COLIBRIUM ADDITIVE
a GE Aerospace company

Building Industry-Ready Metal Additive Systems

Laser Powder Bed Fusion Anthology

For the ready

Metal additive is no longer a laboratory experiment. As fleets of metal additive systems being to be deployed on an industrial scale, our engineers and scientists are working closely with our customers to advance the technology to its full potential.

But what are some of the complexities and realities of machine development, what does repeatability and reliability mean in practice and what rigor and technical maturity is needed to develop industrial-scale systems? In this anthology, our team guides you through some of those questions and offer an insight into their respective fields of expertise. They're ready! Are you?

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Laser Anthology

Building Better Machines

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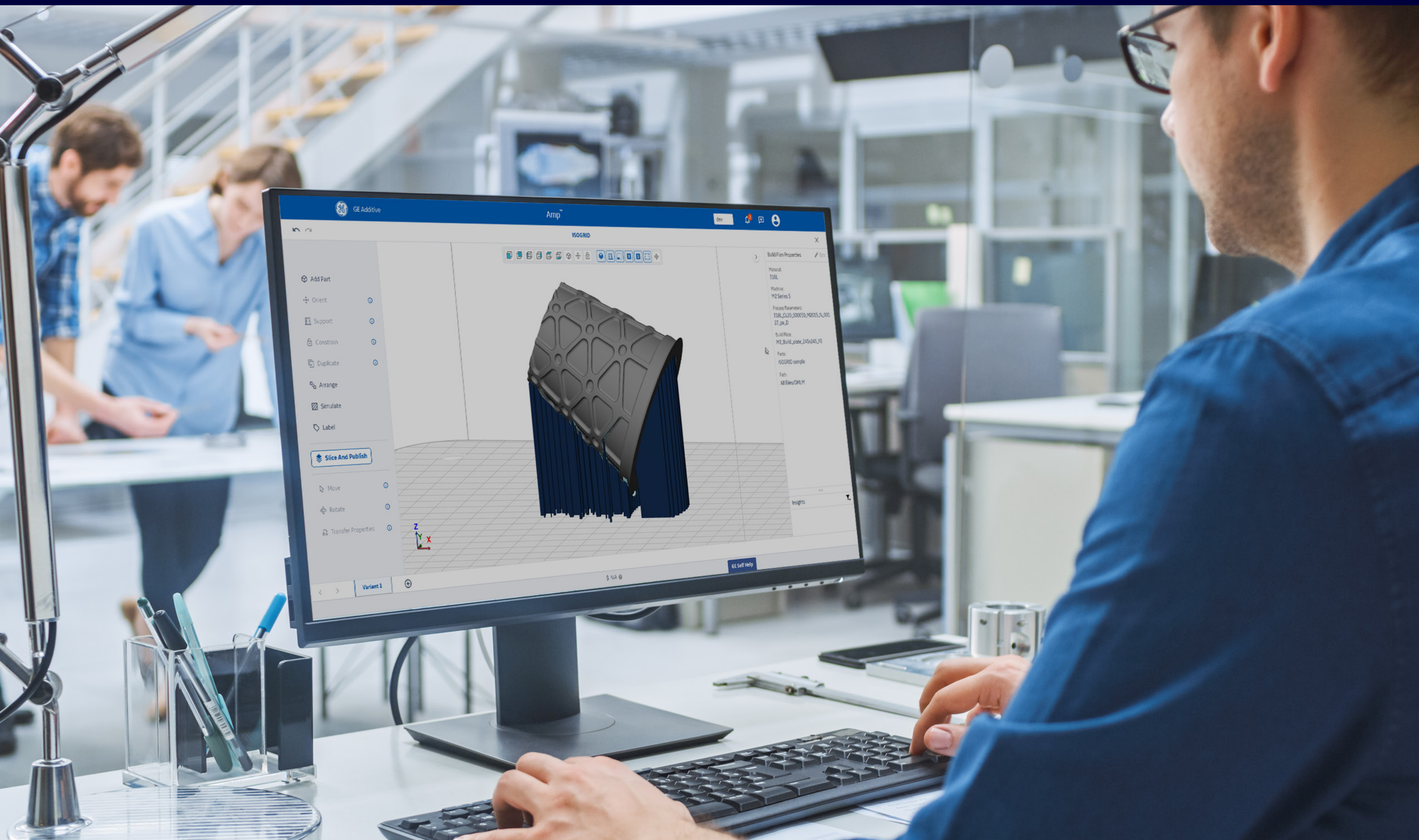


