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From Design to Part

By Alan Richter, Editor

Additive manufacturing methods are becoming more common for production—not just prototyping.

Does being able to rapidly manufacture usable metal parts through additive processes mean that the end is near for cutting tools and the subtractive machining they perform? Hardly. But additive, or rapid, manufacturing is increasingly being used—in addition to prototype work—to produce low-volume runs of relatively complex, smaller, net- and near net-shape metal parts.

Various technologies exist for building parts out of a host of metallic and nonmetallic materials. This article covers a selection of those technologies that are used to build metal parts on a production basis.

Selective Laser Sintering

With its roots in selective laser sintering dating to 1995, before commercialization of SLS, Harvest Technologies, Belton, Texas, applies the technology for low-volume manufacturing of noncosmetic, functional, load bearing-type parts, according to Ron Clemons, director of business development.

Morris Technologies

Examples of aerospace parts (bottom) and medical parts Morris Technologies builds using direct-metal laser sintering.

Learn more about additive manufacturing

Read more commentary on additive manufacturing by visiting Alan Richter's Web log in the CTE Community section online at www.ctemag.com. The redesigned Web site, CTE Plus, features a range of Interactive Reports, a Virtual Company Showcase, daily industry news and editors' blogs at CTE Community.

Production runs typically range from dozens to the low hundreds.

Unlike conventional machining, the more complex the part, the more cost effective it is to make with SLS. “There’s an inverse relationship with complexity and cost effectiveness,” Clemons said.

Harvest has an SLS Sinterstation machine from 3D Systems Corp., Rock Hill, S.C., for producing LaserForm A-6 metal components. Making them is a two-stage process that starts by sending an STL format file to the machine’s onboard PC. (STL originally stood for stereolithography and is the required 3-D format for building parts on rapid prototyping machines.)

During the first stage, a green part is grown layer by layer as a laser sinters, or fuses, metal particles coated with a polymer binder. “The laser does not have enough power to melt the metal,” Clemons said. “The laser is melting the plastic binder together to make the geometry.”

A green part is about 60 percent dense and must be handled delicately while being prepared for bronze infiltration. A user cuts and strategically positions bronze segments that are sized according to the volume and configuration of the green parts. Alumina powder is then poured around the plated setup, which is contained in a crucible, to inhibit drooping and sagging of the parts during heating in a furnace—the second stage.

Harvest Technologies

During the second phase of the selective laser sintering process, a furnace containing the infiltration setup inside a crucible is heated to 2,100° F to burn away the polymer binder and cause bronze to infiltrate the metal parts through capillary action.

The furnace containing the crucible is heated to 2,100° F, which burns away the binder and causes the bronze to infiltrate the parts through capillary action. The result is parts that are generally fully dense. “It’s a matrix and not an alloy,” Clemons said. “That matrix is roughly 60 percent A-6 steel and 40 percent bronze.”

Upon completion, the plate and supports connected to the parts are cut away.

Achievable tolerance depends on part size, but it’s generally about ±0.003" per inch. “It’s not sloppy, but it’s not as precise as a machined part,” Clemons said, adding that surfaces are not perfectly flat and square and therefore require postprocess machining to achieve desired flatness and squareness for certain geometries, such as those found in molds. Harvest uses manual mills and lathes to perform some of the machining but outsources more precise work to machine shops.

In addition, because the SLS machine builds parts in increments of 0.003" to 0.005" layers, a sidewall that's at an angle or is contoured has small steps. A part's surface also has a texture. "You cannot build a perfectly slick, smooth surface," Clemons said. "You need secondary operations."

Direct-Metal Laser Sintering

Another technology for additive manufacturing is direct-metal laser sintering. Similar to SLS, DMLS builds parts layer by layer with a laser solidifying powder into cross sections. The advantage of DMLS is the material is fully dense once sintered, said Jim Fendrick, general manager for EOS of North America Inc., Novi, Mich., a DMLS equipment supplier. He added that the process' standard layer thickness is 0.0008", but it's possible to also deposit 0.0016"-thick layers.

