COLIBRIUM ADDITIVE
a GE Aerospace company

Enabling Metal Additive Production Using Electron Beam Melting Technology

Electron Beam Powder Bed Fusion Anthology

For the ready

While Electron Beam Melting (EBM) technology is similar to laser-based metal additive, they are complementary technologies with unique advantages. Among other features, EBM builds uses a vacuum environment, resulting in stress-free parts.

In this Anthology our experts guide you through the history of EBM, how the process works, and the improvements we have made over the years. Are you ready to learn more about this ground-breaking metal additive technology?

EBM Anthology

01

Electron Beam Melting: An effective choice for industrial metal 3D printing

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An effective choice for industrial metal 3D printing

Isak Elfström, Senior Engineering Manager

By eliminating thermal stress and stacking parts on top of one another, Colibrium Additive's EBM systems are ushering in industrial scale metal additive manufacturing for aerospace and medical devices.

After a quarter-century of development, Electron Beam Melting (EBM) additive manufacturing is is a viable option for metal additive production. Colibrium Additive's EBM printers are not just fast, stable, and reliable but also capable of industrial-scale production runs of thousands and tens of thousands of precision parts per year.

This may surprise some people. After all, for most of its history, EBM technology was overshadowed by 3D laser metal printing. At first glance, the two technologies have much in common. Both print parts in a bed of metal powders, selectively melting and solidifying one layer of powder after another to form a solid part. And, like all additive processes, both give engineers unparalleled freedom to create complex geometries, add functionality, shrink size, and lower mass.

That, however, is all they have in common. EBM, as its name implies, uses a powerful electron beam rather than laser to melt the powders. The combination of ultrafast electron beams and elevated operating temperatures enable EBM systems to optimize the heating and cooling rate of each layer of powder. This slashes thermal stress by orders of magnitude when compared to laser printers and eliminates the need for the heavy support structures to keep them from warping.

As a result, EBM has shown itself to be an effective method to manufacture metals that are difficult to produce in other additive technologies. These include metals that are brittle, prone to cracking, difficult to weld, and hard to machine, including titanium aluminide.

Unlike other metal additive technologies, EBM printers make can full use of the powder bed's entire build volume. Colibrium Additive's EBM machines print stacked parts–sometimes with no support between them–that start with the build plate and can go to the top of the build envelope.

This makes it possible to make scores of parts in a single run. Some EBM systems can routinely print more than 150 acetabular cups (for hip implants) at a time. This ability to scale–the more parts per run, the higher the productivity and the lower the cost per part–is what makes true industrial scale EBM printing possible.

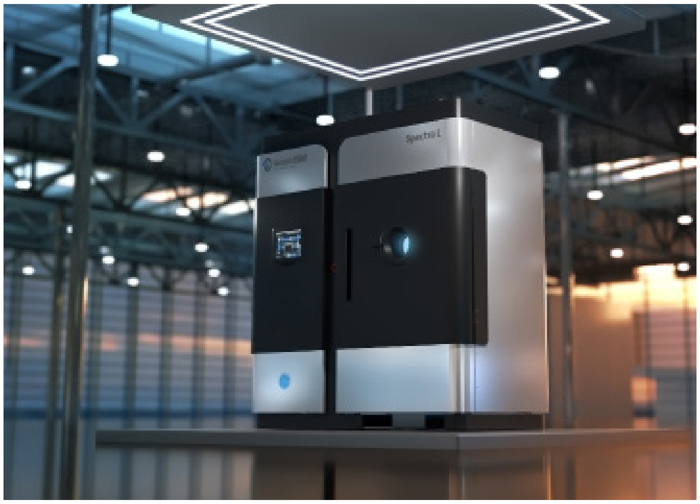
It is an impressive resume for a process that did not even use an electron beam when it was first invented.

An Evolving Technology

EBM's roots trace back to Morgan Larsson, a Swedish master's student looking for a faster way to print three-dimensional objects from metal powders. The original idea was to try to tame arc welding, a common industrial process that uses the heat created by an electric arc to weld metals. In 1997, Arcam AB was formed to commercialize the arc metal printers.

While arc welding printed parts much faster than lasers, it had a problem: precision. It was hard to coax an electric arc to hit the same spot with the same place with amount of energy twice. That sent the Arcam team looking for alternatives. They found one at Volvo Aero (now part of GKN), which used an electron beam to weld parts together. Arcam's crew borrowed the machine over a weekend, and before they left, it was already working better than arc welding ever had.

In 2003 Arcam sold its first EBM machine to North Carolina State University. The machine had a small build plate, worked with a limited number of materials, and had trouble



printing fine features. On the other hand, it was fast and based on the same principles that power today's more advanced EBM machines.

Those principles begin with the use of accelerated electrons as energy carriers. Electron beams tunnel into the material and homogenously melt the particles. This is a great advantage when working with reflective metals, since e-beams are less likely than lasers to vaporize the surface of the powders before melting their cores.

E-beams are also very efficient. Pure copper, for example, absorbs only about 2 percent to 10 percent of a red laser's energy, while EBM absorption efficiencies run between 65 percent to 85 percent.

Improved absorption efficiencies enable EBM systems to melt coarser powders than other metal AM technologies. Not only do EBM powders cost up to 50 percent less than finer mixes, but they are also easier and safer to handle.

Eliminating Thermal Stress

Beam steering and elevated operating temperatures are the key factors in EBM's ability to make parts with very low thermal stress. Beam steering describes the system that moves the laser or e-beam to selectively melt only part of the powder bed. Laser printers manipulate laser location and shape using mirrors. These mechanical systems are subject to the laws of inertia and so they are relatively slow.

EBM systems, on the other hand, use electromagnetic coils to control beam position, shape and focal point. Since they have no mechanical parts, The latest Arcam printers can change e-beam locations at speeds of up to 8000 meters per second. This enables EBM systems to control precisely how fast each location on the powder bed surface melts and solidifies and reduces.

Another advantage of EBM is that it takes place in a vacuum at elevated temperatures. Unlike photons, collisions with air will sap the energy of accelerated electrons before it reaches the powder bed. As a result, EBM operates under a vacuum of about one-billionth of an atmosphere.

It takes a closed environment to maintain a vacuum, so the EBM build space retains heat like a thermos bottle. In fact, the spaces between the coarse powders are also devoid of air and serve to further insulate heat and keep it from dissipating. This drives up operating temperatures, making it possible to heat each layer of metal powders to 1000º C or higher before hitting them with the electron beam.

Higher temperatures deliver two advantages. First, it reduces the amount of time and energy needed to melt each layer of powder, since the metals start out much closer to their melting point. Second, it reduces the e-beam's energy consumption. Even a large EBM printer like the Spectra L draws only about as much power as two electric tea kettles.

Like ultrafast e-beam steering, elevated temperatures also alter the rate at which melted powders cool. The temperature of laser-melted powders typically drops by hundreds of thousands of degrees Celsius per second as

they go from their melting point to room temperature (or slightly above). Such high-speed cooling creates large thermal stresses that would bend and twist parts if they are not melted to the build plate and anchored down by support structures. The resulting parts often require heat treatment to relieve those built-in stresses.

EBM, on the other hand, starts at elevated temperatures, so there less of a drop from melt to solidification. In addition, EBM's electromagnetic coils make it possible to deliver quick bursts of heat to multiple locations on the build, optimizing the cooling rate to relieve stress still further. This is why EBM printers produce parts that have very little residual stress. As a result, EBM parts do not need stress relief and require much fewer supports than other metal additive methods.

EBM's hot process enables it to print parts using materials that would be impossible or uneconomical to make by any other metal additive manufacturing process. This includes parts made from titanium-aluminide, a strong, lightweight, heat-resistant alloy that is prone to cracking; thick parts whose internal stresses would otherwise be too high; and thin, free-floating beams.

Pioneering Applications

When Arcam commercialized its first EBM printer in 2003, it hoped to print tool steel, a hard and difficult material to machine. That market never really caught on, so the company switched its focus to applications where EBM printing added value to already-expensive components.

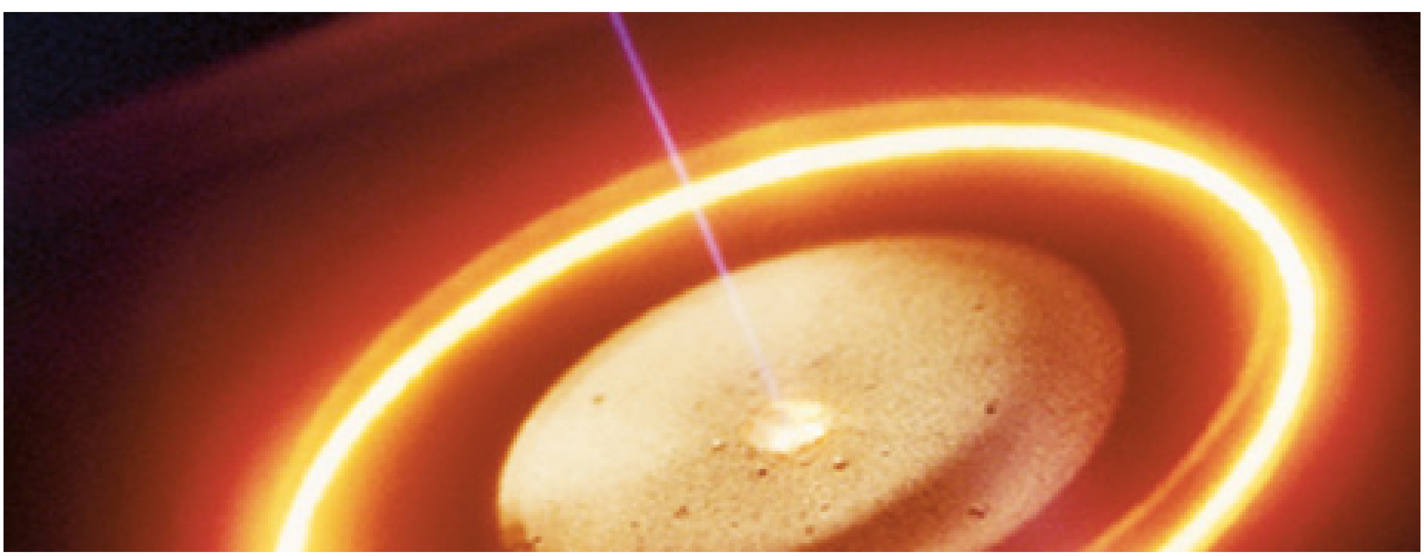
Two markets stood out. One was aircraft engines, where any reduction in weight, especially in rotating parts like turbine blades, delivers significant fuel economies over the lifespan of the engine. The second was orthopedic implants, especially acetabular cups used in hip implants.

By 2006, Arcam was working with two small Italian companies to print acetabular cups. The cups act as sockets in ball-and-socket hip implants. The semicircular cups fix to the hip and hold a ball attached to rod implanted in the thigh bone. Traditionally, physicians screwed or cemented cups into place, but new porous surfaces let bone grow into the cup and lock it in place.

Those porous surfaces did not come cheap. They required several additional and costly processing steps. EBM, on the other hand, could print the cup and textured surface in a single operation, simplifying production and saving time and money. It took a year to develop the fine textured surface, but the application proved a success.

Around 2008, Arcam began working with Avio Aero, an Italian manufacturer, to develop titanium aluminide (TiAl) low-pressure turbine blades for the new GE9X engine. Each GE9X holds 228 blades. Since each blade weighs half as much as the nickel alloy parts they replace, they play a key role in reducing the engine's fuel consumption.

Although titanium aluminide is often called a metal, it is actually an intermetallic, a metal with ceramic-like strength, heat resistance, and, unfortunately, brittleness. It is notoriously difficult to machine without cracking. It is not



amenable to laser printing, which creates residual stresses that also lead to cracking. It took more than a decade to develop the application for EBM, but since 2019, GE has been printed thousands of TiAl blades annually.

The turbine blades and acetabular cups were both successful projects, and not just because they met project goals. They also drove Arcam to enhance its EBM printers to meet the most demanding requirements of two of the world's most highly regulated industries.

GE Aerospace was so impressed with EBM's capabilities and potential that it acquired Arcam in 2016 and made it a core business of Colibrium Additive. AP&C was also part of that transaction and is now the world's largest producer of titanium metal powders. Backed by Colibrium Additive's global research team and marketing reach, EBM is staking out a larger role in industrial production.

Productivity

These improvements show up in Colibrium Additive's current EBM printers, which have been optimized to reduce variations during industrial production.

This starts with the coils used to steer EBM's electron beam. Ordinarily, deflecting electron beams with electromagnetic coils causes disturbances within the beam. EBM uses large deflection angles, and these cause greater variations in e-beam power and shape. For its latest generation of EBM printers, Colibrium Additive reengineered the coil system to compensate for those variations. It also developed a system to calibrate beams automatically, reducing deviations caused by manual calibration.