Building Better Machines

By Rene du Cauze de Nazelle, Senior Product Manager, Colibrium Additive

Real-world additive innovation versus half-baked attempts

As the popularity of home baking soared during lockdown, making crusty bread, cakes, or perfectly polished macarons appeared so easy on television that many rushed out to buy a fancy new oven.

Some manufacturers embraced metal additive manufacturing with the same enthusiasm. At any trade show, they could see wildly imaginative designs and impossible-to-machine shapes. Companies were inspired and bought expensive metal laser printers. They thought they could simply press the print button and create something wonderful.

Unfortunately, neither baking nor 3D printing works that way. Making the perfect loaf takes more than just a good oven. It also takes the right ingredients and tools. It takes recipes that nail down every detail. And, most of all, it takes someone who understands exactly how to combine everything at exactly the right moment.

The same is true for metal additive manufacturing, though the procedures and equipment are far more complicated than those used to make a cake. Humanity, after all, has been baking since the earliest days of civilization and has thousands of years of experience. Metal additive technology, on the other hand, is only around 30 years old. We are still developing the ingredients, recipes, tools, and knowledge needed to get the most out of this extraordinarily adaptable process. Buying a machine without the right platform of technologies, materials, and knowledge to support it, is unlikely to yield positive and repeatable results.

Still, a good oven—or, in our case, a reliable laser metal printer—still counts. Thanks to real-world innovation, today's metal additive printers, like our M Line system, are evolving rapidly to provide the support, ease-of-use, and even recipes that manufacturers need to turn their ideas into cost-effective parts that add value to their products. This started by rethinking design.

Turning CAD on Its Head

Starting in the 1990s, computer-aided design (CAD) began to sweep through the design world. Today, nearly all engineers rely on sophisticated CAD software for its speed, simplicity, ability to handle design changes, and ease of collaboration.

Yet CAD came with limitations when it came to designing for metal additive manufacturing. This is because most CAD designs inevitably started with defining the X, Y, and Z axes, drawing straight lines to create blocks, and then fleshing out parts built around simple geometries. This design process is well defined and taught at engineering schools. It reflects the type of geometries metal machining can produce.

3D printing turns the CAD rulebook on its head. Now, engineers can take a digital pen and sketch any shape they want. Still, all this freedom raises lots of questions: What happens if I do not draw straight lines, shave off material I am used to seeing to reduce weight, or add protrusions inside a channel to modify the flow of gas moving through it? Can the machine actually print anything I design? Can I meet my specifications repeatably? Can I do all this cost-effectively?

Not surprisingly, these types of questions can cause a certain amount of anxiety, especially when an executive-level manager expects you to answer them. Among engineers who have been sold on the myth that 3D metal printing is easy to do, it might even cause panic.

The truth is, like baking, it takes an ecosystem of tools, ingredients, and recipes—plus a knowledgeable "chef"—to create something that adds value.

This is why support is so important. This might range from a printer that warns if parameters are drifting or software that provides step-by-step recipes to print parts. This type of support enables engineers to start with simpler projects and work their way up to complex components that add value and functionality to their products yet are repeatable and cost-effective to manufacture. Think of it as moving from a simple pound cake to a gravity-defying souffle.

This all starts with selecting the right oven, or in our case, printer.

Building Better Machines

Anyone who takes baking seriously knows that even the best ovens have a lot of variability. Set it for 177 degrees C, but the actual temperature will vary depending on the height of the rack and the depth of the food. A loaf of bread on a bottom rack may never brown properly, while the one on the top might char the crust.

Such variability might be acceptable when making a loaf or two at home, but it is unforgivable when printing high quality metal parts. The M Line system, for example, prints parts using laser powder bed fusion (L-PBF), a process that melts thin (as small as 20 microns) layers of metal powders and fuses into components hundreds or thousands of layers high. The resulting parts are dense, with wrought metal-like properties that are used in aerospace, biomedical implants, and other demanding applications.

