MAKING THE UNMAKEABLE

Combining Additive Manufacturing with Proven Metal Casting Processes

AUTODESK.

INTRODUCTION
HOW TO MANUFACTURE THE IMPOSSIBLE

The lightweighting trend in design and manufacturing grows stronger every day. In automotive and aerospace, it is driven by rising global demands to improve fuel economy and lower emissions in ground vehicles and aircraft. In the medical industry, using smaller devices with less material increases design flexibility and improves the patient experience.

Two areas of significant promise in the lightweighting world are generative design and additive manufacturing. Generative design helps engineers come up with design solutions that would be virtually impossible to imagine and impractical to model with traditional CAD software. Additive manufacturing brings these previously "un-makeable" designs to life. Together, the two technologies are beginning to help engineers across numerous industries radically reduce total weight or significantly improve the strength and durability of components without adding weight.

Where this approach has been limited, however, is with larger products. Additive manufacturing can print the complex, high-performance structures created by generative design, but 3D printing with metal is restricted to relatively small objects and only certain alloys. Metal casting, on the other hand, can be used to make very large structures of virtually any metal or alloy. But traditional mold-making processes used in metal casting limit the shape and complexity of what can be made with casting.

Today, these limits are disappearing as experts in generative design, additive manufacturing, and metal casting collaborate to make the most of all three technologies. This eBook explores how and why this is happening and provides a detailed look at an award-winning example of the innovation that is possible when these ideas converge.

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ADDITIVE MANUFACTURING

A new fabrication technology rewrites the rules of design and production.

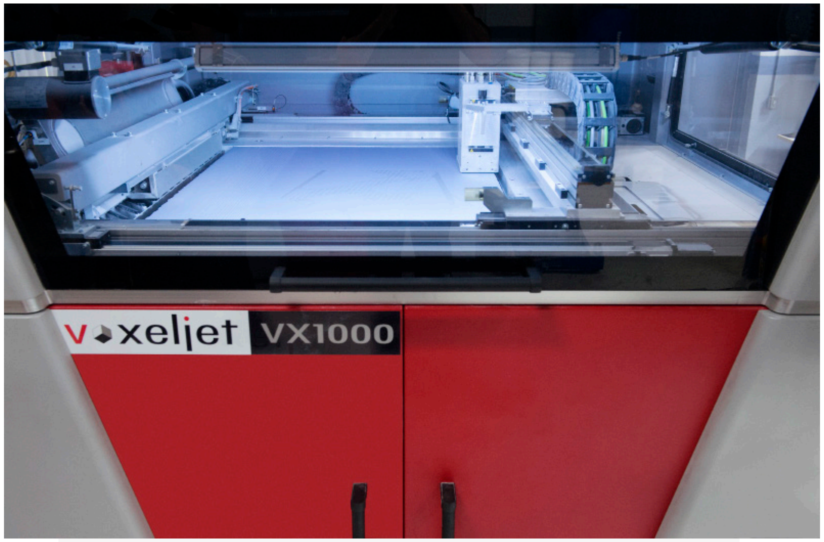
ADDITIVE MANUFACTURING

Additive manufacturing (AM), also known as 3D printing, is growing quickly. The total market for AM products and services is currently $4 billion and could exceed $10 billion by 2021. New kinds of printers and new materials are launching regularly and overall costs are starting to decline.

The appeal of AM is clear. These techniques, which involve creating three-dimensional objects with layers of material under the direction of a computer, allow product designers to create geometries that are impossible to produce any other way.

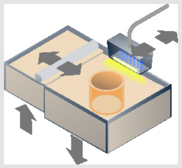
Freedom of design is not the only appeal of AM. It also has the potential to redefine the dynamics of factories and supply chains, eliminating time and cost associated with shipping and distribution. Relatively speaking, its environmental footprint is smaller than other techniques.

But its design potential — and the related economic impact — is its most important advantage. This is why AM and generative design are often discussed together.

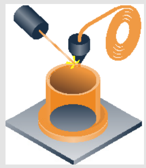


Binder jetting machine printing an investment casting pattern using polymethyl methacrylate (PMMA) powder.