The new EBM printers also maintain their temperatures with a much narrower range, which enables the processing of crack-prone alloys.

Maintaining such a narrow range is not easy. In some ways, it is like trying to keep a set temperature in a bathtub: Add too much hot water and the temperature will rise, but add too little and it will fall. Most people use their finger (if they are not already in the bath) as a sensor to see if they are getting it right.

That does not work in an EBM system. Electron beams deliver far more heat than bath water. This creates a highly dynamic environment whose management cannot wait for sensor input.

Instead, Colibrium Additive uses a time-dependent heat equation based on the known input of the electron beam

and the heat capacity of the material. This is verified using cameras that measure small changes in the temperature of the powder bed surface.

The ability to compensate for electron beam deflection and manage heat within a narrow range are two important reasons why EBM printers can print stacks of parts. They improve uniformity and reduce thermal stresses to an absolute minimum. As a result, they do not require the supports used to anchor parts to printer base plates to prevent warping.

While most EBM parts employ minimal support structures, others can use no supports at all. In fact, Colibrium Additive's EBM machines can print tightly stacked parts that float freely within the powder bed. These parts require little if any post processing and do not require stress relief.

True 3D nesting is the reason EBM printing is so productive. While electron beams are very fast –a single electron beam can keep up to 70 melt pools "alive" simultaneously–it takes time to heat the build space to its working temperature. But once at temperature, EBM can print stacks of parts that can go from the build plate to the top of the build envelope. This dramatically lowers the average amount of time needed to produce each part. The more parts in a run, the more productive EBM becomes.

Today, Colibrium Additive's printers have proven themselves by producing parts from some of the world's most difficult-to-process metals, such as titanium aluminide. They are well suited to production runs of thousands and tens of thousands of parts and, depending on the design, even hundreds of thousands of parts over the course of time.

As EBM printer tolerances tighten and efficiency rises, so does surface and feature resolution and geometrical freedom. At the same time, the cost per part is falling, thanks to EBM's ability to use less expensive coarse metal powders, eliminate post-printing heat treatment to reduce part stress, and avoid additional support structures. This will enable Colibrium Additive's EBM printers to address larger markets in the future.

Aerospace engine parts and medical implants are just the beginning.

EBM Anthology

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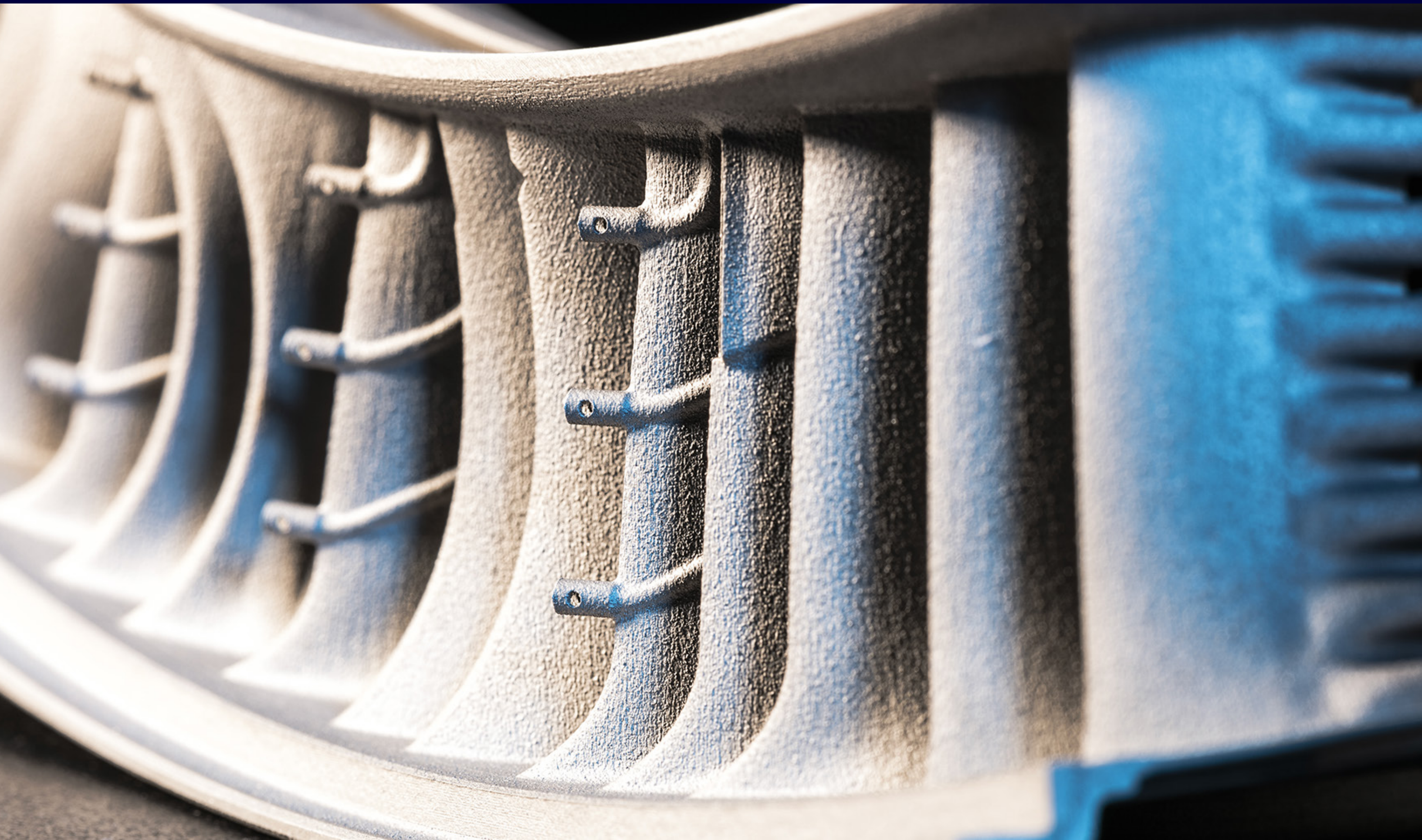
Colibrium Additive's leadership position in EBM

Ulf Johannesson

Managing Director EBM



Colibrium Additive's leadership position in EBM

Ulf Johannesson, Managing Director EBM

We wanted to discuss what makes Colibrium Additive the clear leader in Electron Beam Melting (EBM) additive manufacturing. Before we do that, though, let's clear up a preconception some people have about EBM. They think of it as a variant of laser metal 3D printing. Are they alike or are they really very different technologies?

Laser metal 3D printing and EBM are different technologies – whilst they both print from a powder in the 3D printer's powder bed, a key differentiator is that EBM uses an electron beam and laser metal 3D printing uses a laser. There is some overlap but EBM is the only additive process that prints nested parts, stacks of parts that rise from the build plate to the top of the powder bed.

What is the sweet spot for EBM technology. Who should consider using it?

Colibrium Additive's EBM systems are printing parts from the most crack-prone, difficult-to-machine, hard-to-weld, most reflective, and most refractory materials, including titanium alloys, nickel alloys, cobalt chrome, pure copper, and high-alloy tool steels. It is the only additive process that prints parts from crack-prone titanium aluminide.

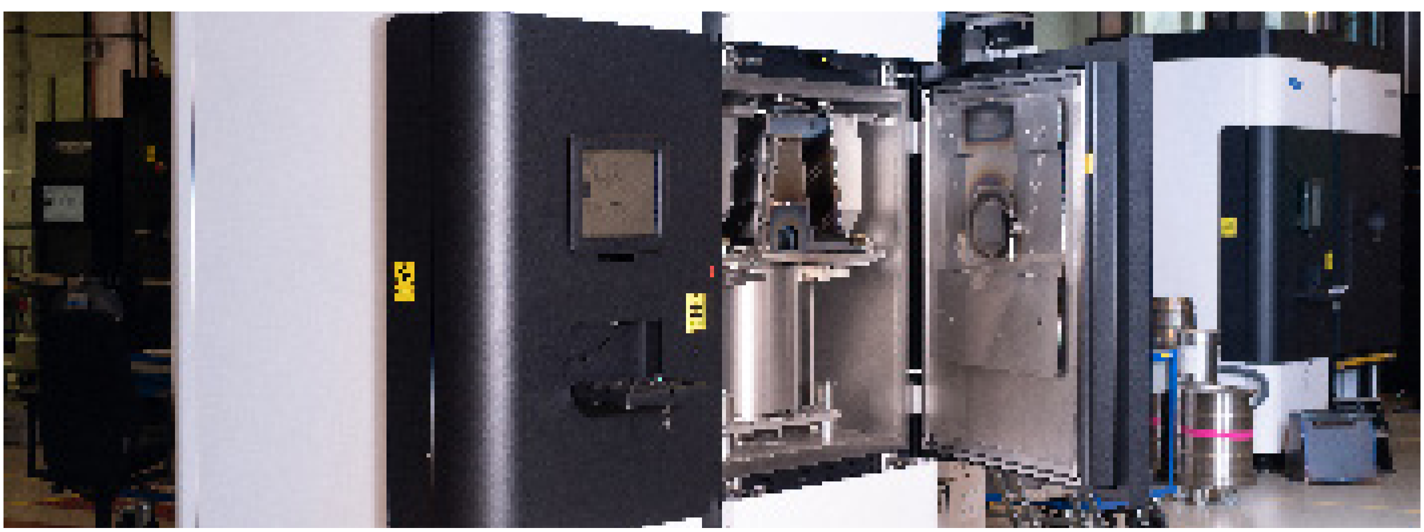
In terms of use, clearly manufacturers working in the medical, aviation and aerospace industries come to mind. Today's EBM printers have proven their cost-effectiveness in these highly demanding and regulated industries. Traditionally, surface finish has been better using laser than EBM, which is superior for things like intricate mesh structures for bone growth, but I think if we compare laser with the newest EBM machines, we actually achieve both – we can control net structures really well and also achieve a very nice surface finish if that's required.

How does this translate into production advantages for users?

I see two key production advantages that EBM offers users. The first is productivity. The high-temperature vacuum process relieves stress, which enables part stacking for volume production, meaning you can utilize your build chamber to the maximum. Secondly, EBM allows the production of difficult materials, such as titanium aluminide and other crack-prone materials.

Aerospace and medical are both highly regulated industries. Is that a focus for EBM? Why?

If you look at the history of additive manufacturing, academia first focused its research in the medical field due to the possibilities of titanium. Then the focus switched to aerospace for much the same reason. Is it an active choice



to go after such highly regulated industries? I would say no, it's more that these are segments that have a great use, and fit, for this technology and they happened to be regulated.

It is not easy for companies to achieve volume production in regulated industries with a relatively new technology. What makes that possible?

EBM offers equipment with the ability to hold tight tolerances as well as a thorough understanding of material and how it interacts with e-beam. We are also experts in the transfer of application knowledge to customers.

The challenge for a long time has been that we have been the only company providing EBM technologies, and we have had to do a lot of industry education together with our early adopters. Now, it's nice to see that, as the technology is more well known, it's becoming much more widely accepted. There is now healthy competition in the EBM space because the market sees the demand. I think this speeds up acceptance of the technology.

I would say that, given our unique position and length of experience in EBM, we have many and long-term use cases. There are patients who have been walking around for a long time with implants manufactured using our EBM technology. It's now a proven concept for parts in both the medical and aerospace sectors, we know how to provide the information needed to achieve certification and validation in a regulated space.

As the company that developed the technology, we have both the processes in place and a large research team on hand to guide our customers.

Let's take some of these points one by one. Let's start with equipment. Tell me about your latest EBM printers and how they differ from past models.

We are really proud of our new Spectra models. After 20+ years' experience, we have been able to capture a lot of technology development in these machines. The build chamber is larger, so you can make bigger parts or you can put more smaller parts in the same build. Productivity has gone up dramatically compared to the past.

They have an improved ability to repeatably build parts with less variation thanks to new technology that reduces disruptions when the electromagnetic coils are steering the electron beam. This makes everything more consistent and is important in high-volume production when it's essential that uncertainties are minimized. Manufacturers need to know that in any machine in which you print that everything comes out with a certain quality level.

The beam also moves 8,000 m/sec, fast enough to keep several melt pools open at the same time. This can improve thermal stress and allow for the optimization of a material's microstructure by controlling cooling rates. Last, improved thermal management provides the ability to hold temperatures within a 50 ºC range, making it possible to produce titanium aluminide (TiAl) and nickel alloy parts that are prone to cracking if processing temperature varies too much.

What about materials? How do EBM powders differ from laser powders and why is this important?

EBM is more sensitive to powder quality, especially surface chemistry since, the powder is both sintered and melted. EBM powders have a larger particle size distribution range, are easier to manufacture and cost less. They are also easier to handle. For customers, this means that it's possible to source a wider range of powder for your machine.

