function, and assembly

Additive manufacturing has progressed far beyond fragile models, and advances in system technology and materials have opened the door to fit and functional testing of sophisticated designs.

Scientists at Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) streamlined the design and production of fish tags at Lab 22, a 3D printing facility in Melbourne, Australia. Using an Arcam EBM system, the team was able to design, re-design, and produce titanium fish tags in less than one week with less material waste. Established in October 2012, Lab 22 manufactures a range of prototype products including biomedical implants and automotive, chemical processing, and aerospace parts.

A lineup of fish tags, showing progression of the design from the earliest (left) to the latest prior to fitting with wires and electronics, courtesy of CSIRO

Two AM system manufacturers worked together to combine AM with printed electronics to create a functioning assembly for Aurora Flight Sciences. They produced two “smart wing” structures for an unmanned aerial vehicle (UAV). Stratasys manufactured the wing structures with FDM, using ULTEM 9085 aerospace-grade thermoplastic. Optomec then used its aerosol jet process to print electronic circuits and active devices directly onto the wing structures. Printed circuits included a strain gauge, an RF antenna (which has a small video camera attached to it), a circuit that delivers power to a propeller, and an LED. The wings were shown at the Defense Manufacturing Conference in December 2011.



Smaller of two UAV “smart wings” with printed circuits powering a propeller and LED, courtesy of Optomec and Aurora Flight Sciences

Two engineers at SelectTech Geospatial (Springfield, Ohio) designed and built a UAV using a Dimension 3D printer from Stratasys. The designers had no aeronautical design education, and relied on iterative design, prototyping, and testing to refine and improve their drone. The result of this exercise was an airframe built entirely out of ABS. Environmental control system ducting was integrated into the structure, as can be seen in the following CAD image.

CAD image of fuselage-to-wing interface for UAV (left) and UAV on flight line (right), courtesy of Stratasys

This application illustrates the power of design iteration, combined with quick-turnaround, functional prototyping. The full-size production UAV will have a carbon-fiber airframe for a superior strength-to-weight ratio.

Tooling

by Michael Siemer

In cases where AM cannot overcome the need for tooling, opportunities may still exist for using AM to produce the necessary molds or inserts for production. Several tooling options are available that can yield molds in a variety of plastics, composites, and metals.

Two broad categories of tooling are available through AM. One category is an indirect approach, where master patterns are used to produce a mold or die. An example of a pattern-based, indirect method is a silicone rubber mold produced from an AM master. The second category is a direct approach, where an AM machine builds the actual tool or tooling inserts directly.

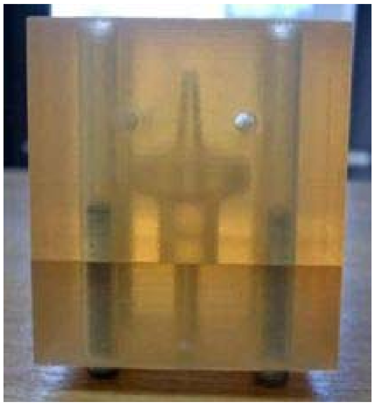
Silicone rubber tooling has been used for decades to make urethane parts, and sometimes epoxy parts. The process employs thermoset resins instead of thermoplastics, but many material options are available that mimic common thermoplastic materials.

AM-produced master pattern (upper left) and molded urethane casting (center), courtesy of Met-L-Flo

A number of other indirect, pattern-based methods of prototype and short-run production tooling have been developed. Visit wohlersassociates.com/ tooling2015.pdf to read about many of these methods. Several have been commercialized, but few have experienced success in the marketplace. Silicone rubber tooling has been, by far, the most successful.

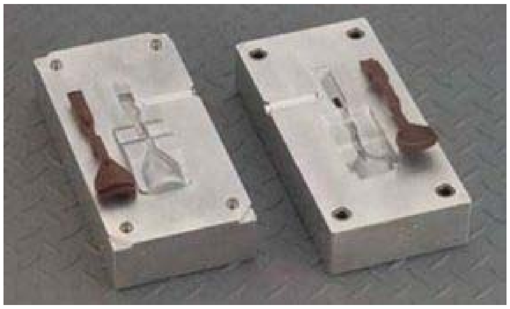
Direct approaches to tooling using AM do not require the production of a pattern. Instead, AM processes are used to produce tooling or tooling inserts directly. These approaches can be used to reduce the number of steps in the tool-making process, which can yield both cost and schedule benefits, depending on the geometric features and processes required.

The following image depicts a three-piece stereolithography tool used to make a tip for a silicone cervical cell collection device. The shape of the part, which entails undercut features, was injected using silicone rubber. The part was removed using air pressure to expand the component away from the inner, die-locked core.



Three-piece stereolithography tool for rubber molding, courtesy of Met-L-Flo

The following example is an aluminum tool used to produce wax patterns for investment casting. The tool was made by ultrasonic additive manufacturing from Fabrisonic.



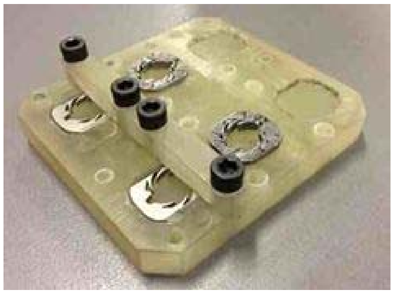
Aluminum tool and wax investment casting patterns produced with UAM, courtesy of Fabrisonic

Another advantage of using AM for tooling and inserts is the capability to create conformal-cooling channels within the tool. These channels allow coolant to pass through the mold in passages that conform to the shape of the mold cavity. Conformal cooling removes heat from the mold or die faster than the straight-line channels in machined tools. Tests suggest that conformal cooling can reduce cycle time by 30% or more and improve part quality. The result can have a significant impact on part cost and production rates.