L-PBF printers orchestrate the interaction of many complex subsystems, from precision lasers and thermal management to powder handling and advanced software.

The goal is to create parts with highly precise physical properties, dimensions, and microstructures with little variation from build-to-build and machine to machine.

To meet this requirement, every layer printed on an M Line system—some as thin as 1/3 of a human hair laid end on end—must be perfect. There is no room for the variability found in even the best commercial ovens.

Yet stability alone is not enough for L-PBF printers to find a niche on the factory floor. Like the M Line, they must also raise their productivity game.

One way to do this is to increase the size of the print chamber. Larger chambers deliver two important advantages. First, they can print more small parts in a single run with potentially lower unit costs.

Second, they can print larger components that consolidate multiple parts into a single build. GE Aviation's new Catalyst advanced turboprop engine, for example, uses 12 large 3D-metal-printed sections to replace an astonishing 855 discrete parts—and all the welding and assembly that would have been required to put them together. In this case, laser printing not only yielded lighter weight and more durable components but did so at a substantial cost savings.

Yet enlarging the print chamber presents new challenges. The larger the chamber, the more difficult it becomes to generate the consistently laminar gas flow over the powder bed needed to produce one perfect layer after another. This can be overcome with improved components, simulations based on lots of data, and iterative engineering.

Still, larger chambers also require more time to build parts, which reduces their productivity. To speed things up, printers add lasers so they can print multiple parts or regions of larger parts simultaneously. Using two lasers raises productivity about 80 percent, but raising that to four lasers boosts productivity only 60 percent further. Over time, the productivity gains from adding additional lasers flatten out and, at some point, the system's complexity and inability to operate all lasers at the same time, far outweighs any productivity gains.

So, consider how this plays out in the M Line's build chamber. The chamber itself measures 500 × 500 × 400 mm, which is four times the area and nearly five times the volume of our M2 Series 5. The M Line also uses four 400-watt lasers and plans to introduce a unit with four 1kW lasers. The lasers, which all run at once, generate a very high thermal load that makes it even more difficult to manage gas flow over such a large volume.

To do this consistently, we launched a program to understand and control thermal load and every other critical-to-quality (CTQ) component and subsystem that went into the M Line printer. This ultimately involved identifying more than 2,000 different CTQ variables and taking multiple measurements of them over time and during an increasingly complex series of builds. We developed control strategies based on this information using statistical methods to minimize build-to-build and machine-to-machine variations. The validation program involved multiple printers and lasted more than 18 months—and it yielded printers that are inherently stable.

Smarter Sensing

Most good bakers understand their oven. They know the oven's hot and cold spots, and they often use precise sensors to measure temperature and humidity so they can achieve the best possible outcome.

Our CTQ program has eliminated the M Line's equivalent of cold and hot spots. In fact, it achieves consistent builds up to the edge of the build plate.

As for sensors, the M Line uses an array of them to boost the system's intelligence and provide valuable feedback to operators. This is an important change from the past, when most 3D metal printers sensed only critical parameters like oxygen, humidity, and thermal load. Operators would track their data to see if they were in or out of spec and adjust the printing process accordingly. This took a lot of time and a skilled workforce.

Today, printers use more sensors and process the data they collect to provide more operator guidance. Take, for example, the M Line's build plate. Additive manufacturing systems print from the bottom up, melting and solidifying one layer after another. After each layer, the printer recoats the part with a fresh layer of metal powder and begins the process again.

The quality of the part depends on the thickness of the layer. If the layers are too thin, the lasers may melt or deform previously printed layers. If the layers are too thick, the lasers may leave behind layers that are not bound uniformly to one another. To measure this, the M Line uses a camera to make sure the recoating step fully covers all previously printed sections of the part. Smart software then compares the image of the build plate superimposed over a second image taken after recoating. If there is a short feed, the machine will alert the operator to redose.

Imaging technology can also monitor the melt pool to ensure the uniformity of the melt pattern. This ensures the laser is delivering the precise amount of power needed. Sometimes, the images can also detect defects.