Can you talk about what it takes to characterize materials before using them?

It can take years to characterize materials as well as characterize material-machine interactions. This requires a database of past application development. In addition, when we launch a new powder, together with the machine, we do a process verification to ensure that we adhere to the requirements set for the material (typically industry standards).

Managing powders in a production environment is never easy. How has EBM automated this process?

This was very basic in the early days, which is why we have a new unit called our PRS 30 Powder Removal System. It's an advanced powder recovery station that offers a high level of automation for high-volume production. You take your whole build out and it goes into a closed system to avoid powder dust particles in the air, creating a safer environment for operators as well as greater productivity as it is semi-automatic and in a closed environment. For those working in a regulated industry, this closed environment also ensures a low risk of contamination.

A lot of companies have found it difficult to incorporate AM into their supply chain. Why is this, and how do you help your customers succeed?

At Colibrium Additive we have our AddWorks™ services, engineering and design consultancy for additive manufacturing. I think where most additive attempts fail is when customers just try to develop a normal, standard part with printing. You have to use the full capabilities of additive to design or re-design your part to get the most out of the technology – the shapes you want, the strength you need where you need it, reduced weight, reduced material, reduced waste.

You need to understand the technology and have it in mind from the beginning of the design process to bring forward all the potential of additive manufacturing, rather than just change a manufacturing method without doing anything else.

It's difficult for people to move to something new from processes that they are comfortable with. Before we sell a machine we can prove that EBM additive manufacturing works, show them the proof points and help them to make that transition with confidence.

If you look in the aviation and aerospace arenas, the whole principle of manufacturing has changed with EBM. How can you reduce the components of a part from 10 to 20 down to two? You can reduce your complexity, work with weights, work with geometrics, reduce your inventory – the switch to metal AM impacts the full supply chain, not only the manufacturing moment.

I don't think we have seen anything yet with what we can do with turbine blades. If you look at the medical implant or orthopedic industries, countries with large, aging populations are going to need many, many more parts and this is a huge opportunity for EBM. We've enjoyed a lot of success so far, but I believe we've only just been scratching the surface.

We started talking about how EBM differs from laser metal printers. As EBM systems have grown more capable, are they able to compete for applications that automatically go to laser printers now?

I don't see it as a competition between EBM and laser; the technologies continue to complement each other but it's true there is a gray area. I do see that with EBM we now have much better control of the surface finish than before and that makes EBM attractive where previously laser might have been chosen and this opens up new opportunities.

We are starting to see more EBM competitors emerge. What us from the pack?

Quite simply, experience. This is not easy and it takes a lot of knowledge and engineering hours with the inventors in-house to deliver the best results. At Colibrium Additive, since we have multiple technologies, we don't always need to be the experts on everything. We can focus on core technologies like the vacuum system, the gun itself, the material things, and we can work with others to create nice control cabinet design, for example. Compared to new market entrants, we offer stable, robust equipment, well-characterized powders, patents for new capabilities and proven industrial scale production in aerospace and implants.

Leadership is about the future. What is your vision for EBM?

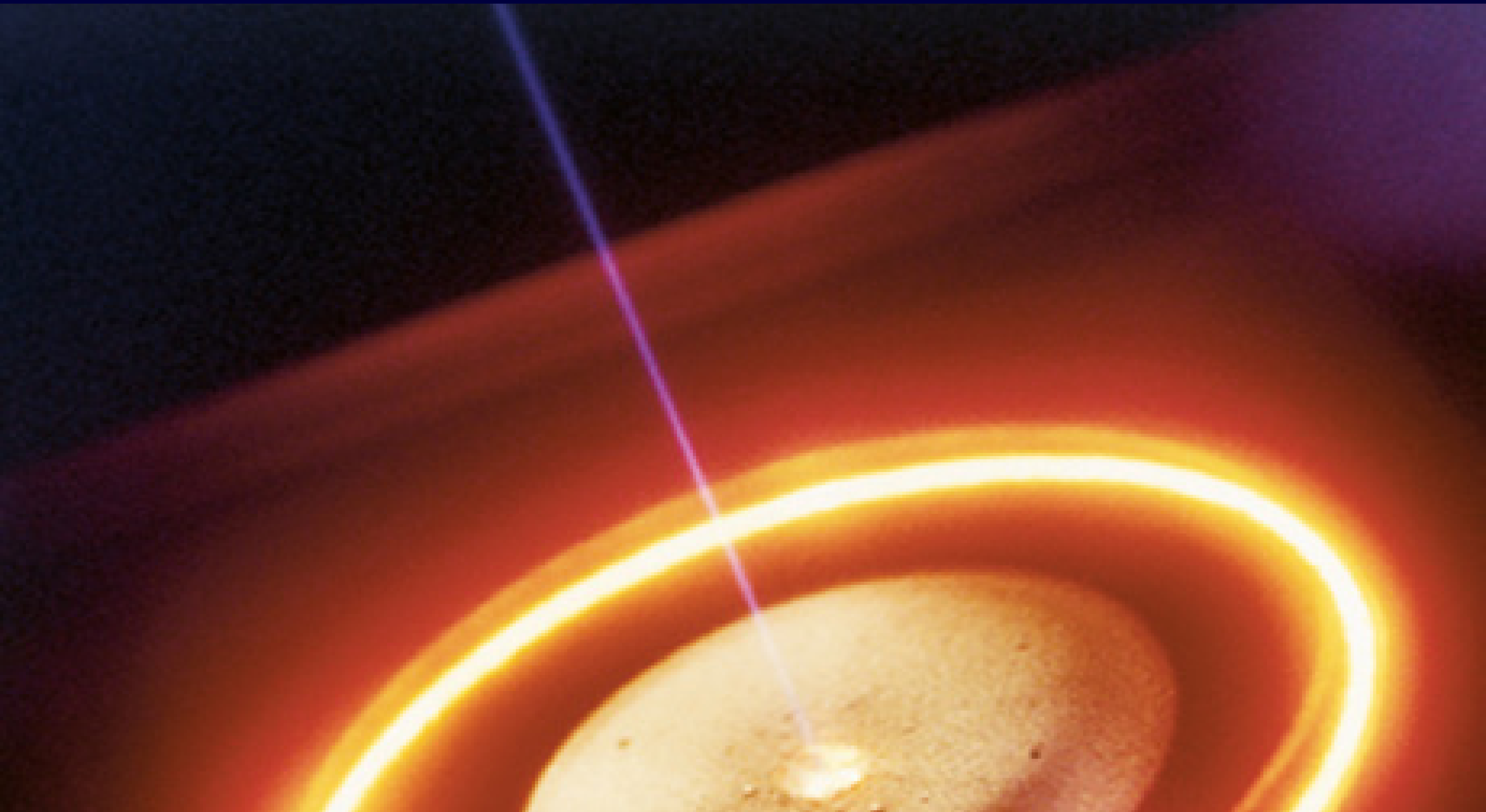
Everyone is talking about adopting additive manufacturing technologies and there is a lot of space to do this with the uniqueness of EBM and what it allows you to manufacture in certain materials. Of course, we believe strongly that there is a great future for additive manufacturing and it's clear that there will be new technologies and machine models that continue to emerge. There is a growing market space where EBM is a great fit and material development is going to make a huge difference down the road, which will make our applications even greater.

03

EBM Anthology

Electron Beam Melting: The evolution of EBM production

Matthieu Petelet
Staff Engineer



Electron Beam Melting: The evolution of EBM production

Matthieu Petelet, Staff Engineer, Colibrium Additive

By building on one product success after another, Colibrium Additive's EBM printers have established themselves as viable options for industrial-scale production.

Today, Colibrium Additive's EBM systems are printing parts from the most crack-prone, difficult-to-machine, hard-to-weld, most reflective, and most refractory materials. This list includes titanium alloys, nickel alloys, cobalt chrome, pure copper, and high-alloy tool steels.

For a variety of reasons these alloys are challenging to fabricate with conventional methods. The last decade of development has demonstrated that gamma-titanium aluminide and electron beam are genuinely made for each other.

Working with such difficult materials sounds like a recipe for high costs and low yields. Yet this is not the case. Today's EBM printers have proven their cost-effectiveness on some the world's most demanding and highly regulated applications. Their growing use in aerospace and orthopedic implants vouches for EBM's robust reliability and repeatability.

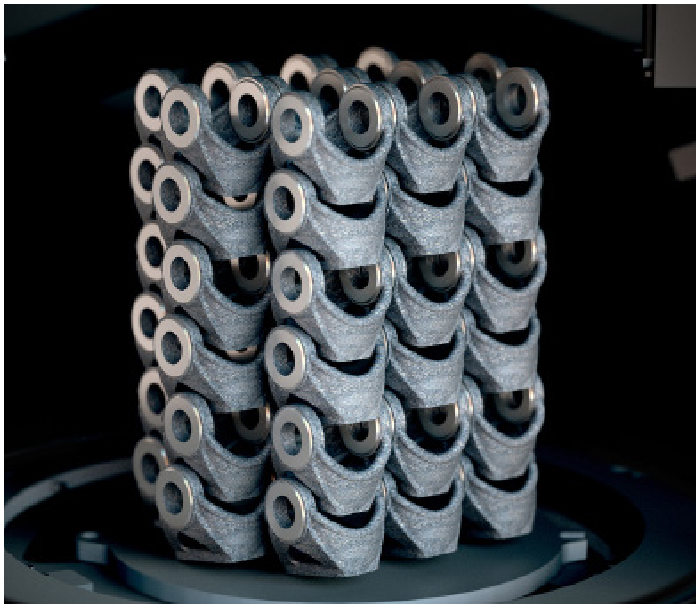
Every year, EBM machines produced by Colibrium Additive print thousands of titanium aluminide low-pressure turbine blades for the GE Aerospace's GE9X turbofan engine. It has produced satellite components and parts from highly reflective copper powders. On the orthopedic side, EBM devices have printed hundreds of thousands of acetabular cups used in total hip implants and is moving rapidly towards the production of other large joint implant components.

These parts can be printed competitively because EBM technology differs fundamentally from other metal powder bed technologies. These differences make it the only additive process that prints nested parts, stacks of parts that rise from the build plate to the top of the powder bed. Many of these parts have only the scantest support structures. Others float in the powder bed without any support at all.

Stacking enables high-volume production, greatly increased productivity, and reduced post-printing machining and finishing. This is true even for titanium aluminide, and it starts with electron beam technology.

Each GE9X engine uses 288 fifth- and sixth-stage low-pressure TiAl turbine blades. By making them from titanium aluminide (TiAl)

instead of nickel alloys, GE Aviation slices the weight of each blade in half. In commercial aviation, every ounce trimmed from a part's weight yields fuel savings that are multiplied throughout the aircraft's 30-year expected operating life. Those savings are even higher for rotating parts, and the TiAl blades rotate 2,500 revolutions per minute.



Taming Titanium Aluminide

To understand what makes EBM different, consider how it prints titanium aluminide low-pressure turbine blades for the latest turbofan engines. Developed for the Boeing 777X, the GE9X is one of the world's largest jet engines. Today, Colibrium Additive's EBM machines are printing

Each GE9X engine uses 288 fifth- and sixth-stage low-pressure TiAl turbine blades. By making them from titanium aluminide (TiAl) instead of nickel alloys, GE Aerospace slices the weight of each blade in half. In commercial aviation, every ounce trimmed from a part's weight yields fuel savings that are multiplied throughout the aircraft's 30-year expected operating life. Those savings are even higher for rotating parts, and the TiAl blades rotate 2,500 revolutions per minute.

TiAl, however, is not an easy material to work with. Commonly described as an alloy, TiAl is actually an intermetallic, a material with properties halfway between a metal and a ceramic. Like ceramics, it is strong and heat resistant. Also, like ceramics, it lacks ductility, which makes it brittle and prone to cracking.

GE had previously cast TiAl blades for another engine. They proved hard to cast because of their lack of ductility. When a typical metal cools in a cast, its ductility will let it deform slightly to accommodate differences in the rate at which different parts cool. With TiAl, however, those differences create enough stress to crack the casting. Low production yields led the company's engineers to consider 3D laser metal printing, which would also allow them to optimize the shape of the twisted blades.

That did not work out because 3D laser printing created thermal stress in the blades. When the spots where the laser melted the powders (called melt pools) solidified, the temperature dropped back to room temperature (or slightly above).

Rapid temperature drops generate thermal stress in parts, making them want to bend and twist. This is not just true for titanium aluminide, but for laser-printed metals. To prevent those stresses from warping parts, laser printers support each part with robust structures that weld them to the build plate and keep them from moving. In the case of TiAl, built-in thermal stresses caused a large number of blades to crack when they were removed from the build plate.