Linear Mold (Livonia, Michigan) produces inserts for injection molds on a regular basis and has used DMLS technology from EOS to produce tooling inserts for nearly a decade. The following image shows an automotive door handle produced in 30% glass-filled nylon that initially used conventional, machined P20 tool steel cores. The original tool performed poorly, with a high scrap rate and cycle-time performance issues. New cores with internal conformal cooling channels were re-created using DMLS, resulting in a cycle time reduction from 35 to 16 seconds (a 54% improvement), less part distortion, and a lower defect rate.

Automotive door handle (left) and DMLS conformal cooling cores (right), courtesy of Linear Mold

AM is also being applied successfully to the production of many other types of tooling, including jigs, fixtures, templates, gauges, drill guides, and other devices. The following image shows a machining fixture tool produced on an Objet Eden333. Titanium clips, which were produced on DMLS equipment, were held on the six-cavity fixture for a machining operation to remove metal support structures. Finished clips are shown on the left of the photo and unfinished clips are shown in the center. Although not visible, the bottom surface of this tool does double duty as a fixture for another part.



Machining fixture produced with PolyJet technology, courtesy of IMDS

Real, value-added change can take a long time to implement. Even as effective AM tooling methods evolve, a company that is already very knowledgeable and efficient in its current methods will typically be reluctant to initiate change. The most effective driver for change is often competition. When a few trailblazers prove the value of an emerging process, competitors often follow.

Metal casting

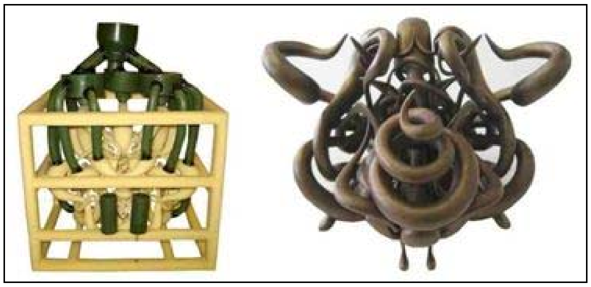
AM processes have long had applications in metal casting. Sand, flask, and investment casting are a few of the processes that can be driven with AM patterns, as well as AM molds and cores. The success of AM techniques in metal-casting applications varies considerably from one casting process to the next. These processes are explained at wohlersassociates.com/castmetal2015.pdf.

Pattern-based sand casting for an Orlando theme park ride part, courtesy of Mydea Technologies

For metal casting in small to medium-sized runs, many organizations use patterns from an AM process in conjunction with investment casting. These patterns are made of wax or a material that behaves much like wax during the shelling and furnace processes at investment-casting foundries.

QuickCast stereolithography pattern used for metal investment casting, courtesy of Mydea Technologies

Using AM for investment-casting patterns has become a standard practice across a variety of industries including automotive, medical, and jewelry. Voxeljet's AM equipment produces PMMA patterns for investment castings such as the metal artwork shown in the following image. Wax sprues were attached to the original AM pattern post-build. The final bronze casting is shown on the right. Other common AM processes and techniques used in producing patterns for metal investment casting include the QuickCast stereolithography build style, laser sintering, multi-jet modeling, and FDM material extrusion.



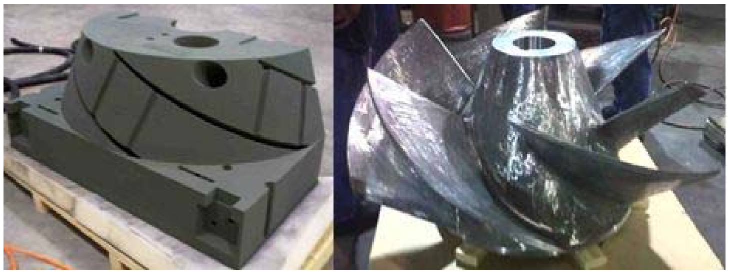
Yellow PMMA pattern with green wax sprues (left) and the final metal casting, courtesy of Voxeljet

Metal castings come in all shapes and sizes, and span many industries. The jewelry industry uses AM technologies to make some of the smallest, most precise metal castings. Wax-based AM systems provide jewelers, goldsmiths, designers, and large jewelry manufacturers a way to quickly go from design to wax patterns that are used for lost-wax castings.

Art and design programs at universities have taken the lead in training and developing new designers and operators of advanced manufacturing equipment and post processes. At the Kendall College of Art and Design (Grand Rapids, Michigan), the Metals and Jewelry Design department operates a digital fabrication lab. The lab’s Solidscape R66 3D printer is used to make patterns for casting. The design curriculum in the Metals and Jewelry program emphasizes the role of digital technologies within the traditional setting of training in the craft. Students are taught hand skills such as stone setting and metal casting alongside CAD design and additive manufacturing.

Wax pattern (left) made on a machine from Solidscape and final product (right), courtesy of Caitlin Skelcey

Standard Alloys, a foundry, machine shop, and part repair facility in Port Arthur, Texas, faced a critical lead time requirement for producing an impeller for a large pump. It turned to ExOne, which has a regional office in Houston, to shorten the sand-casting process. ExOne built the core for the 1,450-mm (57-inch) diameter impeller in less than a week. The core was split and printed in two different builds on the Max Platform, then pieced together for use at the foundry. This process eliminated the need for a corebox to produce the core, and reduced the time required to produce and deliver the serviceable impeller casting to less than eight weeks.



One half of split core (left) and finished impeller (right), courtesy of ExOne

The following images further demonstrate the sand casting process using AM-produced molds and cores. The sand mold and core were produced on a Voxeljet system. The Voxeljet V4000 is capable of producing sand mold components with dimensions up to 4 x 2 x 1 m (157 x 79 x 39 inches).