It is worth noting that M Line's sensors are not just measuring variables. They are using those measurements to make inferences and alert operators when they see a problem. Ultimately, as sensor and control technology evolve and manufacturers grow more familiar with the technology, we will begin to see closed-loop control systems that automatically measure and adjust printing parameters to meet operator goals.

System Support

If additive manufacturing hardware has grown smarter and more dependable, software has become more helpful. CAD software has begun to move into the 3D-printing age.

It is not just leaving behind the simple geometric forms of the past, it also provides entirely new functions, like automatic design optimization. It can, for example, remove unnecessary mass while retaining strength, creating parts that often emulate the curved and irregular shapes found in nature.

We recently launched our own software solution, Amp™, to help engineers bridge the gap between their advanced CAD models and metal 3D printing. The cloud-based software simulates print runs to ensure parts are arranged for maximum productivity and ensures that iterative melting/solidification cycles do not cause stress buildups. It also prepares CAD models for metal 3D printing without the need for manual healing and revision and manages multiple workflows so engineers can collaborate with each other as their concepts move from design to printed part.

Another key feature of Amp, especially for manufacturers just getting started in additive production, are its materials-specific “recipes.” These are based on Colibrium Additive’s extensive characterization of metal powders and blends and our own best practices. Like the recipes in a good cookbook, they provide a list of ingredients and step-by-step directions to everything from machine calibration to print orientation and laser power.

The M Line system has its own internal software, which has also grown more sophisticated. Build Explorer, for example, leverages data from the system’s sensors and warns operators if potential issues arise during the build. This software will eventually automate many of the checks operators now perform on their machines before starting a job, while guiding them through steps that must be done manually. The system will also log successful builds so operators can compare them to new builds to make sure the parts in the build chamber are within tolerance.

Software functionality will continue to grow with the release of new versions. Eventually, it will be able to check and automatically calibrate the printer and monitor and control the production process.

The goal of Colibrium Additive’s software, as well as its printers and sensors, is to consistently support the M Line operator to produce the highest-quality parts possible. Yet, what about ingredients? We have solutions for that as well.

We sell our own line of powders optimized for Colibrium Additive printers and work closely with customers to help characterize the performance of new alloys and powder blends.

We also have a solution based on our vision of how manufacturers will use the M Line in the future. While most factories are likely to start with a single printer or two, we believe they will eventually be running ten or more printers and making thousands of parts.

That calls for a new way to move, sift, recycle, and blend new and recycled powders. Today, this is often done manually. We have developed an automated, industrial-scale system that can extend to an entire bank of machines. It is faster and less labor-intensive than manual-feed systems and produces a very high grade of powder.

We provide this ecosystem of support because additive manufacturing is not easy. But through continuous product improvement, more sensors, and upgraded software, it is getting easier. You may not be baking souffles the first time you start a project, but everything is now in place to get you to that level of excellence in as short a time as your resources allow.

Laser Anthology

Building Industry-Ready 3D Metal Printers

Dr. Andrew Simpson
Executive Technology Leader, Colibrium Additive

Building Industry-Ready 3D Metal Printers

Dr. Andrew Simpson, Executive Technology Leader, Colibrium Additive

Are metal additive machines ready to meet industrial demands?

While early laser-based metal 3D printers were first commercialized over two decades ago, it is only in recent years that experienced users of additive manufacturing have begun to deploy additive technology for industrial-scale production.

Today's laser-based metal 3D-printing systems come in a variety of technologies and sizes, each with its own range of capabilities, speeds and price points. With so many different printers across the laser powder-bed fusion (L-PBF) category, it might be easy to think they have become a commodity. This is far from the truth. While most L-PBF printers have grown faster and more affordable, until recently only a very few have demonstrated the ability to handle the demands of production at scale.

Today's machines are an intricate combination of precision hardware and advanced software capable of transforming metal powders, as thin as ~10 microns, into fully dense parts with properties equivalent to wrought metals. To do this, they must orchestrate the interaction of many complex subsystems, from precision lasers and thermal management to powder handling and advanced software.

Yet, for an industrial-ready system, putting these subsystems together is merely the start. To convince technical and business decision makers that L-PBF is ready for their factory, the system must produce precision parts with geometries, properties and metallurgies that are consistent from part to part, machine to machine, and even from factory to factory. And they must do it day in and day out while operating with minimum disruption.