Electron beam technology solves the thermal stress problem in several different ways. To begin with, EBM printing takes place in a vacuum, which taps the heat built up in the powder bed. This raises temperatures, which can reach well above 1000 degrees C. Since TiAl melt pools do not have to cool down to room temperature, cooling generates less thermal stress.

Equally important, EBM uses magnetic coils to steer its high-energy beam. This enables electron beams to move many orders of magnitude faster than printer lasers, which rely on mechanical mirrors. In fact, Colibrium Additive's latest EBM printers can deliver thousands of pulses per second while changing the location of the electron beam at speeds of up to 8,000 meters per second.

This enables EBM to keep dozens of melt pools open simultaneously. By controlling the energy, size, focal point, and duration of the pulse, EBM printers tightly control the speed at which the melt pools solidify, further reducing the amount of stress that builds up in the part. (The same technique also enables the printers to tailor the microstructure of the resulting part by controlling its cooling rate.)

By optimizing thermal stress, EBM can print parts with little or no support structures. This makes them much easier to remove from the build plate and boost yield.

Printing Aerospace Parts

It took a while to work out how to print aerospace parts. In its search for an alternative to Ti-Al casting, GE Aerospace turned to Avio Aero, an aerospace manufacturer in Cameri, Italy. Avio had partnered with a smaller local company, ProtoCast, to laser print titanium alloy parts for a military jet. It advertised itself as a company able to solve tough materials problems.

GE Aerospace wanted to see if Avio could make the blades by additive manufacturing. Working with ProtoCast, they first tried laser printing. When that failed due to thermal stress problems, ProtoCast was ready with an alternative: an EBM printer. It took years to master the application. Working together, Avio and ProtoCast tweaked the EBM equipment to thicken the powder layers, speed up printing times, and better control the temperature during the build to relieve stress.

In 2013 GE Aerospace acquired Avio, and then, in 2016, Arcam (which along with the acquisition of Concept Laser) was the genesis of Colibrium Additive. Commercial production began in 2019. Today, rows of EBM printers are turning out thousands of TiAl blades annually at the company's Cameri facility. They then send the blades to Avio's Pomigliano factory, where they are ground, milled, polished, tested for potential flaws, and then plasma sprayed with a heat-resistant coating.

Colibrium Additive used their success to improve EBM printers' statistical process control. Using a variety of sensors, the company developed a way to interrogate the quality of the melt at each stage of the build and assess the quality of final part after completion.

EBM has had other wins in aerospace. In 2011, Astrium (now Airbus Defence and Space) mounted one of the very first EBM-printed titanium components on-board Atlantic

Bird 7, a Eutelsat GEO telecom satellite for digital broadcasting markets in the Middle East and North Africa. Since 2016, Zenith Tecnica, a contract manufacturer in Auckland, New Zealand, has printed hundreds of titanium alloy structural parts for Maxar Technologies in Westminster, Colorado, a leading satellite manufacturer.

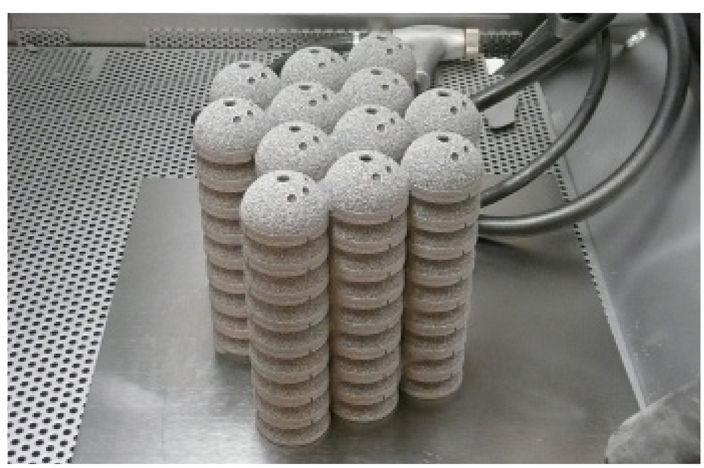
EBM printing enables engineers to create the shapes and thermal behavior required by a satellite's close confines while reducing mass and assembly complexity.

Colibrium Additive has also expanded its materials offerings to include commercial development amounts of pure copper and high-carbon steel. Pure copper powders are more economical to process on EBM because they absorb 80 percent of an electron beam's energy, compared with 2 percent for red laser metal printers. EBM systems also do a good job of controlling thermal stress in high-carbon tool steel parts, which are prone to cracking in laser metal printers.

Stacking Orthopedic Implants

Aerospace components are not the only parts made from Ti-6Al-4V. The alloy is also widely used in orthopedic implants because it is strong, light, and biocompatible. One of the first mass products to catch on were small titanium cages used for spinal fusion surgery. The companies that make these cages differentiate their products by their fine features. Laser printers had the speed and resolution to replicate those critical features while reducing cost. Today, laser printers produce most of the world's spinal cages.

When it comes to larger joint implants, like hips, knees, and shoulders, laser printers have had mixed success. The larger the part, the fewer parts a laser printer can produce at a time and the higher the per-unit cost of each part. Most companies have found that it costs less to cast or machine the parts than to print them.



There is one exception, however: acetabular cups. The cups are used in hip implants, which work like a ball-and-socket joint. The cup goes into a carved-out space in the acetabulum (hip) bone and acts as the socket. A hole is drilled into the thigh bone to hold a rod with a ball at the end. This ball goes into the cup, allowing the leg to swing.

In the past, acetabular cups were either cemented or screwed into position. This took time in surgery and eventually wear and bodily fluids degraded the cement and screws and loosen the joint. To get around this problem, medical companies invented cups with rough, porous surfaces that friction-locked into the hip. This allowed natural bone to grow into the cup and lock it into place, creating a more durable bond.

Producing those cups by conventional manufacturing methods was not easy. While the cup itself was relatively simple to machine or cast, creating a tough, porous friction coating over it required multiple specialized processing steps. Most small and mid-sized companies that did not have the equipment to do this in house. Instead, they sent cups from one contract manufacturer to another to complete each step of the process. Implant developers often found themselves with limited visibility into a supply chain that dragged on for months and months.

Additive manufacturing offered a simpler production route since it integrated coatings with the production of the part. Since acetabular cups were relatively small, they were a good fit for laser metal printers. The downside of lasers, however, is that only printed one layer of parts at a time, which limited productivity.

In 2006, Arcam began working with two Italian companies to develop the application for EBM. It took a year to get the coatings right. Then in 2016, Arcam began stacking cups during each build.

This totally changed acetabular cup production economics. By leaving only a thin layer of unmelted powder between each cup, large EBM systems could print 20 stacks of eight cups each, or 160 cups per build. EBM also let producers mix and match cups of different sizes or to build other orthopedic hardware or tools in unused spaces within the build box.

Because of its large build volume, high productivity, and rapid turnaround times, EBM is well suited to making other implants as well. In fact, Colibrium Additive and Orchid Orthopedic Solutions, a leading global orthopedic implant contract manufacturer, are currently working to increase the addressable part portfolio with EBM printers to make a variety of hip, knee, and shoulder components for implant providers.

EBM still has a lot in common with laser metal printing technologies. EBM and laser technologies are unique and each offers its own advantages. Like laser, EBM offers the design freedom to make complex parts and add functionality.

EBM has several features that set the technology apart. It works with a range of the most difficult-to-print-or-process alloys. It overcomes thermal stress. It uses stacking capabilities to facilitate industrial-scale production for a range of parts.

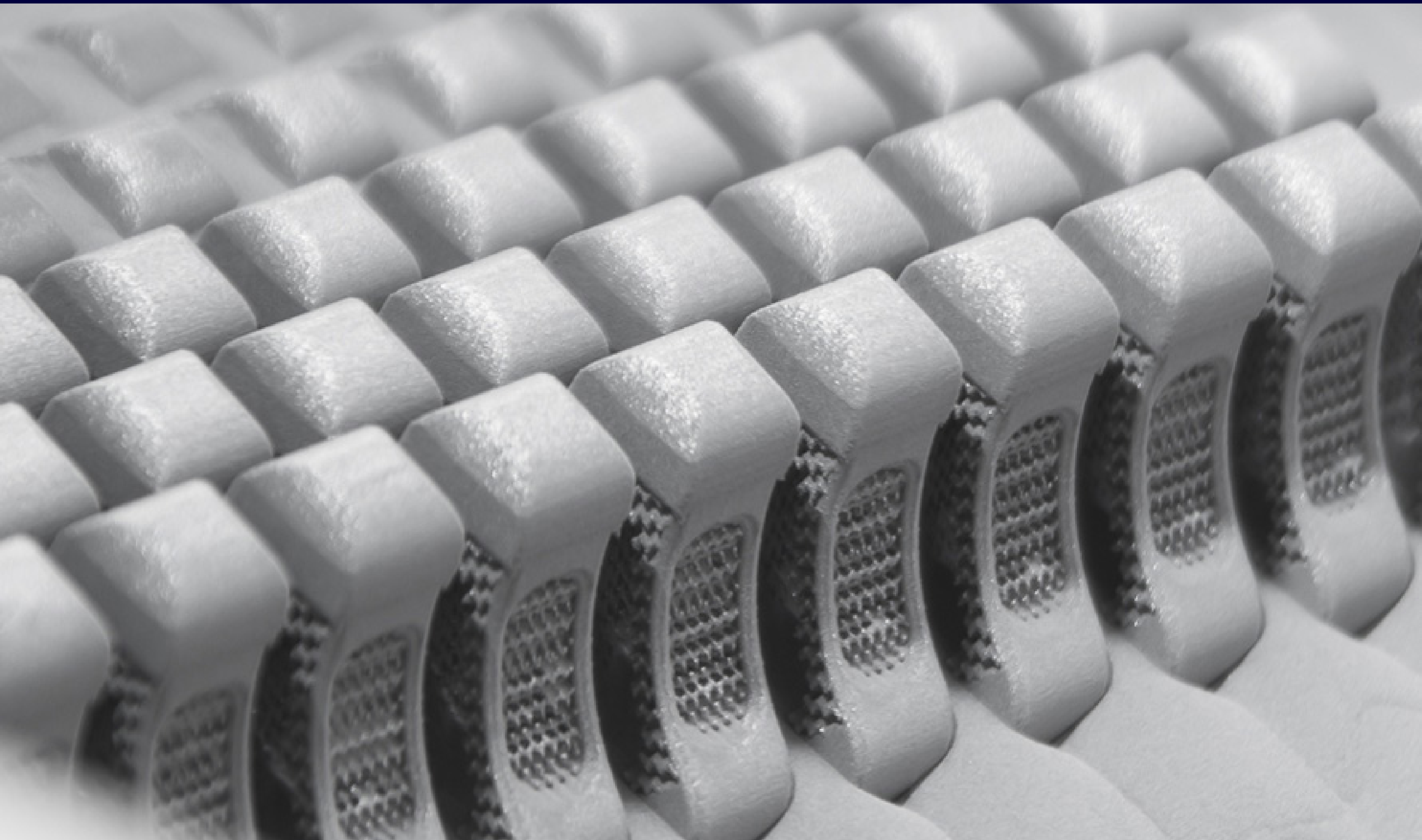
EBM proves itself as an excellent way to add value to a broad range of products and secure a cost-effective serial production.

EBM Anthology

04

Get the facts on vacuum environment in EBM

Phillip Mahoney
Staff Engineer



Get the facts on vacuum environment in EBM

Phillip Mahoney, Staff Engineer

The vacuum environment is one of the most critical aspects of Electron Beam Melting (EBM) that enables the machine to function properly. It is also responsible for creating parts with a high quality and for preventing contamination in both the pre-cursor powder and the finished part. Without it, the parts you would get out of the machine would not be worth keeping. In this article, we catch up with Philip Mahoney, staff engineer at Colibrium Additive, to discuss how the vacuum environment works and why it is highly compatible with electron beams.

What defines the vacuum process for EBM and how is this different from how parts are built in other additive systems?

In EBM, we operate the processes in near vacuum—more specifically in a medium to high vacuum—whereas other modalities use an atmospheric environment. The atmospheric condition in some machines is different than the air we breathe as it's made of an inert gas, but they work under atmospheric conditions that arenot ideal for an electron beam. In the EBM vacuum, an atom of gas can travel anywhere between 1 mm and a few hundred cm before they interact with another gas atom. This means we can process our materials in a pure atmosphere to build our parts.

Why do we use vacuum processes in EBM?

If you look at EBM, it is a powder-bed fusion additive manufacturing process during which you lay down layers of powder one after another. If you look at some of the other powder additive methods, they are driven by light and the energy is delivered by photons. Light can easily travel through a gas without being interrupted. However, if you are using an electron beam to deliver energy rather than a beam of photons, then there is a charge associated with that beam, which interacts with other atoms in the process—including any gas atoms in the build environment. So, a vacuum is required to deliver the electrons in a columnated way to melt your material. While a vacuum environment does come with some build advantages, EBM metal additive would not be possible without it.