ADDITIVE MANUFACTURING PROCESSES

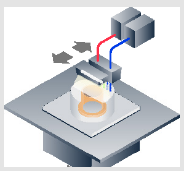


Binder jetting

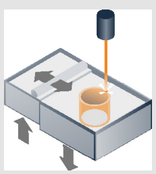


Directed energy deposition

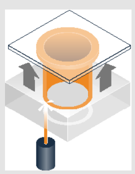
Material extrusion



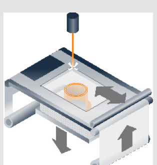
Material jetting



Powder bed fusion



Vat photopolymerization



Sheet lamination

ADDITIVE MANUFACTURING CONTINUED

Generative design uses powerful software tools to explore an almost inconceivable number of design combinations in pursuit of user-defined goals. Each iteration informs the next, and the end result looks much different than a traditional product. Think of lattices and organic-looking or cellular structures that tend to resemble bone.

AM and generative design are a perfect fit for lightweighting efforts. Together, they allow manufacturers to design and produce parts that use less material without sacrificing strength. Lighter parts that consume less material set the stage for significant gains in energy efficiency and production costs.

Where AM is limited is in material selection. This is particularly true with metal AM, which can be done with just a couple dozen metals while typical casting processes can be performed with a near unlimited portfolio of high performance alloys, including metal matrix composites. Metal AM also faces hard caps on the size of the parts it can produce, the speed at which they can be delivered, and the amount of post-processing required. Together, these hurdles are preventing engineers in industries that have the most to gain from the relaxation of design restrictions—automotive, aerospace, and medical technology—from adopting it in a more widespread way.

METAL CASTING

A trade that is thousands of years old finds a new calling.

METAL CASTING

To say that metal casting is a mature industry is a vast understatement. The first products cast in metal made their debut thousands of years ago. Casting is incredibly well understood, and there are hundreds of thousands of engineers, foundries, and factories with deep expertise in it.

The entire metal casting industry was approximately $35 billion in 2016. Because the field is so large and well established, metal casting tends to be more cost-effective than metal printing, especially for larger parts. Scaling up from prototypes to production castings can be done very efficiently. And because the processes and the materials are so familiar, it is easy to make accurate predictions about part strength, durability, and performance.

All of these advantages make metal casting an ideal fit for high-performance applications in aerospace, automotive, and medical technology, all of which benefit greatly from predictable material behavior. These applications can be made with more than 400 commonly used alloys, and in other cases it is relatively simple to produce custom materials for unique specifications.

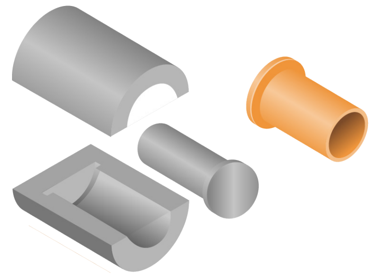
Metal casting has two main categories, depending on whether or not the original pattern or mold is permanent. Here we are focused on what is called "expendable mold casting," because as we will see, the critical connection to AM technology comes in the form of a mold made from ceramic or sand.

INVESTMENT CASTING

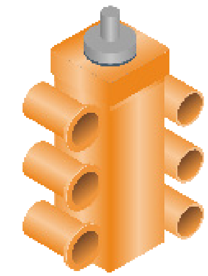
Investment casting is a high-resolution process that can produce parts with wall thicknesses down to 0.5mm. It is also a high-fidelity process, so the surface finish closely resembles the original pattern. It is certified for applications in aerospace, automotive, and medical technology.

Also called "lost wax" casting, it starts with a wax object to be reproduced in metal. A shell is built up around the wax object as it is repeatedly dipped in a ceramic slurry. The wax is then burned out, and the resulting cavity is filled with liquid metal. Every feature on the pattern is transferred into the ceramic cavity and then into the metal geometry. This allows engineers to achieve very fine positive space features, including complex heat sinks and other complicated design elements.

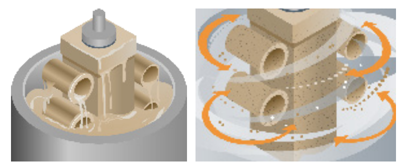
Investment casting is frequently used to manufacture products made from high-performance aluminum, magnesium, stainless alloys, and nickel superalloys. However, it can also be automated to produce a wide variety of intermediate industrial applications at scale. Depending on the complexity of the design and the volumes required, lead times for investment casting range from two days to 36 weeks.