DMLS also creates a smoother surface finish than SLS, according to Greg Morris, COO of Morris Technologies Inc., Cincinnati. "It's roughly equivalent to an investment cast surface finish," he said. "It's somewhere in the 125 to 200 rms range." Morris added that the process is able to hold tolerances of ±0.001" to 0.002" per inch, depending on part geometry, size and alloy.

EOS of North America

The lower image shows a sintered chromium-cobalt dental bridge, which is typically cast (top) instead.

Morris Technologies has five EOS DMLS machines and its sister company, Rapid Quality Manufacturing, has three. Morris Technologies primarily does prototyping and short runs and then can transfer the finalized and proven design to RQM for production runs. "RQM will then apply all the necessary quality and process controls and provide validation to the process as being a manufacturing methodology," Morris said, adding that RQM is performing pilot production and ramping up. "I can't say we have any project where we're producing tens of thousands of parts right now," he said, "but that's where I see it going."

To fully realize the benefits of rapid manufacturing, parts must be designed for an additive process rather than taking an existing part that can be machined and building it on an additive machine. "If I have the ability to redesign a part to take advantage of rapid

Free form fabrication

OPTOMEC'S LASER ENGINEERED Net Shaping (LENS) takes a different approach to additive manufacturing than other laser-based technologies. Rather than sintering a powder layer in a bed to build a component within the bed, LENS feeds powder through four nozzles to a focal point where the laser is also focused. The laser head moves in the X- and Y-axis directions to build a layer in free space and then indexes in the Z-axis to build the next layer. Pitch and yaw rotation of the table holding the part and/or deposition head enables fabrication of more complex geometries.

One of the advantages of LENS is that it's easy to add features to, rework or repair an existing component, according to Richard Grylls, product manager for Optomec, Albuquerque, N.M. "You just place a component in the machine and add material directly to that component," he said.

End users can also apply the technology to build new parts, but repairing parts is currently a more common application. "With new part production, we found we're typically replacing a well-established, existing process, and it's harder to replace that process in the manufacturing cycle," Grylls said, but he added that he expects the market for new part production to be greater in the future.

By being able to efficiently add material to existing components, LENS is well suited for mass customization, hybrid manufacturing and repair applications. For example, a surgical instrument may have a universal handle and shaft, but the business end of the instrument varies according to the patient. "Significant cost savings can be achieved by fabricating the fixed elements of the surgical instrument using a traditional manufacturing process and adding the variable elements using LENS," Grylls said.

An aerospace example is a thin-wall case with numerous bosses on it. Rather than machining a large amount of material away from a thick workpiece to produce the finished part, a thin case can be made by traditional means and the bosses added via laser deposition, drastically reducing cycle time and cost. "The way we look at it is in terms of waste ratio," Grylls said. "In aerospace, they call it the buy-to-fly ratio. It's how much raw material you have to start with compared to how much ends up on the finished component. With traditional subtractive processes, the amount of wasted material can be significant, and the cost of the waste can soar when you are dealing with expensive metals, such as titanium. In the LENS additive approach, there is little material waste."

Coating a part's surface is another appropriate LENS application. "It's not sprayed on, so there's no risk the coating could spall off," Grylls said. "With the LENS process, the surface coating is metallurgically bonded to the base component, providing wear resistance or any other property you wish to have in that coating."

The LENS technology is suitable for a range of materials, including titanium, 316 and 420 stainless steel, H-13 and A-2 tool steels, F-75 cobalt chromium, 625 to 718 Inconel and metal-matrix composites. The standard specification calls for powder sized from 44 to 150 microns, but powders outside that range may be possible.

In addition, the LENS process is performed in a hermetically sealed environmental chamber with closed-loop controls. "That produces parts with outstanding metallurgical properties," Grylls said.

He noted that machining will always be the preferred method for high-volume production, but additive technologies, such as LENS, will have their established place for mass customization and performance-critical rework. "How many will that be? My guess is one out of every 10 machine tools," Grylls said. "That's still a very massive market."