Building industry-ready laser printers is an imposing task. I know this from personal experience, having led a team at Colibrium Additive that has spent the last four years continuously improving our M2 Series 5 and getting the M Line system commercially ready. By describing the steps our team took to ensure our M Line system meets industrial standards out of the box, we hope to demonstrate why we believe L-PBF printing is ready for production at scale today.

Customer-Centric Innovation

Since its formation six years ago, Colibrium Additive has been in the unique position of working closely with GE Aviation, an early proponent and now super user of metal additive technologies, creating flight-critical parts and systems of parts within a highly regulated industry.

With well over a decade working with additive technology, GE Aviation continues to set the bar high for the entire additive community. One example is in the field of materials science. GE Aviation's materials team has decades of expertise in everything from alloy development to the analysis of finished part microstructure. That experience and insight has proven invaluable to our team in creating additive manufacturing systems that print parts across the entire build plate using robust and stable parameter sets.

Both Colibrium Additive and GE Aviation also leverage Lean Manufacturing and a Six Sigma quality infrastructure. This involves extensive testing of multiple runs on multiple machines to ensure that we can print parts within specification and that any variations in those parts are not statistically significant.

Validation

To develop the M Line system (as well as the M2 Series 5), Colibrium Additive leveraged GE Aviation's formal new-product-introduction process, which ensures we understand our goals and line up resources early, go through several rounds of engineering refinement and ultimately validate products in ways that ensure they are ready for factory floor production.

Development starts with a consensus design review, during which we lay out our broad objectives, make sure they align with the needs of our customers and target critical-to-quality parameters our printers must meet. This is followed by conceptual, preliminary, and detailed design reviews. During each of these stages, we narrow down and model possible solutions, build subsystem test rigs, and eventually create prototypes that demonstrate how we will meet customer requirements.

Then comes the real work: validation. It ensures that our L-PBF machines meet their specification goals and operate reliably. The process may take one year or longer.

For the M Line, this involved measuring more than 2,000 different variables on at least three individual machines during runs of increasingly complex parts over a period of one year, collecting over nine million data points on the performance of the machine systems. We also monitor other systems that have been operating for several years to understand how wear conditions arise, so we can either prevent them or compensate for them with software.

Since additive printers are actually a collection of subsystems, that is where we start. With sophisticated sensors, we monitor subsystem components and behavior. Some are obvious, like how precisely the build plate lowers itself in 30- to 50-micron increments during the build.

Others seem obvious on the surface, but we dive deep into the details. Take, for example, the speed and temperature of gas flowing into the build chamber. We monitor it at different heights and locations to ensure consistent temperatures—and parts—up to the edges of the build plate. We also monitor the temperatures within the lasers and mirrors and the housings that hold them. We measure laser stability, wavelength and spot size, then double-check how well two or more lasers work together to create a single, seamless, monolithic part.

Our goal is to eliminate subsystem variations. After doing that, we integrated those subsystems into three M Line prototypes for system-level testing. We had several goals in mind. First, we wanted to make sure that each module continued to achieve consistent results while interacting with the printer's other subsystems. Second, we needed to demonstrate that they all worked together to print parts with build-to-build consistency over time, so that the 1,000th build has exactly the same physical and metallurgical properties and geometries as the first.

Finally, we needed to demonstrate that our subsystems and system would provide consistent performance with little variation over the printer's or system's lifespan. This is incredibly important to existing and potential customers, especially those making demanding products for aerospace, medical and other industrial applications. While every L-PBF machine manufacturer, including Colibrium Additive, uses software to compensate for small drifts in processing parameters, software should never be used as a band-aid for an unstable printer.

Industrial grade

Innovation in additive manufacturing is difficult and costly. At Colibrium Additive, our formal process is more than just a set of guidelines we follow internally. We are able to tap into knowledge and additive infrastructure across the wider GE network. We also include customers at every stage of our development process, as well as outside experts to evaluate potential solutions. We do thousands of tests and analyze every statistically significant variance and failure mode.