How is the vacuum environment created?

In EBM, a series of turbopumps is used to run the build and create the vacuum. When a gas particle enters these pumps, it gets sucked through and pulled out of the back of the machine through the exhaust—and nothing can get back in that way. So, you physically pull the gas out. This vacuum level is on the border of a medium and high vacuum, so a medium level is the equivalent of a gas atom travelling anywhere between a few mm to a cm, without interacting with another gas particle, while a high vacuum is anywhere from a few cm to a km.

How often do the turbopumps need to be replaced?

Turbopumps at customers with valid service contracts are replaced/refurbished every four years. However, the one I'm currently working with is around five years old and I have not touched it. It ultimately depends on what you are doing in the machine with respect to the different materials being used and the evaporation rate of those materials.

If you are evaporating a lot of material, then it has to go somewhere. Some it can go into the turbopumps, and they may have to be replaced more frequently. If you are working with materials that are more stable under vacuum, such as titanium, you'll have a clean build where you are not outgassing material into the vacuum pumps. These pumps can last many years with minimal maintenance.

What would be the difference if you used EBM in air?

You generate an electron beam by heating up a material so that you remove the electrons to form an electron cloud. You then accelerate these electrons using an electrostatic field. This generates a potential that accelerates the beam towards the material and delivers the energy to the part you are trying to melt.

If atmospheric gas gets in the way, then the electrons will interact with the gas molecules, and they can't get from the electron source to the melting location. With the vacuum, there are fewer particles in the way, so the electron beam moves from the source to the material without being hindered.

What is the reason for using a medium-high vacuum, and would there be any benefit in using an ultra-high vacuum instead?

It's all to do with the metal additive process. In terms of generating an electron beam, the higher the vacuum, the better. If you have a very high vacuum, you will not only melt your material when the beam hits it, you will vaporize it.

This is not what we want, and it becomes complex because different elements evaporate at different rates. For example, if you take Ti-64, there is about 6% aluminum and 4% vanadium content in the alloy, but aluminum evaporates much more readily than the other elements. So, a very high vacuum can change the composition and characteristics of the material you are trying to print with (which can lead to many issues).

We also use a lower vacuum because of the nature of EBM. Because we use a beam of electrons, the electrons that hit the material have to go somewhere and many end up in the powder. If there is a build up of electrons in the powder, you can get what's called a smoke event—which is a mini powder explosion inside your machine during which the electrons bind to the powder and repel other electrons bound to other elements of powder within the build.

We overcome this by feeding in a small and controlled amount of helium into the build, because the helium atoms become ionized (positively charged ions) and combine with electrons in the powder to prevent the smoke event from taking place.

Using a vacuum means that you can create parts to a much higher chemical clarity than you can with other systems.

How do you determine what level of vacuum you use for each material? Is there a certain process or is it a standard vacuum across the board?

It depends on the volatility of the material. We usually stick to a single pressure for all materials that we process, but there are edge cases where we need to adjust the vacuum level. So, anything that's magnesium or zinc based needs a higher pressure to supress evaporation—as these elements readily evaporate in a standard atmospheric pressure, never mind a high vacuum.

By increasing the pressure, some of the electrons in the beam are more susceptible to being scattered by gas molecules as the vacuum is not as strong, nor is the air as pure. This can affect some of the features that you want to print, especially really fine structures below 200 microns, as this scattering broadens the electron beam, and the fine resolution that is usually associated with the beam starts to degrade a bit. But you can account for this change in resolution in your build.

What are the advantages of building metal additive parts in a vacuum environment?

When you produce a part with additive in highly regulated industries, such as aerospace and biomedical, the parts tend to go through a hot isostatic pressing (HIP) process. The HIP process heats the part to a certain temperature and applies a pressure to the part to compress and close any internal voids that have formed during printing. The result is a fully dense part, and while we aim for no voids when printing, the stochastic nature of additive means that voids can be formed from some irregular powder particles on the bed or from some small degrees of oxidation in the powder.

If your part has been formed under atmospheric pressure and you HIP the part, there is the potential for those voids to open during service, because the internal pressure created from compressing the gas in the void can cause it to open up again.

This is particularly true in high-temperature application parts, such as in turbine engines. In EBM, because you have this high vacuum environment, you don't have the same pressure in the voids due to the voids being filled with vacuum instead of gas. So, that HIP process will close the void, but there'll be nothing pushing against that void to open it up again and that's a key advantage of using a vacuum.

You also have the advantage of a clean working atmosphere. If you are feeding a gas into the process, you need to make sure that the gas is clean, because any contaminants in it will end up in the process. Using a vacuum means that you can create parts to a much higher chemical clarity than you can with other systems.

The final advantage is a higher degree of sustainability. The powder you use will be exposed to the atmosphere as you go through the powder recovery process and the loading process. This can lead to the oxidation of the powder that subsequently ends up in the build. The high vacuum and high temperature environment of the EBM build chamber can destabilize a lot of the oxides in the build and liberate the powder back to its initial state. So, EBM helps with increasing the lifetime of the powder, as well as improving the sustainability and robustness of the process, because you are not having to bring in brand new powder to the machine every time you want to build.

Is there any advantage of using vacuum with reactive materials?

Yes, because it's easier to maintain a higher chemical purity in the chamber. You get out what you put into the system, and if you are working with materials—such as titanium—that have a really high affinity for oxygen, then processing those contaminated materials is going to be much more difficult. With EBM, there is not as much oxygen in the chamber to start with, and when you go through the melting process, you liberate any oxygen that may have built up in the material, so it allows you to work with reactive materials—especially those that are reactive with oxygen. We find when we build and test our parts

against the initial powder chemistry, the final part tends to have less oxygen in it that the powder it is built out of.

Is there anything that the vacuum process enables in EBM that would be otherwise difficult to achieve?

With EBM, you can recycle the powder multiple times due to the vacuum atmosphere that limits the uptake of oxygen during the process. You can also use the vacuum to determine what state your build chamber is in, because if something is outgassing in the chamber and producing contaminants in the system, you can monitor how the vacuum environment changes over time. You can do this in EBM because the electron beam directly interacts with the vacuum environment, and you can look at key signals in your build process to determine if there is anything wrong. It's something that's difficult to do with atmospheric systems, and it usually requires a mass spectrometer to be employed to continually analyze the gas. Conversely, EBM self-monitors and is particularly useful for biomedical and aerospace applications where the parts need to be of a consistently high quality.

Overall Outlook

The vacuum environment is a crucial part of the EBM system, not just in providing a means of operation but also providing a number of benefits that you don't see in over systems—from a consistently clean environment to a self-regulating troubleshooting process, a much more stable part after a HIP process, and a much higher degree of sustainability and powder recycling capability.

If you have a tight control over your vacuum environment, then you can produce chemically pure parts that are typically difficult or expensive to produce using atmospheric additive manufacturing systems.

If you'd like to find out more about EBM and how you can utilize the vacuum environment to your advantage, then **get in touch with us.**

EBM Anthology

05

Get the facts on electron beam unit design

David Svensson
Advanced Lead Engineer

Get the facts on electron beam unit design

David Svensson, Advanced Lead Engineer

EBM is an additive approach that can build a range of high-performance parts and is highly dependent on the electron beam unit (EBU) and internal vacuum environment of the machine. EBM offers a high degree of customization that is driven by employing different scan strategies and the ability to move the electron beam across the build plate with a high degree of speed and accuracy. In this article, we catch up with David Svensson, senior EBU engineer at Colibrium Additive, to discuss the importance of the EBU unit in an EBM machine and what advancements have been made in recent years to EBU technology.

What is the EBU?

In EBM, the electron beam unit is the sub-system that generates and controls the electron beam that melts the layers of metal powder in the build chamber. There are two parts to the EBU, both with different functions. The first is the emission where the electron beam is generated, and the second is the beam optics sub-system, which is responsible for focusing and deflecting the beam so that it can move over the build area.

So, the EBU generates the electron beam. How do you generate a beam of electrons?

Electrons are a part of almost all matter, so we just need to get the electrons out of a material, accelerate them and focus them into a beam. Historically, tungsten was the material of choice for the electron emitter in EBM systems, but now we use lanthanum hexaboride (LaB6) single crystal cathodes as the electron-generating material in all our latest systems.

The cathode is heated to thousands of degrees kelvin at which point some of the electrons in the cathode have enough energy to leave the surface, so called thermionic emission. Once an electron has moved far enough away from the cathode, it is subjected to a strong electrostatic field, which accelerates the electron towards the build surface. In the Colibrium Additive EBM systems we use an acceleration voltage of 60 keV, which defines the amount of energy that each electron will impart on the material being printed.

Another key aspect to the beam generation is the fact that the electron beam created and maintained under vacuum. This is important because if the beam were formed in air, it would scatter after just a few millimetres. Another reason why good vacuum quality is essential for stable operation of an EBM system is to prevent the formation of high voltage arcs between the cathode and the rest of the EBU. Finally, good vacuum is also a requirement to ensure that the emitting performance of the cathode remains high.

How is the beam power controlled?

In the beam generation you have the cathode that's kept at the acceleration potential and then you have an anode that is at ground level. In our systems we also use a third electrode, called a grid or Wehnelt, to control the beam power. By changing this grid potential, we can alter how likely it is that an electron will exit the cathode to the anode.

There is an analogy: imagine the electrons as golf balls at the top of a tall hill where each ball has some random velocity downwards. If they are allowed to move down the hill, they will accelerate as they roll down. We could control how many balls roll down the hill by adding a "speed bump" (grid potential) close to the top.

If the speed bump is very tall, it is likely only the balls with the highest speed will have enough energy to reach over the bump. And a very short speed bump will permit almost all balls to roll down the hill and accelerate. The grid potential works like the speed bump, since it controls how likely it is that a given electron will pass and be accelerated.

So, we use the grid potential to control the number of electrons in the beam. This directly translates to how powerful the beam is, which allows us to vary the power during the build. For example, you might want to use a high beam power (up to 6 kW) in the early stages of a layer for the pre-heating sequence, but when you are melting finer details like contours, you are going to want a much lower power (around 600 W). This is all controlled by varying the potential of the grid in the EBU.

In laser technology, you use a mirror to move the laser. How do you move a beam of electrons?

Using a mirror would not be an option since you are using electrons instead of photons in your beam. Electrons can, however, be affected by both magnetic and electric fields. So, for our beam of very fast electrons, we use magnetic deflectors to move the beam over the build area. To move the electron beam, you subject it to a magnetic field that is perpendicular to the beam direction. This creates a force perpendicular to both magnetic field and the direction of the electron beam, which we use to move the beam in any direction on the build area.

One of the main differences in using magnetic deflection over mirrors is that you can deflect the beam without the need to mechanically move anything. A magnetic field can be controlled at very high speeds by just changing the current in the deflection coils.

For example, when we melt the contours of a part, we use something that is called "multi-beam." The name is a bit misleading because we don't actually use multiple beams; it's just a single beam that jumps very fast to maintain several melts at the same time. With the naked eye, it looks as though you have several beams moving around the build, but it's really just one beam moving very fast across all of these different melt pools.

How fast does the electron beam move?

The beam can jump at speeds on the order of km/s over the build area when moving between areas that are being melted. The speed is then dropped down to speeds on the order of m/s when we're melting the powder. The other way to interpret "beam speed" is the speed of the electrons along the beamline.

Remember that the source of the speed of our electrons is the acceleration voltage at 60 keV. At this level of acceleration, you must consider relativistic effects since Newton's laws of motion are not sufficient as you approach the speed of light. Including these relativistic effects, the electron beam moves at approximately 45% the speed of light. This means that it takes an electron about seven billionths of a second to move from the cathode before it hits the powder. So, it's very fast when viewed from the side and still quite fast when jumping across the build plate.

The development of more advanced EBUs has enabled the development of more demanding melt processes.

How is the position measured and calibrated in a Colibrium Additive system?

The software that controls the position and size of the electron beam on the build surface requires a calibration in order to ensure both accuracy and precision. In all our latest Q and Spectra systems, we use an auto beam calibration system, which is a procedure that is performed when the cathode is changed (approximately after 800 hours of build time).

Older generations of EBM machines used a manual process that was significantly more time consuming and relied on the skill of the operator. The automatic beam calibration system offers a way to achieve a fast and high-quality calibration without any dependence on the skill of the individual operator.

The auto beam calibration is at its core an optimizer that adjusts the settings for the electron optics sub-system. This optimization is made possible by our fast, accurate and repeatable method of measuring the position, shape, and size of electron beam.

Measuring any properties of a sharp, high-power electron beam can be challenging due to the high energy density at the surface of the beam target. The problem is that a beam that rests for even a short amount of time in one position will melt almost any material. To work around this problem, we use our calibration plate that has specially designed beam targets designed to work in conjunction with an X-ray sensor to perform our measurements.