—A. Richter

manufacturing, then I could get better performance as well as cheaper parts," said Fendrick. That might mean taking multiple machined parts and building them together in one additive operation. In one application, a blood centrifuge that required 30 machined parts was consolidated into two parts using laser sintering, Fendrick said.

RQM is working on a couple of jobs that were designed for DMLS. One is a dental application that falls under the category of mass customization, where a basic component is efficiently built in multiple configurations to suit different groups of people or even individuals. "Think of dental crowns for multiple people," Morris said.

Fendrick noted that dental copings and bridges are also suitable candidates for mass customization using rapid manufacturing to achieve a lower cost per part and quicker turnaround than traditional casting. "They're all custom. They're all different," he said. "We can build up to 200 copings in one build and do two builds a day."

Another RQM application is for the aerospace industry that involves smaller complex components. "That is a wonderful example of where the technology has been leveraged from the ground up, taking advantage of its capabilities to produce a part that you could not cost effectively make any other way," Morris said.

Additive Awareness

Knowing that some parts can be built more cost effectively and efficiently and actually having engineers design those parts for additive manufacturing is challenging. "Machining is so popular, and there's a workforce that can look at a part and often knows immediately what it's going to take to produce," said Terry Wohlers, president of Wohlers Associates Inc., Fort Collins, Colo., a consulting firm that tracks rapid prototyping and additive fabrication. "Whereas with additive manufacturing, people don't fully understand the technology because it may be relatively new to them. There's a learning curve to knowing when it makes sense to use the technology."

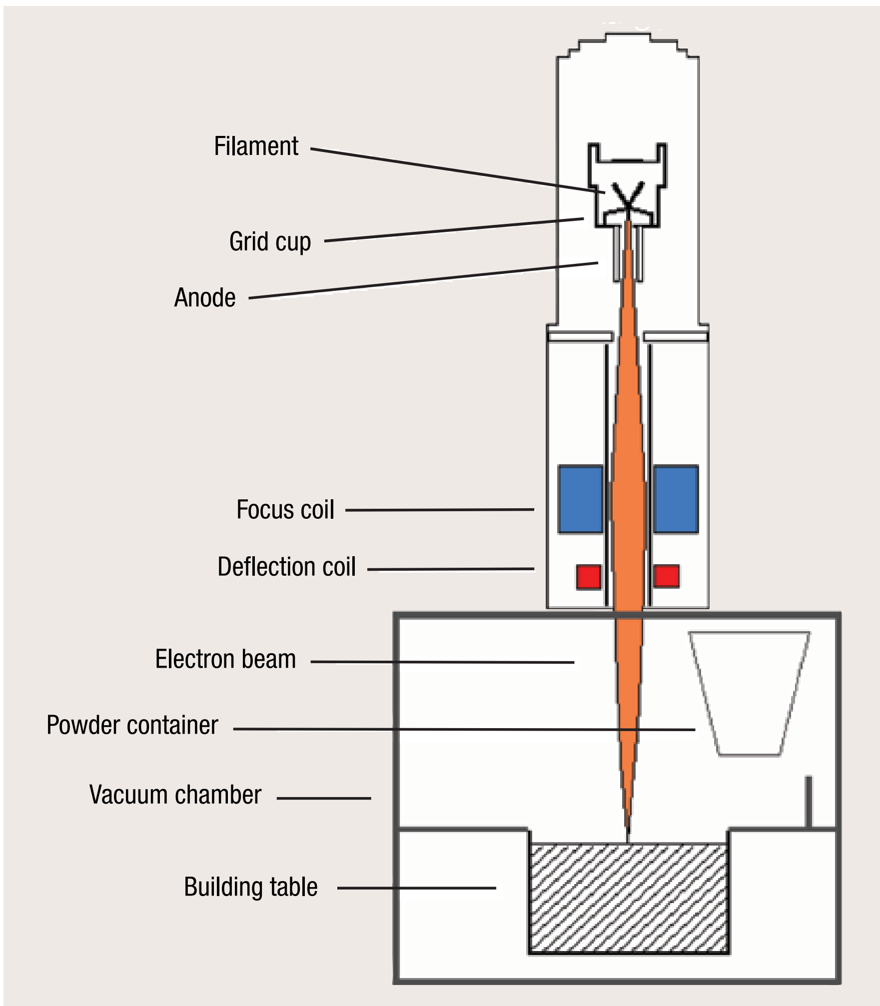
Even when additive technology is used to produce parts, part designers might not be taking full advantage of it. That includes reducing overall part count by building assemblies or building all of a part's features into it to reduce or eliminate postprocess machining. That's something Forecast3D, Carlsbad, Calif., encourages its customers to do, said Alex Fima, director of operations. "For example, they're normally not including threads in their solid models for components that require threads, and we're encouraging them to do that so we can build the threads into the net part and simply chase the thread rather than performing a whole tapping operation."