We began this process as soon as we acquired Concept Laser in 2016. Since then, we have completely reengineered our portfolio of printers to turn them into reliable industrial assets. They produce parts safely with the right quality, scale and cost to compete with conventional machining in applications that place a premium on complexity, weight and durability.

Like other manufacturers, we provide services that help customers get the most out of their investment in additive manufacturing. For many companies, this involves answering engineers' questions about software and machine parameters. For others, it extends to in-depth technical support to help select the right material for an application or to design or redesign parts and components to maximize the value of their L-PBF printers. Most companies offer similar services, but they cannot call on the immense library of knowledge we share with GE Aviation.

Engineers should continue to question any machine manufacturers' claims that seem too good to be true, especially when it comes to achieving industrial scale performance. I regularly see certain manufacturers over-selling the promise of additive technology, while struggling to provide cost-effective capabilities. This is the primary reason there are so many 3D printers gathering dust in the corners of factories around the world.

To avoid that fate, keep asking questions about the cost, speed and capabilities of additive manufacturing. Demand proof. The best way to evaluate an industrial-ready machine is to see it in action. Visit one or more factories running dozens of printers. Look at the parts they make and ask about variation. Check financial models to see why it makes sense to make that part additively. Ask about reliability. And—this is important—talk with customers who have used printed parts and ask about their quality and durability.

At Colibrium Additive, we have hundreds of L-PBF, Electron Beam Melting (E-PBF) and increasingly Binder Jet printers in operation. Our L-PBF machines have made hundreds of thousands of complex parts, and our customers plan to make hundreds of thousands more in the near future.

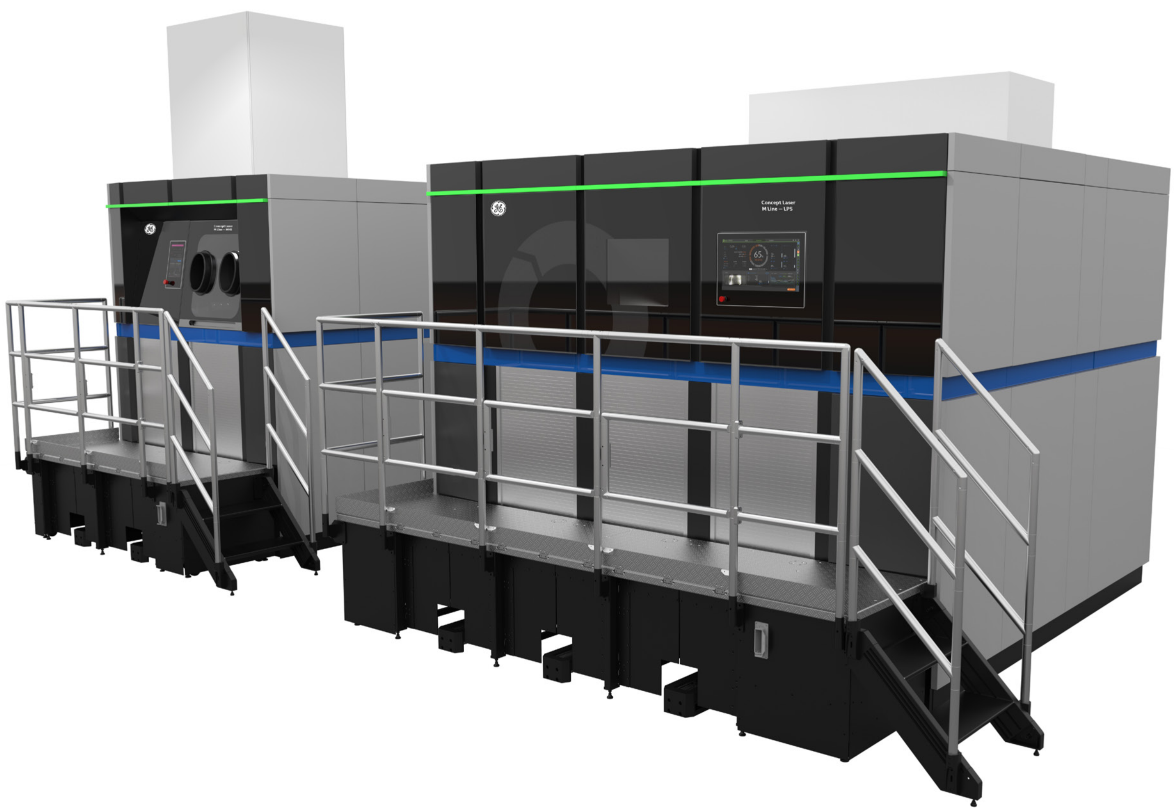
We are proud of what we have accomplished. That is why we invite your skepticism. Seeing is believing, and we want you to see for yourself that our L-PBF machines are industrial-ready for your most demanding applications.