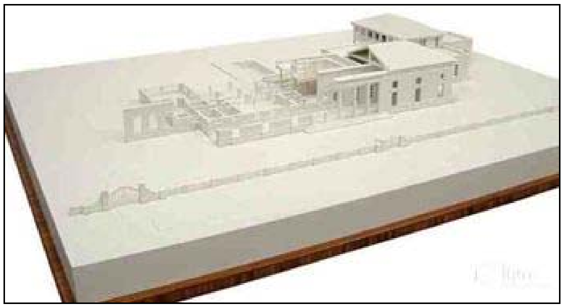
Sand mold and core (left) and unfinished casting (right), courtesy of Voxeljet

Architectural

by Charles Overy

AM technologies have a variety of uses in architecture including conceptual design, client communication, public meetings, and display. Physical models are a well-accepted method of design communication, and the favorable reception of AM models is increasing in the architectural field.

RMT Architects designs premium homes and other projects for U.S. clients. It frequently commissions a physical model before construction for design review with the client. For a custom residence, RMT commissioned a model at a scale of 25.4 mm = 2.44 m (1 inch = 8 ft.) that displayed both the interior and exterior spaces. RMT's CAD model in SketchUp was processed in CADspan and Materialise Magics, and was then sectioned. The sections were built on LGM's ZPrinters. The building site's terrain was machined from a urethane block. Total fabrication time was under two weeks.



Residential model for RMT Architects, courtesy of LGM

AM technologies provide architects and civil engineers with the ability to modify models and present ideas in public meetings where drawings and two-dimensional images are difficult to comprehend. Jacobs Engineering is involved in the redesign of an aging highway bridge in Glenwood Springs, Colorado. The bridge's design and construction plan have received a great deal of local attention. Shapeways built the bridge shown in the following image using laser sintering from civil engineering CAD drawings processed by LGM. The surrounding buildings were drawn in Studio Max by a contractor, imported into and processed with Magics, and printed on

ZPrinters. The surrounding terrain was machined. The model is being used for public meetings and display. As the project progresses, the model will be updated. Two to four alternative bridge designs were scheduled to be fitted to the model to help visualize options.

Model of Glenwood Springs bridge for Jacobs Engineering and Colorado Department of Transportation, courtesy of LGM

Because AM has reduced the time to build a model, firms can create prototypes for their clients at varying scales for different purposes. Blast Deflectors Inc. (BDI) builds airplane enclosures for ground testing of jet engines at airports around the world. For an airport in Dubai, BDI commissioned a large, full-color model. It was constructed from parts built on Objet and ZPrinter machines, and was painted after the parts were assembled.

Model of engine ground test enclosure for Dubai airport, courtesy of LGM

3D printing is also changing the way traditional architectural models are made. The capability to show clear windows and the transparency of a building are often critical to conveying a design. Patrick McCauley, the master model maker for Centerbrook Architects and Planners, used both clear and opaque stereolithography resins in the model shown in the following image of the Southern Connecticut State University Library. The center glass elements were built in clear SL resin as a single piece, and then the building cladding bands were masked and painted. The wings of the buildings were built in opaque SL resin, and then masked and painted to match the brick and concrete textures. Small details such as light posts and columns were also fabricated in SL, interfacing well with the traditional machined and laser-cut base and terrain elements.

Model of Southern Connecticut State University library, courtesy of Centerbrook Architects and Planners

Medical

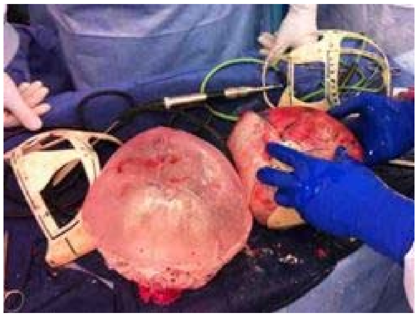
by Andy Christensen

Medical applications range from non-custom, off-the-shelf implants to custom models for surgical planning, custom implants and prosthetics, and personalized instruments for surgical procedures. AM has made inroads in all of these applications, and several products made with AM processes have received regulatory clearance.

Anatomical and surgical models

Anatomical models produced by AM are made for a specific patient using data from a medical-imaging study, predominantly computed tomography (CT) or cone-beam computed tomography (CBCT). These physical replicas of a patient's internal bone or soft-tissue structures are useful to surgeons for planning complex surgical procedures and deciding on the best courses of action for treatment and procedures.

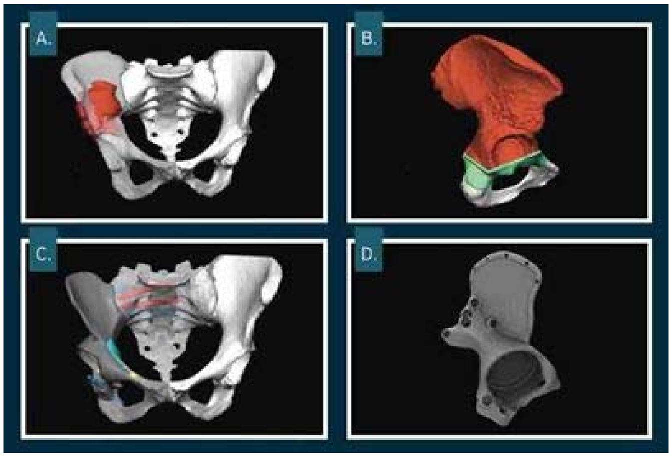
Typically, models for planning bone reconstructive surgery are used by specialists in the areas of neurosurgery, oral and maxillofacial surgery, plastic surgery, spine surgery, orthopedic surgery, and otolaryngology (ear, nose, and throat surgery). The most common uses for models include bending metallic reconstruction plates for fixation, creating custom implants, and measuring and fitting complex devices meant to lengthen shortened bone segments such as a leg or jawbone. Reported benefits of these models of bony anatomy include 1) shortened surgical procedures because of advanced planning, 2) better results based on the ability to optimize bone reconstruction, and 3) custom, patient-specific implants to fit a patient's unique anatomy.



Cranial SL model being used in surgery to contour the patient's bone for a better fit, courtesy of Medical Modeling Inc.

Custom prosthetic design

Once medical professionals were able to work in a virtual, three-dimensional space with a patient's unique anatomy, it was only logical that custom designs of implants and other prosthetics would follow. Custom prosthetic design has proven to be one of the most widely used AM-facilitated applications in the medical industry as shown in the following image.