Forecast3D has several EOS M270 DMLS machines for creating medical instruments and implants, valve components and some aerospace parts. Prototyping accounts for 60 to 70 percent of the company's additive work, and rapid manufacturing volumes range from 50 to 500 parts. Forecast3D also performs CNC machining, but finds that rapid manufacturing doesn't take business away from its CNC business because "many people aren't designing hard, organic-shaped parts," Fima said. "They're designing for CNC."

Fima added that customers also aren't typically designing bimetal parts for additive applications, but Forecast3D will soon begin offering that capability.

Metal Melt

Another rapid manufacturing technology selectively melts a metal powder with an electron beam. Arcam AB, Mölndal, Sweden, manufactures the equipment, which is distributed in the U.S. by Technology Resources for Manufacturing Inc., Indianapolis. With EBM, a CAD file is electronically sliced into thin layers



Technology Resources for Manufacturing

Schematic of Arcam's electron beam melting process.

and each layer is then built by melting the layer in a powder bed. An electron beam first scans the selected area to preheat it close to the powder's melting temperature and then melts the material before another layer is added.

Because an electron beam moves at up to a kilometer per second to melt a part's X- and Y-axis dimensions, the part's Z-axis height determines how long it takes to build. One configuration for Arcam's A-2 machine enables building a part up to 14" tall.

Technology Resources for Manufacturing

Electron beam melting is able to create hybrid structures, such as this one with solid and mesh sections in the same part.

Performed in a hard vacuum of about 10^{-4} millibars, EBM produces homogenous parts with virtually no stresses in them and draws nothing from the atmosphere, according to James B. Robinson, Arcam's director of U.S. marketing and liaison. Avoiding interaction with the atmosphere is particularly critical when producing titanium parts because titanium is very reactive to oxygen and other elements. "Even if you try and shield titanium with an inert gas, there's still going to be an affinity for the oxygen, and the oxygen is drawn to the metal, which can make the material out of specification," Robinson said. He noted that the process also uses cobalt-chromium powder.

Robinson said a finished part's material has a uniformly fine microstructure, and the EBM-produced material is stronger and more ductile and has a higher elongation percentage than conventionally produced counterpart material. According to Arcam data, EBM-deposited Ti6Al4V has an ultimate tensile strength of 1,037 Mpa ±28, a yield strength of 948 Mpa ±27 and an elongation of 15.5 percent ±1.9 at room temperature. This compares to an ultimate tensile strength of 930 Mpa, a yield strength of 885 Mpa and an elongation of 12 percent for wrought (annealed) Ti6Al4V, and a 1,000-Mpa ultimate tensile strength, 896-Mpa yield strength and 8 percent elongation for an as-cast casting.

Besides producing a high-quality material, EBM is also able to build continuous hybrid structures that can have solid sections combined with a mesh section. "How would you even make that mesh? It's impossible to machine," Robinson said.