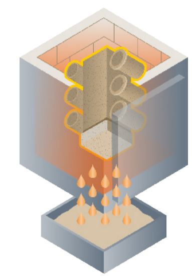
Step 1
Making the pattern



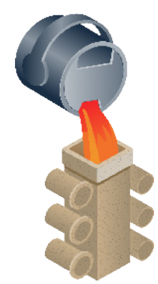
Step 2
Assembling patterns on the sprue



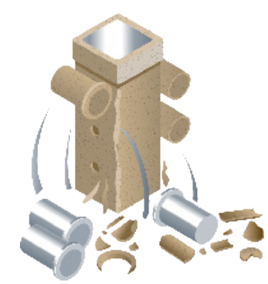
Step 3
Dip & coat to create ceramic shell



Step 4
Wax burnout and pre-heating

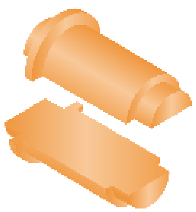


Step 5
Pouring metal & casting the parts

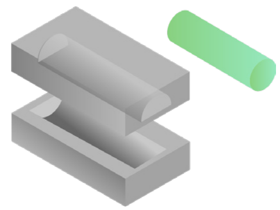


Step 6
Removing parts from shell

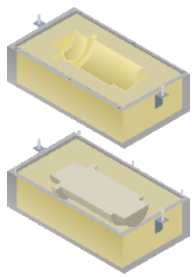
SAND CASTING



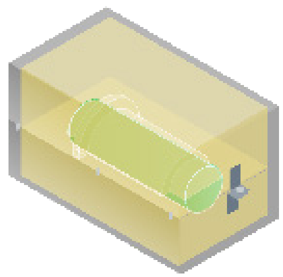
Step 1
Making the pattern halves



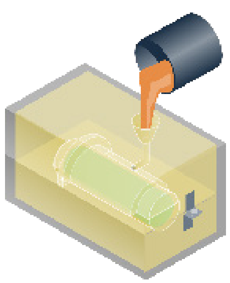
Step 2
Creating the core features



Step 3
Using patterns to create sand mold



Step 4
Inserting core and assembling mold



Step 5
Pouring metal & casting the parts

Step 6
Removing parts from mold

Sand casting is similar to investment casting but is typically done on a larger scale due to the lower cost to create sand molds along with its lower tolerances and rougher surface finish, similar to that of a cast iron skillet. It is widely used in mass manufacturing, including automotive parts, pumps and valves, structural applications, and other large-scale industrial products ranging from 400 to 30,000 pounds.

As with investment casting, fabricating the tooling for sand casting is the most labor-intensive and time-consuming part of the process. The tools are used to form the sand mold. The "sand" is a mix of fine sands and epoxies or other binders that can be baked or air cured. The mold is then assembled, metal is poured into the mold and the heat from the metal degrades the epoxy. This makes the sand very easy to remove along with the metal delivery system, or rigging.

SAND CASTING CONTINUED

Traditional sand molding is limited by the fact that it must use moldable geometries. Each half of the mold requires one tool. Each core, which represents the internal negative features of a product requires an additional component. Cost and lead-times scale dramatically for complex parts.

Using AM in sand casting loosens these constraints considerably. Direct sand printing the mold eliminates much of the engineering time involved in re-designing parts to make them moldable for more flexibility in developing the rigging, which reduces total cost. AM can also be used to print the cores, allowing better positional tolerances because there is no tolerance stack up as there is when assembling multiple traditionally-manufactured cores. This removes even more cost while allowing more geometric flexibility and improving quality.

Using AM for molds and cores is very attractive for all of these reasons, as well as the fact that sand casting foundries are often asked to produce one-offs (such as a large part for an aircraft carrier) or reverse-engineer existing parts. In both situations, AM makes the process faster and easier.