Digital design of a custom implant: A) tumor highlighted in the right hip; B) large amount of the bone to be removed (in red); C&D) digital design of a custom implant; courtesy of Medical Modeling Inc. and Ossis

Traditionally, many custom implants were designed and made by hand, using an anatomical model as a basis and artistry for design. Moving to a more digital workflow for design of implants has led to more control and consistency, as well as a reduction in total design time.

Virtual surgical planning and personalized surgical instruments

One of the most interesting developments to come out of the medical AM field over the last few years involves a combination of computer-based surgical planning and custom, personalized instruments produced for guidance during surgery. Virtual surgical planning is quickly becoming a standard of care for guided total joint replacement of the knee and for complex maxillofacial reconstructive surgeries.

By simulating the surgical procedures prior to surgery and using personalized surgical guides, templates, and instruments, the surgeon and other members of the medical team can better care for the patient. They can do so by 1) improving or perfecting the surgical plan, 2) improving efficiency in the operating room with intuitive tools and better knowledge of needed hardware before surgery, and 3) improving patient outcomes. Common applications of this technology include reconstruction of the facial skeleton for cases of trauma and tumors and for reconstruction of the knee by total knee arthroplasty (replacement). All of the largest orthopedic implant manufacturers are using this technology and report that tens of thousands of patients are being treated with guided surgery and custom AM-fabricated instruments every year.

Custom cutting guide in use during surgery to resize a patient's jawbone; the guide was designed with CAD and manufactured with stereolithography, courtesy of Medical Modeling Inc.

Custom and off-the-shelf AM-fabricated implants

Additive manufacturing of implants in materials such as titanium, titanium alloys, cobalt–chrome alloy, and polyetherketoneketone (PEKK) is being carried out across the globe at an increasing rate. With regulatory approvals in Europe and the U.S. spurring some of the growth, many implant products made by AM are available in the U.S. market. The metal powder bed fusion processes from Arcam and EOS are used for the fabrication of metal implants, and laser sintering has been used to produce implants in both PEEK and PEKK.

Most of the interest in using AM for fabricating implants stems from its ability to produce porous structures of almost unlimited geometric complexity. In orthopedic surgery, porous surfaces are helpful for implants that will be implanted next to bone. An implant is better fixated by using screws and by the mechanical "locking" of bone to the implant surface. This locking is caused by porous surfaces, historically added to smooth implants by the means of plasma spray coatings, beads, and other methods to produce roughed, "bone-friendly" surfaces. With AM, the porous surface can be three-dimensional, and is created as an integral part of the implant fabrication process. Tens of thousands of AM-fabricated metal implants are currently produced every year, and this number is expected to grow into the hundreds of thousands.

Off-the-shelf (non-custom) acetabular cup with integrated 3D porous surface for total hip replacement surgery; produced in titanium alloy using EBM, courtesy of Arcam

Biocompatibility of AM materials

A variety of AM materials can be used for most medical-modeling applications. Some applications, however, require the material to be "medical grade." Certain processes produce models in ISO 10993-tested materials, which may allow for sterilizing the model and limited in-vivo exposure to human tissue (i.e., in contact with human tissues for short periods of time). Applications include the use of anatomical models for intra-operative reference and new instrument design and testing during actual surgery. It is important to note that this does not imply that these materials can be implanted. The only known commercially available AM polymer that can be implanted is polyetherketoneketone (PEKK) sold by Oxford Performance Materials (South Windsor, Connecticut). These PEKK implants are manufactured using plastic powder bed fusion systems.

AM materials are available that have passed certain baseline standards for biocompatibility. Machine and material suppliers should be consulted for a list of materials that have been tested to ISO 10993 standards for biocompatibility. Even though a raw material may successfully pass ISO 10993 tests, it does not mean it can be used without further, more product-specific, testing. Once a company has established its particular manufacturing process steps, the tests must be performed with "as-processed" parts. This ensures that the manufacturing process, if controlled, will yield parts that are suitable for use in a particular application. Depending on the product application, further testing may be needed to qualify the material for the application.

Regulatory clearances of AM products

Several AM products have gained marketing clearance from the FDA through its 510(k) pre-market notification or full pre-market approval (PMA) process. Most of these devices have been short-term-use, custom instruments such as knee-cutting guides. The first FDA clearance of a metal AM implant was in September 2010, when it approved a hip implant commercialized by the orthopedic firm Exactech (Gainesville, Florida). Since that time, several additional FDA clearances have occurred that relate to custom instruments (mostly built using LS and SL processes) and other long-term implants for the hip, spine, extremities, and cranium.

Many tens of thousands of acetabular cups had been manufactured using EBM by Adler Ortho, Lima Corporate, and other orthopedic implant manufacturers. About 50,000 acetabular cups are estimated to have been implanted into patients around the world. Five companies are operating more than 25 EBM machines and are in full production with the technology.

EOS claims to have received at least two FDA 510(k) clearances for implants between 2011 and 2013. One of these is a titanium alloy part for foot and ankle surgery marketed by Trilliant Surgical (Houston, Texas).

Oxford Performance Materials received FDA 510(k) clearance for the first polymer AM implant in February 2013. Its custom cranial implant is patient-specific and produced on laser sintering equipment in polyetherketoneketone (PEKK). The first U.S. implant was created and implanted in March 2013.

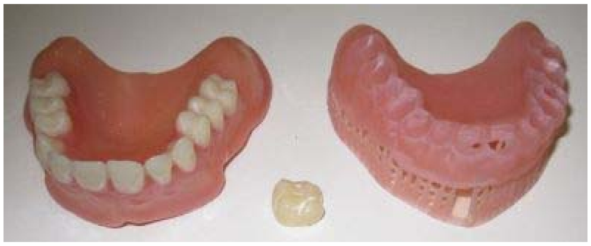
Dental

by Steven L. Rouse

EOS, the German-based manufacturer of laser sintering systems, has an installed base of about 100 EOSINT M (metal) machines in the dental industry. According to the company, these machines are producing more than five million copings each year for the production of dental crowns and bridges.