We scan the electron beam over our beam target in a predetermined pattern and then use the resulting X-ray signal to get a very precise measurement of the position and size of the electron beam. The auto beam calibration system can perform thousands of measurements in the same time that it would take a human to calibrate just a single position.

Why is it important to ensure proper cleanliness in an EBM system?

The emission is the first step in the formation of the electron beam, and this is dependent on the surface properties of the cathode. One of the problems that can occur is that if you introduce contaminants into the vacuum chamber, you can degrade the cathode's ability to emit electrons. This can have a severe effect on the spot quality which may, in the worst case, impact the build.

For example, an operator who reloads the machine without wearing clean gloves could introduce contaminants in the form of oil or water from their hands into the machine. These contaminants will then outgas during the vacuum pumping sequence and some will end up on the cathode, degrading the cathode and therefore the spot quality. It's therefore essential to follow advice procedures when handling the vacuum part of the system to avoid damaging the spot quality, as this will have an adverse effect on your build.

How does the EBU affect the new concept of Point Melt?

The performance of the EBU is central to an effective Point Melt strategy. Over the years, we have made significant improvements to the EBU that have resulted in significantly less variation in spot size and spot shape over the build table.

Historically, large deflection angles in our big machines have presented challenges with respect to spot quality at the edges of the build table. Our melt processes have been carefully adapted to handle the variation in order to ensure reliability and quality.

In the latest generation of Spectra machines, we have been able to reduce the variation significantly, and this has had a large impact on the available process window for different melt strategies—including Point Melt. In Point Melt, it's essential to have a consistent spot size and spot shape, because there is a more direct connection between the electron beam spot and the resulting melt pool. We have been able to realize more sophisticated melt processes using the latest generation of EBUs because of the reduction in variations.

Are there any improvements that have recently been made to the EBU?

The big step up from the Q series to the Spectra is the improved beam optics, which have led to the reduction in spot size and spot shape variation. We have also introduced a new vacuum pumping stage that provides an improved vacuum quality in the emission region. This has allowed us to reduce the sensitivity to impurities so we're now able to handle more contamination from the chamber before it becomes an issue for the emission.

The improved vacuum pumps have an impact on the process as well, because how you melt the powder has an impact on the vacuum quality of the EBU. Better pumping capabilities can also allow for a larger process window. The development of more advanced EBUs has also enabled the development of more demanding melt processes, so the available parameter space that our process developers can use is expanded and more robust.

Overall Outlook

The EBU is the component of an EBM machine that is responsible for generating, focusing, and controlling the electron beam as it moves across the build plate. There are number of factors that contribute to a good environment for the EBU, with the vacuum being one of the most important to ensure your machine functions optimally.

The EBU has undergone a lot of innovation over the years and the EBUs used in the current generation of additive machines are much more robust, have greater capabilities, and offer the potential to utilize more advanced melt process steps and scan strategies than ever before.

If you'd like to find out more about these new EBUs and how they can be utilized for your builds, **get in touch with us.**

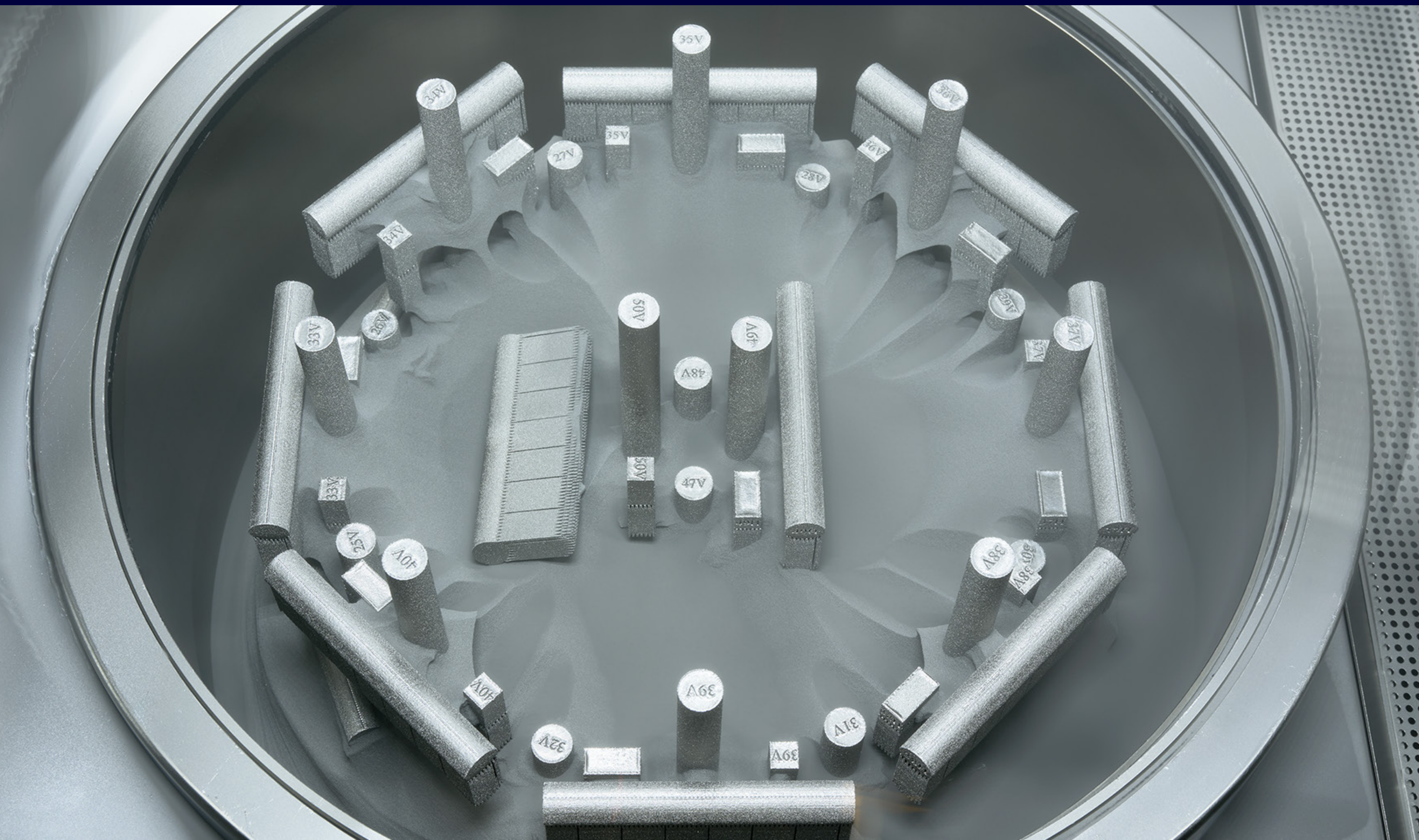
06

EBM Anthology

Get the facts on melt pool strategy in EBM

Anders Snis

Senior Engineering Manager



Get the facts on melt pool strategy in EBM

Anders Snis, Senior Engineering Manager

In Electron Beam Melting (EBM) and other additive technologies, ensuring that the metal particles are fused together properly is key for ensuring a high part quality. The melt pool is the liquid metal that forms under the intense energy of the electron beam and is responsible for fusing the metal particles together. Ensuring that you have the most optimal strategy for utilizing the melt pool and particle fusion is paramount to achieving the desired material properties in your part. In this Get the Facts article, we catch up with Anders Snis from Colibrium Additive to discuss the different melt pool strategies available for EBM, including a new approach called Point Melt.

Can you explain what a melt pool is in additive manufacturing?

The melt pool is the liquid state of the metal. So, when you melt the metal with the electron beam, the energy of the electron beam hits the surface of the metal powder and the energy from the electrons is transformed into heat. This generated heat melts the metal particles that are in close vicinity to the beam's position and subsequently turns the metal into a liquid melt pool. When you move the beam away from the melt pool, the liquid solidify into solid metal again and in this way powder particles become fused together.

In additive manufacturing, the area of the melt pool (and subsequent fusion) on the powder bed that we are working with is very small and it is usually less than 0.5 mm in depth and less than 1 mm2 in area–although, the size does vary from print to print. The melt pool also moves at the same speed as the electron beam when it moves across the powder bed. When the electron beam(s) move, it could be a point (going from point to point across the bed) or a hatch that moves across the bed, typically with a speed of 1 m/s or more.

The melt pool size doesn't vary substantially from print to print, but depending on settings you could have different melt pool sizes in different materials and for different process setups, for example if you change the layer thickness

How does the size of the melt pool affect the final part quality?

You always want to optimize the size of the melt pool based on the material properties that you want to achieve in the final part. If you have a bad control of the melt pool, then it's likely that you get a bad material out of the machine. So, you don't want the smallest melt pool size as you possibly can, because that will make the melt pool smaller than the powder particles (which range between 5 and 150 microns). If your melt pool is too small, i.e., smaller than the powder grain, then you are only going to melt a single powder grain at a time.

So, instead of fusing the particles together with each other, you are going to form small balls instead of a solid and dense part, leading to increased levels of voids, pores and incomplete melted areas within the part that leads to poor mechanical properties.

So, you want to keep the melt pool big enough that you can melt a number of metal particles simultaneously and fuse them together effectively. However, you don't want the melt pool to be too big either. If the melt pool is too large, then you will also get a bad part because either the surface finish will be bad, or you will have the wrong microstructure in the part.

If the surface of the melt pool is too large, then you can get a problem with "swelling." This is when the melt pool is so large that it creates a wave of liquid, so when the area cools it produces a wavy surface instead of a flat surface.

Also, if the melt pool is too big, then you can melt through the powder too much and create a surface underneath the part – which is very bad – so you want to control the depth of the melt pool and how the part will look like on the underside. Finally, you don't want to melt too large of a volume, as this usually means that the melt process is slower and limits the productivity of the additive system.

How does the cooling rate affect the microstructure of the part?

The cooling rate is really important. The melt pool is in a liquid state once the beam hits it, and when the beam moves away, the liquid cools down and solidifies to become solid metal. The size, shape, and the solidification of the melt pool are controlled by the energy distribution of the energy beam and the scan paths used for melting parts. By optimizing the beam parameters and the scan paths, fully dense materials can be obtained.

If the melt cools too fast, then the liquid doesn't have enough time to fill all the space, leading to cracks, a brittle material, or the wrong microstructure – such as, for instance, an undesired dendrite microstructure. If your melt pool is too large, then it will take a long time to cool down and the microstructure will become too coarse. Faster cooling will give a finer microstructure, so you need to optimize your cooling rate to get the desired microstructure.

This is different for different materials, as some are very sensitive to how you cool the melt, but other aren't, and achieving different microstructures by varying the cooling of the melt can be beneficial for some applications as each type of microstructure gives different mechanical properties to the part.

In EBM you can control the melt pool at a higher temperature than you can with other methods.

Does the melt pool impact the material being used?

The melt pool for EBM is different compared to other additive technologies. Even though the principles are similar, the fundamental physics are different. This is due to electrons being used as the energy source – where they are absorbed by almost any material, can be used with materials that typically reflect light (unlike other methods), and the electrons are absorbed a little deeper than the stimuli in other additive methods because they penetrate the material slightly. The only time EBM is not suitable is when you are printing a nonconductive material.

So, the physics are different, and in EBM you can control the melt pool at a higher temperature than you can with other methods. This is good for the materials that are designed for use in high-temperature applications – such as aircraft engines. One example is titanium-based alloys, especially Ti-64. Because you can control the melt pool at higher temperatures, you don't get thermal stresses in the part because of rapid cooling – but this is based more on the overall build temperature rather than the melt pool itself.

If you look to the melt pool, it affects both the microstructure of the part and the level of pores and cracks in the part. Because of the higher overall build temperature, the melt pool in EBM cools down somewhat slower than in other additive technologies and you typically achieve a slightly coarser grain structure – which is good for some applications, but not others, so like many other aspects of additive, the melt pool should be tailored to the application.

Does melt pool have any effect on the ability to print TiAl parts with EBM?

For high temperature materials like TiAl, the control of the melt pool is not the only part of the process that has to be optimized. Keeping a high and even temperature throughout the build is also very important. Otherwise, the cooling rates of the melt pool and the subsequently formed microstructures may be different throughout the part. This may lead to undesired inhomogeneous material properties. Another aspect that has to be considered for an alloy like TiAl is that the melt pool affects the properties of the build because you boil away aluminium and thus decrease the amount of aluminium in the part. This affects the material properties of the part, but this can be prevented by adding more aluminium into the alloy from the start.It's how you control the trajectory of the beam and how it moves over the surface of the powder bed.

What does that mean and what is involved in a melt pool strategy?