INSIDE THE METAL CASTING INDUSTRY

» 1,965 facilities in the U.S., down from 3,200 in 1991 and 6,150 in 1955

» 80% are small businesses

» 200,000 total employees

» 90% of all manufactured goods contain some metal castings

» The U.S. is the global leader in casting applications and second in production

» 12 million tons of castings produced in the U.S. in 2014

» $32 billion market (U.S.) in 2014

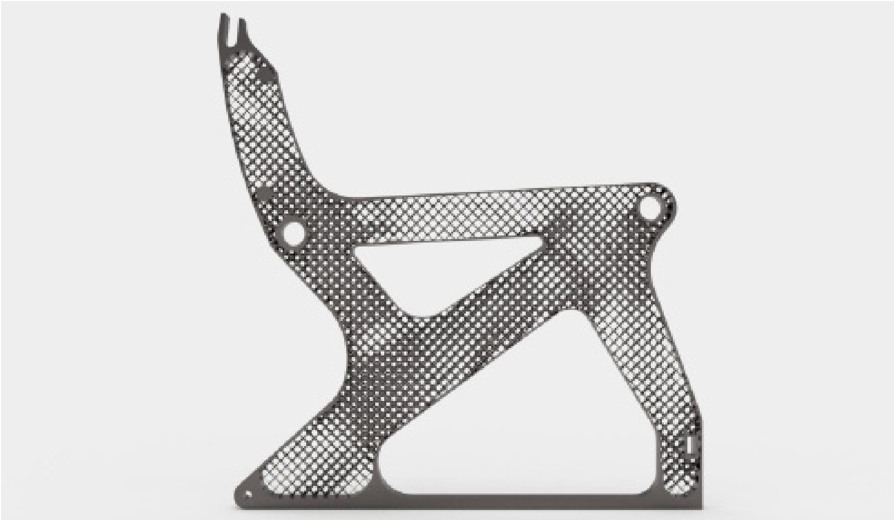
THE BEST OF BOTH WORLDS

How new and old technologies set the stage for a new era of manufacturing.

THE BEST OF BOTH WORLDS

Combining AM and metal casting technologies is not exactly new. AM techniques have been used in investment casting foundries for more than 20 years — typically to print prototype patterns or patterns for short runs of complex parts. The most popular technique has been stereolithography, while other options include laser sintering, direct wax inkjetting, and binder jetting. Each of these has its advantages, and they have significant potential in low volume manufacturing—for example, the cost of one-off parts can potentially be reduced by as much as 60%.

It is clear, however, that there are large and unexplored opportunities to take advantage of AM in both investment and sand casting. One reason for this is a kind of self-reinforcing isolation, in that most foundries are job shops that are rarely exposed to industries that don't already use metal casting. In the same way, industries that are pushing the boundaries of AM and generative design may not consider the advantages of metal casting.



Lightweighting via latticing and topology optimization is one of the biggest potential opportunities. There is a natural fit between the complex geometries produced by generative design and the ability of metal casting to produce these parts in high-performance metals and alloys. Investment casting, for example, can produce lattices with cells as small as 10mm and struts as small as 2mm, while sand casting can handle parts that far exceed the scale of direct metal printing.

THE BEST OF BOTH WORLDS CONTINUED

In both of these cases, AM bridges the gap between the two by printing the patterns and sand molds, which solves a number of challenges at once. Using AM to print patterns enables product developers to escape the limitations of AM with metal. At the same time, it frees foundries to cast much more complicated, "unmoldable" geometries without adding time or money to the process. In fact, foundries can eliminate the most time-consuming step of production — engineering and fabricating the tooling — to achieve savings in cost and lead time for low volumes of parts.

Using AM in this way has a double benefit because many foundries are struggling with the scarcity of skilled pattern-makers. Pattern-making has traditionally been a closely guarded skill passed down through lengthy apprenticeships, a process that today leaves only a few hundred experienced pattern-makers left in the U.S. As a result, many foundries see the appeal of using AM to make patterns without pattern-makers, or even skilled machinery operators.

The end result is a unique blend of three technologies. Generative design helps engineers create products that nobody could have imagined. Additive manufacturing produces the pattern instead of the part itself. And metal casting brings the part to life in extremely strong yet lightweight metal materials that have never before been used to cast designs of this complexity.

CASTING OF THE YEAR

Bringing an innovative latticed design to life in lightweight magnesium.