Build platform of cobalt–chrome copings, courtesy of 3D Systems

The newest AM dental applications are removable partial dentures and dental models. Intraoral scanners enable dentists to send files directly to manufacturing centers, eliminating the need for hand-trimming the dental device at the final fitting. This technology is being implemented extensively in Turkey, where the need for dental restoration is believed to be high.



Plastic dental models, courtesy of Envisiontec

Stratasys Ltd. is another large player in the dental industry for the fabrication of models, abutments, copings, and crowns using PolyJet printers. PolyJet has proven to be an excellent technology for the manufacture of surgical guides for placing dental implants and for other surgical templates. The UK-based orthodontics lab Clearstep uses PolyJet systems to make models for clear orthodontic positioners.

3D Systems' ProJet 3500 systems use multi-jet modeling technology to produce wax patterns for use in traditional casting and for dental models.

Build platform of waxups for copings, crowns, and bridges, courtesy of 3D Systems

Envisiontec's 3Dent system has a vertical speed of 10 mm (0.4 inch) per hour, so an estimated 100 cases per day can be produced on a single machine. Typical cases are comprised of dental models for crown and bridge fabrication, wax-filled photopolymers for castings, and orthodontic devices. Drill guides, temporary crowns, and partial denture patterns are also common applications. Envisiontec also offers other systems for dental applications.

Direct part production

It has been said that 3D printing will revolutionize the way we manufacture almost everything. From collectables and consumer products manufactured by individuals to large-scale production in many industries, the applications for AM are vast. Increasingly, many individuals and organizations are using AM to produce parts that go into final products.

The production of parts using AM is expected to far surpass the current scale of rapid prototyping. The ratio of prototypes to production parts is often 1:1,000 or much greater. In other words, for every 1,000 end-use products manufactured, only one prototype is produced, although this ratio varies widely from product to product and industry to industry. The opportunity for more commercial production activity from AM is immense.

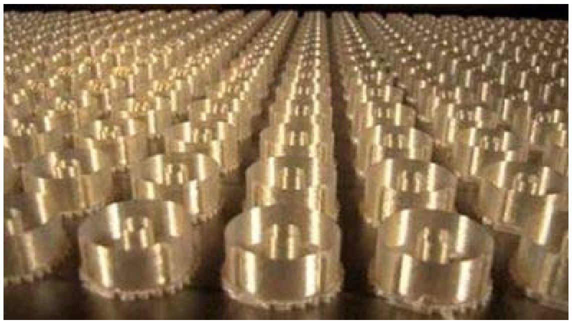
AM is being used for custom and replacement part manufacturing, special-edition products, short-run production, and even series manufacturing. The examples that follow reveal some of the pioneering efforts behind these exciting developments.

Aerospace

GE Aviation will produce the fuel nozzles for its next-generation LEAP engine using metal AM technologies. In the conventional manufacturing process, 19 metal parts are brazed together to achieve a fuel injector assembly that mixes fuel and air. The fuel nozzles are scheduled to be in production by late 2015 or 2016, and eventually will be produced in quantities exceeding 40,000 per year.

Kelly Manufacturing Company (KMC) of Wichita, Kansas is the world's largest manufacturer of aircraft instruments. Its M3500 instrument is a "turn-and-bank" indicator that provides pilots with the rate of aircraft turn. One component of the M3500 is the toroid housing, a part that was produced by urethane casting. Delivery time for 500 castings was three to four weeks.

KMC shifted its production away from urethane castings to a Fortus production system from Stratasys using ULTEM 9085, which is flame, smoke, and toxicity compliant. The new parts offer substantially better dimensional accuracy. Best of all, 500 toroid housings can be built in a single run on a Fortus 900mc system. "The lead time for 500 units has been shortened to three days from order to delivery of parts," said Justin Kelly, president of KMC. Tooling costs have been eliminated, and the cost per piece has dropped 5%.



Build platform with 100 ULTEM 9085 toroid housings, courtesy of Stratasys

Several parts for the small CubeSat satellite in the following image were made by laser sintering. The satellite's main structure is produced with the Windform XT material from CRP Technology. The parts are plated in a high phosphorus electroless nickel to provide radar reflectivity for tracking purposes.

Assembled CubeSat satellite (left) and laser-sintered parts (right), courtesy of the RAMPART CubeSat team

DST Control (Linkoping, Sweden) used FDM from Stratasys to produce 20 of the parts, including the enclosure, that go into its COLIBRI gimbal eye (camera) for unmanned aerial vehicles. The company realized a cost reduction of 66% and a reduction in production time of seven weeks. An estimated 50 COLIBRI units are being manufactured per year, with each including the 20 FDM parts.

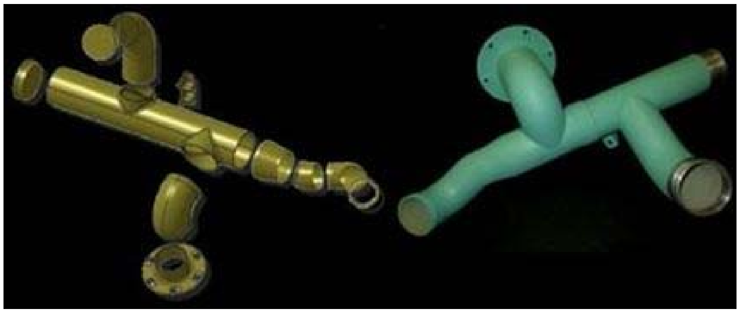
Gimbal eye for unmanned aerial vehicle (left) and FDM parts (right), courtesy of DST Control

An ongoing application in aerospace is the production of environmental control system (ECS) ducting for military and commercial jets. Boeing and its suppliers are using laser sintering technology extensively to manufacture these ducts for fighter jets, and more recently, for the 787 commercial jet. The company has more than 200 part numbers on 16 production aircraft that are produced using AM. More than 100,000 production parts have been manufactured with AM.