It's how you control the trajectory of the beam and how it moves over the surface of the powder bed. EBM uses magnetic coils to control the trajectory of the beam and those coils don't care for where the beam is. This means that the beam can be deflected in any direction and jump around in any kind of pattern across different areas of the powder bed. Therefore, you can create many different 'melt pool strategies' with EBM. For instance, you can melt the interior area of a part with hatching, you can melt the contours with a line melt strategy, and new point-melt strategies are also emerging – something that's only possible with EBM.

Each strategy is focused around controlling the melt. If you are hatching, you are melting in a specific direction, and you move the melt pool in that direction as well (and have solidification in a specific direction). If you are melting in a line, you can have an elongated melt pool in one direction or you can have a series of smaller "dot" melts. If you melt points in a random order through point melt, then you'll have a more uniform/isotropic microstructure because you are not dependent on geometric-based melting like other strategies. So, depending on the part and application, there are different strategies that can be applied to EBM.

You are introducing Point Melt. Could you summarize what Point Melt is and what the advantages of using Point Melt vs other approaches (hatching, etc.) are?

Point Melt is the melting of the powder with "points" rather than with lines or other geometries. Point Melt can be used on both the contours and on the inside of the part, because a point is a point regardless of where it's located. You can put the points closer together on a contour, but you still melt one point, then move on to the next area, melt a second point, and so on. Point Melt strategies have been found to be a useful approach for achieving a homogeneous material with improved material properties and surface qualities.

The biggest advantage is the ability to put together complex parts where the material is always the same. If you take hatching, for example, the length of the hatch lines and how you put them together depends on the geometry you are going to melt. So, you can melt one geometry, change geometry, and not achieve the same results as the first melt because the geometry affects the melt lines – and you have to follow the geometry with the melt lines.

This means that hatch strategies can lead to you having different results for the same material with the same settings, all because the geometries are different. In Point Melt strategies, because you are using points instead of lines, you remove all the issues around different geometries as you are only ever using points to melt the powder. It's like using smaller building blocks and this allows you to build more complex parts and the material will always be the same – no matter the complexity of the part. The only prerequisite for a successful Point Melt strategy is a high deflection speed of the energy beam.

Overall Outlook

There are different melt pool strategies in EBM that are suitable for different materials and applications, including the Point Melt strategy that is only possible with EBM. Optimizing your melt pool strategy to control the melt pool size and cooling rate is key to ensuring that you get a part with a high quality and good material properties that doesn't have a high degree of porosity/lack of fusion.

If you'd like to find out more about the different melt pool strategies that can be used with EBM and which ones would be best suited for your application needs, then **get in touch with us.**

EBM Anthology

07

Get the facts on high-temperature and crack-prone alloys

Markus Ramsperger
Staff Engineer

Get the facts on high-temperature and crack-prone alloys

Markus Ramsperger, Staff Engineer

Electron Beam Melting (EBM) enables you to better print metal alloy parts that are suitable for high-temperature applications. EBM is also the only additive technology that allows you to avoid cracking of difficult-to-manufacture alloys during manufacturing. In this article, we catch up with Markus Ramsperger, staff engineer at Colibrium Additive, to discuss how EBM is being used to create components that can't otherwise be produced with other additive methods in high-temperature applications.

What are high-temperature alloys and their applications?

High temperature alloys are any alloys – like nickel and cobalt-based superalloys as well as titanium aluminide – that are used in applications where the temperature of the application is at 60% of the melting point temperature of the material. If you take high-temperature nickel alloys, their melting point is around 1400 °C, so an application temperature above 850 °C is considered a high-temperature material.

There are number of crack-prone alloys that are suitable with EBM, but not all of them are high-temperature alloys. For example, tool steels that show a carbon content greater than .6% or highly alloyed HSS steels are crack prone due to the martensitic hardening effect in powder-bed additive manufacturing.

TiAl is a high-temperature, crack-prone alloy, but the nature of the intermetallic phases means that it can be used only in applications up to 850 °C. TiAl is used as a lightweight, high-temperature alloy to reduce fuel consumption in engines compared to heavier standard alloys, but the developed TiAl alloy has a limited application temperature range. If you want to go beyond this into the 900 °C + range, then you need to use alloys that contain heavier alloying elements such as cobalt or Ni-based superalloys.

Ni-based superalloys were categorized by their y' content. Y' is an ordered intermetallic precipitation phase which is responsible for the superior high temp properties. The best high-temp properties have alloys showing a high y' content (> 50 vol.-%). This is because the gamma prime phase gives the alloy its high-temperature capabilities and strength. For example, some nickel alloys, such as Ni-718, that are not high-temperature alloys have only around 20% of gamma prime phases in their microstructure. In comparison, nickel superalloys have at least 60% gamma prime phases, and this gives rise to a much better high-temperature performance.

The most famous example is combustion engines, including both turbine engines and the standard car engine. These materials are typically used in the hot sections. So, in an automotive engine, this is in the turbocharger wheels, as an example. In stationary gas turbines and aero engines, these materials are found in both the high-pressure and in low-pressure turbines.

How are these alloys processed today and what are the differences using powder bed fusion additive manufacturing?

All these materials today are processed using mainly investment casting and have been optimized for casting procedures. Casting methods have different processing conditions than those in additive; for example, the solidification of a cast component is quite long However, in additive, you locally have very high solidification velocities, which means that the part cools down much quicker than in casting.

This rapid cooling breeds situations and conditions where cracking of the part is during the AM processing of a part is favorable and, therefore, completely different scenario to casted parts. Because these alloys have not been originally designed for additive, you do need to overcome some challenges to use them. One of the main challenges for the high-temperature application TiAl, nickel-based superalloys and cobalt-based superalloys is their cracking susceptibility.

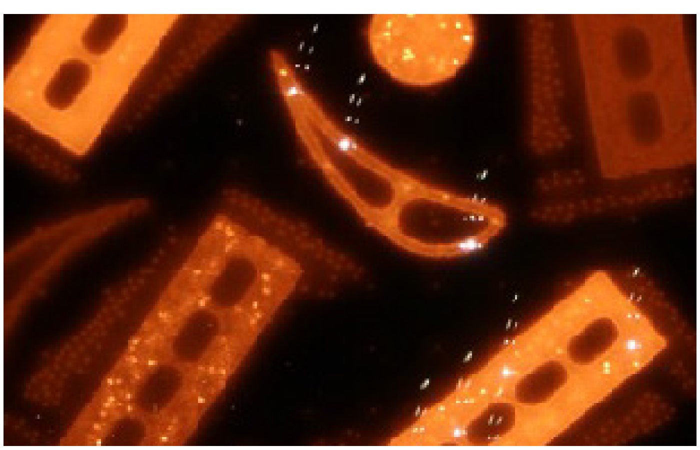
What are the EBM opportunities/enablers for additive manufacturing in processing these alloys?

If you want to process these materials, then you need to ensure that you have low levels of residual stress in the material. Looking back at casting, the slow solidification velocity results in very low residual stresses in the component that you want to cast. On the other hand, in additive manufacturing, you generate high stresses during the quick solidification process.

You can overcome these high stresses in EBM AM by using a hot process. This is one of the main benefits of EBM, because you can work at very high powder bed temperatures, which leads to in-situ stress. So, when producing TiAl and Ni-based superalloy parts in EBM, the build temperature and the internal temperature of the build area is consistently kept at over 1000 °C to ensure that there are low levels of stress in the components.

Another aspect of EBM is that you can employ advanced scanning strategies—such as line melt and point melt—to reduce even more the cracking mechanisms from manifesting in these alloys. This is achieved by utilizing both the high-temperature environment of the EBM build area and the freedom of beam movement that you have in EBM.

EBM is also bringing opportunities to other crack-prone alloys that are not suitable for high temperature applications. If you take tool steels, other powder ped fusion technologies can only produce steel parts with



a 0.5% carbon limit today for a standard production. However, for the processing of high-performing steels—such as cold work tool steel and highly alloyed high-speed steels—you need up to 2.5% carbon, as well as other alloying elements to achieve the required component performance. EBM is the only technology today that allows you to create these higher carbon-content steels.

What is the performance of EBM AM processed material/components in comparison to other additive manufacturing technologies?

We have a high degree of flexibility in the beam movement, meaning that we can employ different scan strategies. The fast and accurate beam movement allows for different types of scan strategies that are not possible in other additive technologies, and this allows us to tailor and control the microstructure that we obtain during solidification.

Tailoring microstructures is unique for EBM, especially if you utilize this to tailor the microstructure within a component. In casting, we can achieve polycrystalline microstructures, directionally solidified microstructures, or single crystal microstructures, and we can achieve all these microstructures unique to EBM.

Other additive methods produce isotropic microstructures as well as some anisotropic microstructures—but not to the degree required for high-temperature applications. These anisotropic features are directly linked to the overall material properties of the part. You need a certain degree of anisotropy to achieve a good creep performance—that is, being able to withstand a constant load at high temperatures.

On the other hand, other additive methods will produce only very fine and homogenous isotropic microstructures. Fine-grained microstructures show a poor performance at high-temperature creep. So, even if you can produce the part with other additive processes, you will get weak mechanical high-temperature properties.

EBM is the only additive technology that can create parts using these alloys where there are no cracks in the as-built condition. When the part is taken out of the machine, it has already undergone a heat treatment process during the manufacturing time, so for some materials, no post-processing treatments are required.

So, with EBM, we are achieving a designed or defined microstructure with an already homogenized and heat-treated material. This leads to a good part performance in as-built conditions comparable or even better than parts produced by other additive technologies. The properties are also comparable or even better to what is achieved through casting methods.

Is EBM naturally a good fit for crack-prone, high-temp alloys that you don't need to alter the machine settings, or is this still something to consider?

We still need to adapt the process to the component geometries. While it's natural that the high temperature process of EBM is favorable for these materials, its not as straightforward as just putting the material in the machine and getting a perfect part at the end. You have got to still fine-tune scanning strategies for the desired component and process conditions for crack-free processsing where they do not crack. And, you often have a narrow process window to prevent these cracking issues.

One of the successes is keeping the process temperature above 1000 °C and in the component, and you need to use advanced software and heat models to keep the internal temperature above this value. There is also the ability to have different melting strategies—line and point melt strategies as mentioned before—to adapt the process to the requirements of those alloys.

The final aspect that allows EBM to be used with these materials much more easily than other additive technologies is that the process is performed under vacuum. This is why TiAl, and other reactive metal alloys, can be processed with EBM as you keep the powder and the components in a protective environment.

What is the maturity of EBM progression toward crack-prone Ni-based superalloys?

The state-of-the-art for EBM-manufactured TiAl is in turbine engines, such as the 9X engine for the new 777 engine, and there are already 228 TiAl low pressure turbine blades produced by EBM that are in service today. These are used in applications up to 850°C and primarily used for their lightweighting ability where weight reduction is a key application and business driver (such as in the reduction of fuel consumption).

For the nickel-based superalloys, especially in applications above 900 °C, we have shown the capability and feasibility to handle all the cracking issues and achieve the required material properties for high-temperature applications. The strategy for us now is to mature the process and machine towards industrial production capability.

Overall Outlook

EBM is an enabling additive technology for processing both crack-prone and high-temperature materials and is the only additive approach that can required high-temperature properties as a creep. While we still need to optimize the machine and process to produce the final part, we can tailor the microstructure and mechanical properties of the part to the application requirements by employing different melt and scan strategies. This is unique to EBM AM.

If you are considering EBM as a production tool, there is an opportunity to significantly reduce your supply chain lead times by bringing the production in house.

If you'd like to find out more about how EBM can benefit your industrial processes, or if you'd like more information regarding high-temperature and crack-prone alloys, then **get in touch with us.**

08

EBM Anthology

Get the facts on productivity in EBM

Mattias Fager
Senior Staff Engineer

Get the facts on productivity in EBM

Mattias Fager, Senior Staff Engineer

Electron Beam Melting (EBM) is an additive technology that produces high-quality parts and can be used with difficult-to-work-with, high-temperature alloys as well as other more conventional materials such as titanium. While the focus of many of the operational features are centered around build quality and part performance, there are different ways to improve the productivity when using EBM. In this article, we catch up with Mattias Fager, senior staff engineer from Colibrium Additive, to discuss the best ways to achieve a high productivity when using an EBM machine.

What drives productivity in EBM?

In our EBM technology we have a very powerful electron beam. In the Q10, it's 3kW; in the Spectra L, it's 4.5 kW; and in the Spectra H, 6 kW. The peak power is mainly used during the preheating and heating phase, whereas in the melting phase we don't typically utilize 60% of this power, but it's still a high temperature.

As one of the few metal AM powder-bed technologies on the market, Colibrium Additive's EBM utilizes an elevated build temperature, the benefits of using this is twofold: the part comes out without any residual stresses and at the same time, the speed of welding can be increased significantly without creating weld defects. When only the melting speed of the EBM is considered, it's one of the most productive powder-bed technologies.