Laser Anthology

03

For Industrial Scale 3D Printing, Technical Maturity Matters

Dr. Wolfgang Lauer
Senior Product Manager, Colibrium Additive



For Industrial Scale 3D Printing, Technical Maturity Matters

Dr. Wolfgang Lauer, Senior Product Manager, Colibrium Additive

Walk through any large-scale factory and you will see a variety of industrial equipment. As different as these machines are, they all have several things in common. They are reliable. They achieve high yields. They meet quality expectations. They produce parts with little variance from run to run and from machine to machine. And they do not require constant operator intervention.

They are, in a word, mature. They are easy to use, and their technology and construction have proven themselves through the years. They can run 24/7 if necessary and produce tens or even hundreds of thousands of on-spec parts, repeatedly.

As an additive industry, we are collectively getting there, but technical maturity is a word still not often associated with metal additive manufacturing.

After all, additive is a rapidly advancing technology where competitors all vie to be first on the market with new features. That often results in metal 3D printers that have not been thoroughly tested reaching the market. Instead, debugging takes place on the factory floor. And while these machines may achieve high yields and quality, they may not do it consistently. Their operating parameters vary too much and may drift over time. In a word, they are not mature.

That is why Colibrium Additive developed its new M Line laser powder bed fusion (L-PBF) system. It is designed for true, industrial-scale, volume manufacturing. Its 500 x 500 mm build plate and 400 mm z-height supports the production of both large parts and higher volumes of smaller parts. It is also designed for 24/7 operation and rapid turnaround between production runs.

The M Line is a big step forward in additive manufacturing maturity. Built with input from our colleagues at GE Aviation, it meets the aerospace industry's highest quality standards for printed part geometry, performance, and microstructure.

Multiple machines have undergone validation testing for 18 months, taking more than nine million measurement points, and using statistical methods to ensure minimal variance in production. This enables the M Line to consistently print low-porosity parts with even stitched fatigue strength to stand up to dynamic as well as static loads. It opens the door to many possible applications in aerospace and most other industries.

Adding Flexibility

Technical maturity is critical to manufacturers who want to take full advantage of everything additive manufacturing offers. They know that additive manufacturing cannot compete with conventional machining on a direct part replacement basis. Instead, they see L-PBF-based technologies printing as a way to integrate higher-value functionality into their designs.

Additive also provides greater supply chain flexibility. On one hand, it can consolidate part count and reduce assembly time, simplifying production. On the other, it enables manufacturers to switch seamlessly between different types of parts while still running at high volume. The M Line system can complete these turnovers between runs in as little as one hour. This gives producers the flexibility to switch between parts as needed or to create customized derivatives of a single design.

Many manufacturers could leverage additive's utility, but first they must learn to trust the technology. So, how can producers tell if additive technology is mature enough to work for them?

Critical to Quality

To answer that question, let's look at how Colibrium Additive developed the M Line. This did not happen in a vacuum. It began in 2016, when Colibrium Additive acquired Concept Laser.

After the acquisition, GE and Concept Laser engineers joined together to redesign the company's M2 DMLM printer. Their goal was to optimize the system's critical-to-quality (CTQ) subsystems, the modules that directly impact part quality. Anyone familiar with laser metal printing will be familiar with them. Among them are:

Optics: This includes laser beam power, precision, shape, and stability, as well as the mirrors used to focus and split beams and the hardware used to mount these elements. Laser quality determines the porosity and microstructure of the final part as each layer melts and then solidifies.