Barriers and Limitations

Rapid manufacturing technologies enable building of parts that would be extremely difficult if not impossible to cast, machine or mold. They can also produce low part volumes faster and more economically than, for example, designing and fabricating tooling for molding or casting and then producing the parts. Still barriers and limitations exist. One is the cost of entry to buy a system. "They're not inexpensive, so you really have to build a business case to justify the purchase of one," said Wohlers, noting that prices range from about $300,000 to $1 million or more for industrial-grade machines.

Harvest Technologies' Clemons concurred. "You're usually looking at a minimum of $300,000 by the time you add up all the ancillaries." He added that SLS is far from being a plug-and-play technology. "If you took a highly intelligent, educated, technical person, an engineer, it would take him months to where he could do a pretty steady, good job, and years before he picked up on all the nuances," Clemons said.

Even with skilled personnel, he noted that it's often easier to produce good parts on a new machine because all the parameters are dialed in accordingly and it's the only time virgin powder is being used. That's because a cost-effective business model requires recycling much of the unsintered powder. "There is a bit of a honeymoon period when people first get their machines," Clemons said. "They get going, everything is fine and dandy and then after a while, there are people who hit the wall. They have to pick up on the nuances and develop creative solutions. When it's the first time you have to do something like that, it can be very difficult."

SLS machines are also sensitive. "Plus or minus 1° F can drastically affect your build at times," Clemons said, adding that the best operators monitor their machines constantly to ensure they're functioning properly.

Depending on the specific technology, the selection of metal powders can be limited, but DMLS, for example, offers a host of metals, including 17-4 and 316L stainless steel, F-75 cobalt chromium, titanium and tool steel. And the list keeps growing. "We're finding more and more metals friendly to run in our systems," said Forecast's Fima. "Certainly, we're able to process more materials than we had originally thought."

Aluminum, however, is one that isn't typically appropriate for the technology. "We can sinter aluminum, but from a commercial point of view, it may not be the best choice," said EOS' Fendrick. "With the application of high-speed machining of aluminum, sintering may not produce any benefits unless a part design that can't be manufactured by traditional methods is required."

Part size is also a limitation because the larger the part, the longer it takes to build. The physics of lasers, such as focal length and attack angle requirements,

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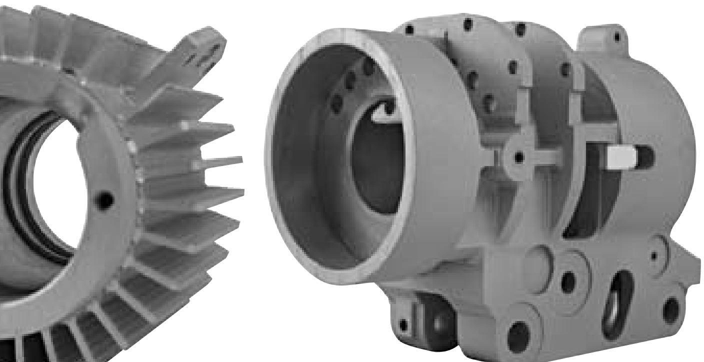


Forecast 3D

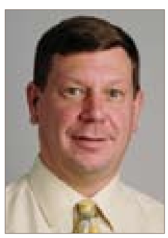
Samples of 17-4 stainless steel parts produced by Forecast3D using a direct-metal laser sintering machine.

limit how big the part bed size can be. "The part bed is 12"×12"×10"," Fendrick said. "If we had a larger one, then we'd also have to design the system to run faster."

Part volume is also an issue. "If you're going to make a million parts, this would not be the technology to use," Fendrick said. "It may be the technology to help build the mold that would make the million parts. I don't think this technology is going to replace traditional machining."

Where rapid manufacturing does make sense, it should continue to make further inroads. This is especially true in medical and aerospace applications, where there's mass customization for the former and low volumes of large end products for the latter.

"I think it's fair to say that in 15 to 20 years rapid manufacturing will be a multibillion dollar business," said Morris Technologies' Morris. "It's going to grow because of the capability you get out of the process. I also think CNC machining will be an integral part of that. They are very complementary." **CTE**



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