EBM productivity is, to a high degree, set by these relations in amount of time recoating powder and preheating and heating in relation to the actual melting, implying that EBM in general gets more advantageous the larger the size and height of the build.

Are the supplied generic process themes optimized for productivity?

When it comes to productivity in EBM, we have historically aimed towards creating parts that don't require any post-build heat treatments, and we work to meet the material requirements as printed. This applies to material properties such as ductility, as well as the static tensile strength.

The themes are set so that they meet certain capabilities to ensure that the degree of fusion is as high as possible, and any lack of fusion is kept to an absolute minimum. These capabilities extend over the entire build envelope, to the entire cathode lifetime, and to the allowed levels of oxygen in the powder so that they can be recycled efficiently, while still maintaining good material properties in the part.

Designing the themes with hot isostatic pressing (HIP) or heat treatment (HT) in mind would greatly improve both productivity as well as geometrical coverage of the process. This means that we could build more complex parts faster, with less supports. This is a level of scalability that hasn't really been utilized yet but could further increase the productivity of EBM machines.

The themes are designed to achieve the highest quality part possible rather than geared towards productivity. This approach also helps to lower the costs of going through validation. However, this means that you can produce high-performance parts every time, and there is still a lot of room left for optimizing the productivity of the product if you know your application and the component that you wish to build.

Once the theme is locked in and production has started, you can incrementally optimize your productivity if you know your components.

Let's talk about the ability to stack parts in the build chamber and improve productivity. What does stacking parts bring to the machine's productivity and is there ever a good point to stop?

Stacking parts is a unique EBM feat ure where the thermal management keeps the correct build temperature as well as minimizes the need for physical supports. By stacking parts with free floating supports in the build chamber, you can utilize the entire build envelope and create a lot of small parts in a single build, without need for additional support removal. This is much better utilized with smaller parts than it is with larger, chunkier components, and this ability to stack reduces the reload time of the machine in between builds.

Regarding the degree of stackability possible, you can stack as much as you like in the z-direction. If you can stack one part at one height, you can stack one part all throughout the build envelope.

In terms of if there is a good time to stop stacking, there is nothing to say that you have to stop from a technical perspective. The only reason to stop producing more printed layers is going to come from either a validation or batch size perspective—in terms of the production of a certain number of different sized parts, or if there are regulatory conditions that might prevent you from printing further. When it comes to determining when to stop stacking, it's more based around those aspects rather than from a technical and productivity standpoint, because once you have started the build, it's always more productive to keep printing.

Another aspect is the ability to overlap parts. If you stack small parts, such as acetabular cups, then you can overlap those parts to make the build even more efficient. Unlike other printing technologies, EBM is not limited by the scanning speed, and so called optimizer will virtually combine, move and optimize the different areas of the build (in a similar manner to fitting Tetris shapes together) to optimize the process.

If the scanning speed doesn't limit productivity, what does?

When it comes the stackability of components in EBM, it's the melting power that is the limiting factor towards productivity. Depending upon geometry and packing density, there could be a point where the subsequent heating needed for each layer can reduce the overall build rate.

Our more powerful systems, like the 4.5 kW electron beam in the Spectra L, have been designed so that the required power to print covers the entire build envelope and you can stack as much as you like. You will also not see a decrease in productivity if you add a larger coverage in the x and y directions.

How does a HIP process affect the productivity of EBM parts?

If you have a requirement to HIP your component, the themes can be altered in a more productive way, allowing for a smaller amount of internal porosity, still on a very low level. The supplied standard themes trade those last residual pores in favor of a lower productivity.

Should you still need it, HIP process works well with EBM parts. When creating parts with EBM, any level of porosity is going to react well with a HIP process because the printing is performed in a vacuum. This means that the gas pores consist of vacuum, rather than gas. So, it's easier to close those gaps with HIP if you have a part that has been created with EBM.

Overall Outlook

While EBM is primarily focused on part quality, rather than productivity, you can still achieve a high level of productivity in your printing processes due to the high power and fast scanning speeds of the electron beam units. Once you add in the ability to stack parts and fill up the build envelope, you can achieve a higher level of efficiency and productivity because you can skip a number of operational steps compared to traditional non-stacked builds.

Are you interested in learning more about productivity and EBM, then **get in touch with us.**

09

EBM Anthology

Electron Beam Melting: Point Melt technology

Electron Beam Melting: Point Melt Technology

Point Melt is an Electron Beam Melting strategy, used in additive manufacturing, where the powder bed is melted through small spots instead of lines as commonly done. This technology enables a more accurate temperature control, reducing temperature gradients and sintering needs. As result, metal parts produced using Point Melt can benefit from a reduction of support needed to build overhangs and an improved surface quality. Point Melt also enables additional strategies such as multiple passes on the same area allowing melt pool control and the resulting microstructure.

Advantages of Point Melt

Point Melt helps control the microstructure and influences the mechanical properties at macro level. The accurate control temperature and solidification process enables:

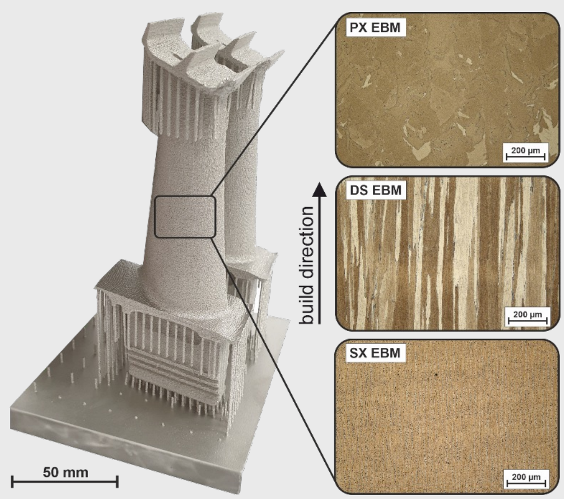
- Isotropic solidification, with small and nearly equally distributed grains
- Directional Solidification (DS), with grains oriented in the build direction
- Hybrid solidification, with different heights of the part having different solidification strategies.

This will enable material properties tailored to the different functions of the part, for example, printing turbine blades using isotropic solidification for the blade root and directional solidification for the main blade body.

Capabilities

Additionally to the microstructure control, EBM process developed using Point Melt can reduce the need of sintering, facilitating the depowering of internal channels. However, the process adopting Point Melt still achieves the highest density possible and is capable of building watertight walls down to 1-2 mm. The reduced energy density applied when using Point Melt will also enable high angle overhangs, i.e., up to horizontal surfaces, to be built supportless.

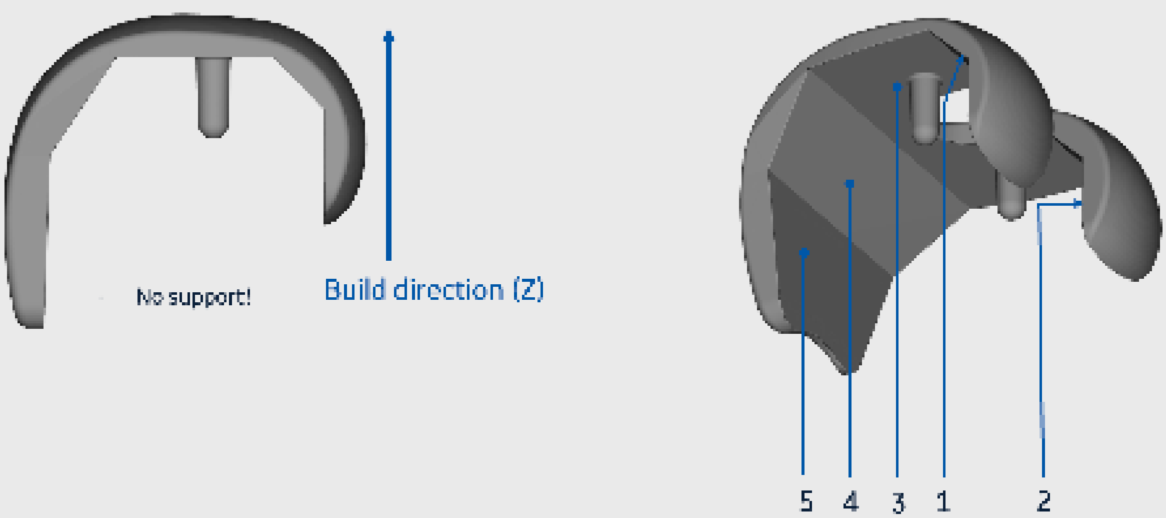
Microstructure control as enabled by EBM Point Melt technology



Turbine blade demonstrator

Point Melt Application: Knee Implant

The example below illustrates the ability to print overhangs without supports and to measure surface roughness in different orientations. NOTE: This is not the preferred print orientation. It is used to demonstrate the capabilities of Point Melt.



	Pos. 1 (90°)	Pos. 2 (45°)	Pos. 3 (0°)	Pos. 4 (45°)	Pos. 5 (90°)
Ra (µm)	13,5-19,5	10,0-1[illegible],2	13,0-18,3	10,2-1[illegible],0	12,6-[illegible]4,8
Rz (µm)	73,4-104,5	5[illegible],2-6[illegible],6	65,5-91,3	[illegible]0,5-58,2	6[illegible]-72,7

EBM Point Melt support-less building capabilities

If you'd like to find out more about Point Melt technology and how it can be utilized for your builds, **get in touch with us.**

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EBM Anthology

Checklist: Build your additive business case

Checklist: Build Your Additive Business Case

The goal of writing your business plan is twofold: Choose parts for additive and assess if additive is going to give you a true ROI.

As you move forward, you can use the following checklist to ensure you factor in all the key criteria of your analysis.

Step 1

Build a Cost Model
Identify possible parts for additive consideration and gather information for each part based on the following:

Material costs	• How does this material cost compare to conventional manufacturing methods? • Determine the type of metal powder needed for a specific component • How much waste—solid or powder—does the process create? • Consider costs savings for reusing unsintered powder
Labor costs	• Prepare the file to print • Inspect and clean optics and build chamber • Remove part from platform • Remove platform from machine • Conduct filter maintenance • Inspect and test machines and powders • Program the machine
Capital expenses	• Additive, thermal processes and inspection equipment • Support equipment, like powder removal, sieving and hoists • Facilities for the machines and additive production • Power backup systems
Operating expenses	• Laser/scanner repair and replacement • Recoater arm inspection/replacement • Inert gas usage • Filter and tooling maintenance • Personal protective equipment (PPE) • Electricity • Build plates
Processing costs	• Feature resolution • Surface finish • Powder removal • Build size and speed • Number of parts per build • Post-processing requirements
Test and inspection costs	• Tensile and functional testing (pressure, flow, etc.) • Non-destructive inspections (e.g., visual, X-ray and CT scans) • Destructive testing (e.g., cut-ups)

Step
2

Evaluate Performance Factors
How will additive impact product life and life cycle costs? Use the factors that apply to your business. Add others if needed.

- Freedom of design
- Weight reduction
- Improved fuel economy
- Improved efficiencies
- Enhanced reliability
- Less warpage due to faster cooling time
- Enhanced part performance
- Improved sustainability
- Supportive of body mechanics in orthopedics
- Serial production and mixed designs and sizes
- Reduced risk of delamination of trabecular structures

Step
3

Identify Supply Chain Disruption
How will additive streamline your manufacturing processes and overcome existing pain points within the business? Use the factors that apply to your business. Add others if needed.

- Part consolidation
- Inventory reduction
- Streamlined supply chain
- Waste reduction
- Freight savings
- Purchase order reduction
- Streamlined supply base
- In-housing of tooling operations
- Reduced workflow
- Lead-time reduction
- Maintenance, repair and overhaul (MRO) improvements

Step
4

Determine the ROI
Based on your business goals and in-depth cost, performance and supply chain data you gathered, run a final ROI analysis using a spreadsheet and data for your company. Does additive make sense for this business case?

- Freedom of design
- Pull together the analysis completed for steps 1–3
- Conduct an ROI analysis to include these elements: part cost, process cost and supply chain impact
- System redesign/AM adoption factors
- Rank the parts for additive based on ROI

After the Business Case Development
Once you draft the business plan, you need to create a presentation and sell your plan to senior management. A typical plan includes the following areas:

- Business objectives
- Market obstacles
- Cost analysis (part, process, performance factors and supply chain)
- Recommendation*

*In some cases, you might not find a business case for additive, which is a good reason to write a business case before starting down the additive path.

Are you ready?

To explore the production advantages EBM offers.
To build complex, stress-free parts.
To take advantage of the latest EBM innovations.
To move into full-scale industrialization.

When you're ready to integrate EBM metal additive into your business, the pioneers in the technology are here to help.

Let's go. Talk to Colibrium Additive today.
colicriumadditive.com