CASTING OF THE YEAR

One recent example of how these technologies can converge was developed at Pier 9, Autodesk's 27,000-square foot technology center in San Francisco. There, research scientists developed an aircraft seat frame that could easily fit in any commercial jet. It looks unlike any conventional seat frame because it was created with generative design. Specifically, Autodesk® Netfabb® software was used to produce the seat's geometry to meet lightweighting goals via latticing and surface optimization. The resulting design is just as strong as any other frame but much lighter.

In commercial aviation, lighter aircraft are the key to using less fuel and reducing carbon emissions. A seat like this would allow airlines to save millions of dollars annually if it were integrated into the entire fleet. Conventional seat frames are made from aluminum. Lighter designs are CNC machined from a single billet, resulting in a lot of wasted material. Others are cast or made from an assembly but they are much heavier.

Fabricating a seat frame with an extremely complex geometry, however, would be prohibitively expensive using conventional techniques, and direct metal printing would not be able to produce a frame this large.

Instead of solid structural beams, the generatively designed seat frame has a bridge with hundreds of smaller lattice cells and several thousand small struts that vary in thickness to bear local loading conditions.

CASTING OF THE YEAR
CONTINUED

This is, of course, the "sweet spot" for combining the strengths of AM and metal casting.

To do this, research scientists at Autodesk reached out to Aristo-Cast in Almont, Michigan, an investment caster with extensive experience in both prototyping and magnesium casting. Aristo-Cast was an early adopter of AM technology, having used it since the 1990s. While the Aristo-Cast team was familiar with the capabilities of AM, they had not used it to produce exotic lattice geometries.

Aristo-Cast first cast a small section of the seat frame's latticing in magnesium using a wax-printed pattern. The result came out very well, but the Aristo-Cast team noticed that some struts needed to be thickened in order to be cast properly.

SAVING ON FUEL & EMISSIONS

	A321 236 seats	A380 615 seats
Weight savings *(per aircraft)*	214kg	557kg
Annual Fuel Savings *(per aircraft)*	9.6 tonnes	63 tonnes
Annual Carbon Emission Reduction *(per aircraft)*	28.9 tonnes	190.1 tonnes
Annual Fleet Savings *(100 aircraft)*	$1,569,365	$10,332,446
Lifetime Fleet Savings *(100 aircraft over 20 years)*	$31,387,300	$206,648,920
Lifetime Fleet Carbon Emissions Reduction *(100 aircraft over 20 years)*	57,800 tonnes 12,298 cars	126,000 tonnes 80,894 cars

The latticed seat frame could theoretically save an airline more than $200 million if applied to a fleet of 100 commercial jets over the course of their typical life span. The frame would also help the fleet reduce emissions by 126,000 tons over its lifetime.

CASTING OF THE YEAR CONTINUED

Next, the full frame was 3D printed with binder jetting technology using PMMA powder (acrylic). The pattern was used to create the ceramic molds for casting the entire frame. Aristo-Cast used its considerable experience to ensure that the cavity filled completely with magnesium.

The final castings were delivered within four weeks. Each frame weighed less than half of its conventionally made counterpart, setting the stage for significant savings in fuel and dramatically less carbon emissions when applied to an entire airline fleet. These potential benefits earned the seat frame Casting of the Year from the American Foundry Society (AFS) and Metal Casting Design & Purchasing magazine.

CONCLUSION
LOOKING AHEAD TO THE FUTURE OF LIGHTWEIGHTING

The convergence of generative design, additive manufacturing, and metal casting has the possibility to rewrite the rules of lightweighting in dozens of applications in aerospace, automotive, medical devices and other industries. Generative design eliminates excess material in unexpected ways. Casting seats in magnesium lets designers achieve similar mechanical properties as aluminum with a material that weighs approximately 35% less. And AM is the bridge between these two worlds, helping foundries cut costs in unexpected ways and produce high performance parts out of a wide variety of materials.

While the use of AM in metal casting is not new, using generative design and simulation software helps everyone involved get more value from these proven processes. These techniques are pushing AM beyond prototyping, making mass manufacturing a realistic goal for even the most complex geometries.

Visit autodesk.com/solutions/additive-manufacturing to learn more about the newest strategies and tools for your additive manufacturing project.