Environmental control system ducting, courtesy of Boeing

Before using AM, the company would assemble up to 20 or more parts to produce one air duct assembly. Each of the individual parts that made up the ducting required tooling of some type, and welding and fasteners were often needed. Today, Boeing manufactures many of these ducts in one piece using AM. This practice has eliminated part numbers (and the inspections and documentation required for each), tooling, inventory, labor, entire assembly lines, and maintenance. The laser-sintered parts also weigh less than the assemblies they replaced, contributing to fuel savings.

Boeing and other aerospace companies are using AM to produce not only ECS ducts, but also electrical boxes, brackets, and other permanent parts for aircraft. Northrop Grumman Corp. produced laser-sintered ducting in two pieces (shown on the right in the following image). The old design (left) consists of nine aluminum pieces that were welded together.



Environmental control system ducting, courtesy of Northrop Grumman Corp.

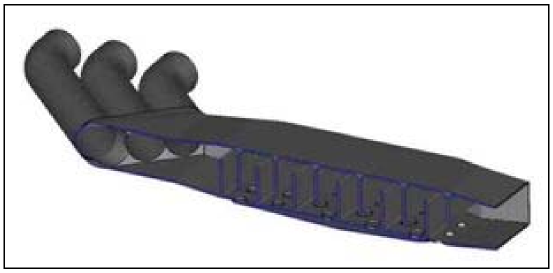
Automotive and motorsports

Mydea Technologies chose to use its PolyJet system to prototype a wire guide for an automobile headrest assembly for a Tier 1 automotive supplier. The prototype was of high enough quality for the production part, so the supplier chose to have 1,000 pieces of the snap-fit part produced by PolyJet in the Durus material instead of having the part molded.

Engineers at Group T enlisted the help of Belgium-based Materialise to manufacture the world's first 3D-printed racecar, the Areion. With access to Materialise's Mammoth stereolithography machines, with their 210 x 68 x 80 cm (47 x 27 x 31 inch) build envelopes, the team was able to print the entire car body quickly and efficiently. The Group T engineers took the initial shell design to a fully finished, 3D-printed car body in just three weeks.

Group T Areion racecar, courtesy of Materialise

The Areion design team integrated unique features, such as clips and connection points, to allow for easier shell assembly and faster access to the inner workings of the car during maintenance. AM also helped with the design and manufacturing of cooling channels, which featured complex geometric shapes. A nozzle and diffuser were printed into the left side pod to optimize cooling. The nozzle/diffuser created a cyclone effect that removed water and dirt from the air before it entered the engine compartment. It also created the ideal flow of air through the radiator at a range of speeds, and even when the car is not moving.



Cutaway of CAD model showing complex cooling channels, courtesy of Materialise

Ford Motor Company is starting to reveal more about its prototyping and additive manufacturing operations. The technology is used to produce prototypes for everything from air vents to cylinder heads.

Technician brushes nylon powder residue from an EcoBoost engine prototype, courtesy of Ford Motor Company

The use of ExOne's sand machines has enabled Ford engineers to more easily and quickly produce sand molds and cores that can be used to create production-representative parts. Ford engineers are using AM to manufacture molds and cores for casting prototypes for its EcoBoost engine. The ExOne process is also used to manufacture cast prototypes of rotor supports, transmission cases, damper housings, and end covers for the new HF35 hybrid transmission, as well as brake rotors for the Ford Explorer.

Technician cleans sand molds manufactured with an AM sand process, courtesy of Ford Motor Company

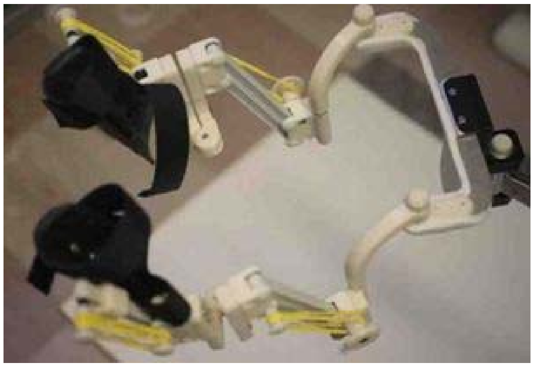
Medical

The need for custom-made products for medical treatment is often a necessity. Because of the potential economic and performance advantages, this is one of the most research-intensive production application areas of AM. As a result, AM is delivering personal solutions for some of the industry's most difficult challenges while making a difference in the lives of patients around the world.

Medical applications are driven by a patient's unique requirements of shape, functionality, and cost. AM was used to create a custom-design robotic exoskeleton for a two-year old patient named Emma who suffered from a condition known as arthogryposis. It is a rare congenital disorder characterized by multiple joint contractures that can include muscle weakness and fibrosis. Typically, an apparatus called a Wilmington Robotic Exoskeleton (WREX) is used to treat a patient with this condition. However, the WREX was too heavy and cumbersome for Emma. Tariq Rahman led a team at Nemours/Alfred I. duPont Hospital for Children that developed a robotic exoskeleton to enable joint mobility for Emma's underdeveloped muscles. Young Emma refers to her custom-designed device as her "magic arms" and is now able to eat, draw, and play like other children.

Emma gives her mom a hug with the help of her "magic arms," courtesy of Stratasys

AM was used to produce a jacket on which the "magic arms" affix. As Emma grows, her jacket is replaced with a larger one. If a part breaks, it is quickly and easily replaced with another 3D-printed ABS part.



Robotic exoskeleton manufactured with a Dimension 3D printer, courtesy of Stratasys

UK-based oral surgeon Andrew Dawood successfully restored an oncology patient's facial features and earned recognition with the development of the "3D-printed" face. Computed tomography (CT) and optical scanners were used to capture bone and surface topography of the patient's skull. Software was used to create physical models for implant placement planning. Digital data was used to print physical models directly from nylon and also to create plaster molds. Implants and frameworks were milled from titanium and positioned inside the patient's jaw. With the prosthetic attached, patient Eric Moger can speak, eat, and drink.

Eric Moger received a silicone prosthesis manufactured from 3D-printed molds and substrates, courtesy of Geoff Pugh

Avatars and figurines

A French 3D printing service, Sculpteo, receives two images of a person and transforms him or her into a mini avatar. The products are produced on a ZPrinter from 3D Systems. The starting price is $84, plus shipping.

Figurine measuring 68 mm (2.7 inches) in height, courtesy of Sculpteo

Japan-based Omote 3D opened its 3D printing photo booth in Tokyo's Harujuku District at the Eye of Gyre exhibition in November 2012. For about $265, a person can enter the booth, stand still as their full body is digitally scanned, and eventually walk away with a 3D-printed miniature replica of themselves.

Photo booth miniature figurines, courtesy of Omote 3D

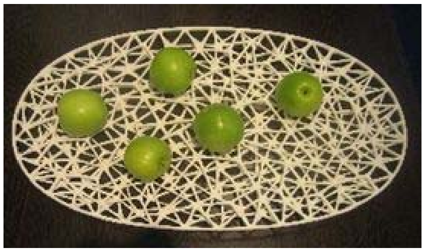
Furniture, home, and office accessories

The .MGX division of Materialise produces special-edition lighting designs, furniture, and other home and office accessories. More than 10,000 .MGX lamps have been sold worldwide.

Gamete.MGX table lamp designed by Xavier Lust and produced by laser sintering, courtesy of Materialise

Designers can produce a table lamp of almost any shape for €199, plus shipping, using a service called i.materialise. The lamp comes complete with a base and light and is delivered in 15 days.

Amsterdam-based Freedom of Creation, a 3D Systems company, offers many lighting and furniture designs, as well as home, office, and personal accessories. The company also provides a collection of iPhone cases, jewelry, shoes, and other interesting products—all produced by additive manufacturing.



Decorative platter made by laser sintering, courtesy of Freedom of Creation

Designer Alexander Pelikan made his “Machine Vision” door handle based on a series of 3D scans with changing resolution. The door handle was presented at Salone di Mobile in Milan, Italy.

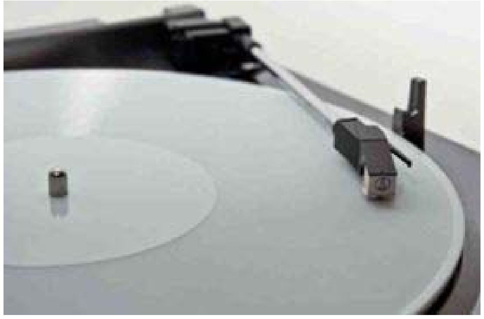
Machine Vision door handle made with ExOne’s Digital Part Materialization technology, courtesy of Alexander Pelikan

Music

Olaf Diegel, a professor at Lund University in Lund, Sweden, has combined his love of music with his expertise in CAD modeling and AM to create radically new electric guitar bodies. Diegel’s designs are complex and detailed, and are functional and lightweight. Most of the guitar bodies were built in polyamide on LS equipment from EOS or 3D Systems.

Hive guitar (left) and Spider guitar (right), courtesy of Olaf Diegel

Amanda Ghassaei, assistant tech editor at Instructables.com, created a technique for converting digital audio files into 3D printable, 33-rpm records that play on ordinary turntables. The 3D modeling was too complex for traditional drafting-style CAD techniques, so Ghassaei wrote a program to import raw audio data, perform calculations to generate the geometry of a 300-mm (12-inch) record, and export the geometry directly to a 3D printable file format. The records were printed on a Stratasys Connex500 at 600 dpi with 16-micron (0.0006-inch) z-axis resolution.



3D-printed record, courtesy of Amanda Ghassaei

Consumer-created products

For many consumers, it's all about customization. People make custom playlists, online news feeds, video queues, and now people are producing custom physical products. Nokia and MakerBot Industries launched a partnership to allow MakerBot Replicator 2 owners to download templates for printing personalized shells for Lumia 520 or Lumia 820 mobile phones. The Replicator 2 prints ABS in more than 20 different colors.

3D-printed Lumia 820 cell phone shells, courtesy of Nokia

Displaying a simple solution to an everyday problem, Billy Zelsnack created an end cap for his pasta box to keep the pasta from spilling out. As AM technology becomes more accessible, a growing number of users will apply it to practical solutions for everyday problems.

Pasta box end cap produced on a MakerBot machine, courtesy of Billy Zelsnack

Art and jewelry

Cooksongold and EOS partnered to develop a precious metal powder bed fusion system for the watch and jewelry industry. The PRECIOUS M 080 produces one-off pieces or volume production in 18k yellow gold. The system's powder cartridge and processing chamber were designed to reduce powder waste to an absolute minimum in order to build parts with the lowest possible material inventory of precious metal powder. Cooksongold also offers 18k white gold and 18k red gold powders, as well as 14k yellow gold, platinum, palladium, and 925 silver.

Laser-sintered 18k yellow gold mesh bracelet designed by Within Technologies and Emily Richard, courtesy of Cooksongold

Many of designer Doug Bucci's creations are cellular forms likened to human cells. Bucci's current limited-edition bracelets are stainless steel infiltrated with bronze. Bucci designs jewelry with the AM processes in mind, saying, "I want to create a different business model, one based on demand and less waste."

Necklace (left) made on the Perfactory system from Envisiontec, and metal bracelet (right), courtesy of Doug Bucci

Designer Michiel Cornelissen has created the Happy Bird earrings and pendant using laser sintering. The whimsical items are packaged in a gift box and available for sale in design stores in Beijing, New York, and the Netherlands.

Happy Bird earrings, courtesy of Michiel Cornelissen

Irish bespoke jewelry goldsmiths and designers DaCapo have long used lost-wax casting and AM service providers to produce jewelry. Its acquired design skills were useful when producing the first rings using titanium-based additive manufacturing. DaCapo sells basic and hand-finished versions of its rings.

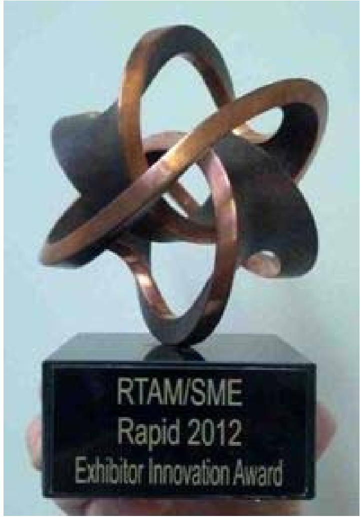
Gaial ring produced in titanium by LayerWise, courtesy of DaCapo

Israeli artist Eyal Gever creates “Disaster Art”—sculptures depicting a frozen moment when a catastrophe occurs. They range from head-on collisions and other accidents to tsunamis and oil spills. He simulates these disasters with sophisticated computer coding, and then builds physical models of the simulations on AM systems from Stratasys.

Disaster art, courtesy of Eyal Gever and BBC

Gifts, trophies, and memorials

A 3D-printed trophy was given to Mcor Technologies, the winner of the Exhibitor Innovation award at the Society of Manufacturing Engineers RAPID 2012 Conference and Exposition. Bathsheba Grossman, whose 3D-printed jewelry and sculptures feature complex geometric shapes, designed the award. Grossman’s creations are typically produced on ExOne’s machines in stainless steel, retextured with hand and power tools, and oxidized to a bronze color. To achieve a similar effect, this award was made with laser sintering, coated with copper, and finished with a bronze patina along its smooth outer edges.



Innovation trophy designed by Bathsheba Grossman, laser sintered at Harvest Technologies, and coated with copper, courtesy of Mcor

The Eni trophy was given to the winners of the Moto GP race (German Sachsenring racing circuit) and Formula 1 race in Budapest, Hungary. It was designed by Italian architect Antonio Pio Saracino and produced by Materialise on a laser sintering machine.

Eni trophy designed by Antonio Pio Saracina, courtesy of Materialise

Pyotr manufactures custom, thematic fountain pens that are packaged in a box and monogrammed with the owner's initials. The pens, starting at €7,000, are the brainchild of Rein van der Mast, an industrial designer in the Netherlands, who saw a need for high-value, mass customized consumer products. All of the pen's parts are produced in titanium by powder bed fusion at LayerWise in Belgium.

The world's first 3D-printed fountain pen, courtesy of SOLide/Pyotr

Individual consumers determine the fountain pen theme after consultation. Van der Mast designed his pen based on the legend of St. George and the Dragon, a theme close to his heart. The fine features of the long dragonhead and the counterbalanced young girl were designed in collaboration with digital sculptor Evgeny Bazurov of Moscow, Russia. Autodesk's Studio Max was the primary software tool used. Netherlands-based Innplate did the chemical polishing and etching.

Marketing and advertising

Creative agency BSUR used a marketing campaign for Dutch radio station 538 that was supported by two "stereoheads" created together with Freedom of Creation in three weeks. These eye-catching props, designed specifically for the campaign, were a physical representation of the creative concept used throughout the national television, billboard, and online campaigns.

"Stereoheads" abducting Dutch radio disc jockey Ruud De Wild, courtesy of BSUR

Museum displays

Danish model-maker Esben Horn worked with University of Texas scientist Jakob Vinther to create a lifelike model of the 390-million-year-old Protobalanus spinicoronatus mollusk. Using a combination of computer animation, CT scanning, and 3D printing, the team reconstructed the skeleton from a broken fossil. The physical model was created using 3D printers, clay, resin, and silicone materials. The finishing touches were completed with airbrushed acrylic paints.

Sculpture of an ancient mollusk, courtesy of Jakob Vinther, University of Texas at Austin

The Smithsonian Institution is using AM to share some of its 137 million items with museums across the U.S. It plans to create a series of models, exhibits, and scientific replicas that will be available for public viewing, all made by AM. In a pilot project, The Smithsonian had a replica of a Thomas Jefferson statue made for an exhibit at the National Museum of African American History and Culture.

Upper portion of a replica statue of Thomas Jefferson, courtesy of RedEye and the Smithsonian Institution

Fashion and high-performance products

Nike launched the Vapor Laser Talon, its first-ever 3D-printed football cleat, in February 2013. Using proprietary materials, a cutting edge cleat plate was constructed with laser sintering technology. The 160-gram (5.6-ounce) shoe was designed to provide optimal turf traction and improved performance by contouring to the foot, allowing the athlete to maintain the drive position longer and sprint faster. Using AM technology, the team was able to make design updates within hours instead of months, and also build shapes that would not be possible with traditional manufacturing methods. Nike took this new product from prototype to final production, producing a fully functional cleat plate and traction system in a fraction of the time.

The Vapor Laser Talon, courtesy of Nike

Mykita is the world's first company to launch an AM production eyewear line branded as Mylon. The company's patented polyamide-based material has been in development since 2007 and produces lightweight parts with outstanding durability. A proprietary, multi-step surface treatment is applied to laser-sintered parts to create a unique visual and tactile appeal.

Eyewear designer Martin Guentert poses to show off his laser-sintered frames at EuroMold 2012

Dutch fashion designer Iris van Herpen showed her "Voltage" collection during Paris Fashion Week 2013. The collection was produced in collaboration with Julia Koerner and Materialise. One skirt and cape combination was 3D printed in collaboration with Stratasys using Connex technology, while a dress was laser sintered from Materialise's new flexible material TPU 92A-1 and painted black.

Laser-sintered vintage couture dress,
courtesy of Materialise

Additive manufacturing continues to extend its reach to a broader, more diversified range of possibilities, with fewer barriers to entry than ever before. As AM technologies continue to advance, expect to see additional groundbreaking applications.