Airflow: Air flowing across the build plate whisks away tiny airborne soot particles generated by laser melting and keeps temperatures stable. Laminar airflow enables consistent printing across the entire build plate, right up to the edges. When airflow is inconsistent and causes turbulence, some soot will remain hovering above the workpiece and laser energy, which can alter material properties.

Layer thickness: DMLM systems melt thin layers of powder as thick as 50 microns or more. After each layer solidifies, the printer lowers the build plate and coats the build with the new layer of powder. When done correctly, this produces parts with uniform geometry and microstructure whose properties resemble those of wrought metals. Micron variations in thickness alter the amount of laser energy reaching the powders, changing the material properties of the final part. Since each small change is multiplied by several layers, even small changes in layer height will cause the print process to fail.

We have addressed each of these and other CTQs, ensuring that each one could meet the specifications necessary to produce high-quality parts. We then integrated them into the final M2 printer and double-checked to ensure they continued to hit their marks on a system level.

Our M2 Series 5 printers have been proven by GE Aviation and other aerospace and medical customers, producing hundreds of thousands of parts in industrial environments. Because we are intimately involved in supporting these machines, we have learned a great deal about their performance over time.

Improvements

This experience is the foundation upon which we have built our new M Line system—but only the foundation. Although the M Line builds on M2's subsystems, there are some significant differences. Take, for example, airflow. The M Line's build plate is twice as wide as the M2's. To achieve the same consistent air speed and laminar flow, significant reengineering was required.

We also had to rethink the trade-offs between the various components. Take, for example, the laser system. The M Line uses four 400 W lasers, compared with up to two 400 W lasers configuration in the M2, and generates far more heat. That heat causes the mirrors to deform slightly, reducing their ability to direct the laser beam precisely. We attacked that problem by not only improving our mirror cooling system, but also by cooling the mirror frame and housing. We also respecified the construction of these components to use materials with lower thermal expansion coefficients to minimize their dimensional variation when heated.

We also wanted to improve the M Line's control over material properties even further. We were already using very high-quality lasers, and further improvements would have been extremely costly. Instead, we invested in contour countermeasures via special stitching algorithms, so we improved material properties just as much as if we had invested in a more precise laser and made the process very stable and robust.

This is especially important when building large parts, where M Line's four lasers work together to create a single monolithic structure. Typically, the point where two lasers meet while printing a single part creates a seam. This edge is often strong enough to withstand static loads. Under dynamic loads, however, the interface must be completely homogenous, or it will concentrate stress and lead to failures. The M Line's improved laser cooling and stitching algorithms ensure the microstructural uniformity needed to handle the dynamic loads generated in aerospace applications.

Proof

While improving critical-to-quality subsystems was important, we wanted to go beyond the generation-to-generation advances most competitive metal laser printer manufacturers undertake periodically. Instead, we wanted to commercialize a truly industrial-ready printer with unmatched reliability and repeatability from run to run and machine to machine.

To do that, we launched a systematic campaign to test and understand each CTQ and subsystem at a level of detail never attempted before. We tested every measurable variable—more than 2,000 in all—on each CTQ and subsystem to understand what drove its behavior. Using that knowledge, we redesigned those units to control their parameters better than ever before.

Even that was not enough. 3D printers have long struggled with variability. Runs on the same machine would drift and the output from two models of the same machine was not always precisely the same. To improve consistency, we needed to reduce variability. The only way to do that was to ensure that when we measured our CTQs, the data showed a statistically significant narrow range of tolerances. We also paid close attention to how CTQ subsystems interfaced with one another in the final system. This enabled us to create a more stable machine that retains the tight tolerances of its components. That was the only way our customers could count on the M Line to make parts that could withstand the extreme aerospace environment and dynamic forces.

We did not record this data in a vacuum. Instead, we did it while printing increasingly complex parts over one-and-one-half years to make sure our CTQs retained their tight variances over a variety of operating conditions.

We also built parts from a variety of materials and measured their properties, from their dimensions and physical specifications to their homogeneity and the orientation of their microstructure. This way we accrued enough data to validate the M Line's performance statistically.

It is one of the reasons the M Line consistently achieves yields of high-quality parts that manufacturers associate with industrial machinery.

The M Line is, quite simply, a mature, proven technology that manufacturers can rely on to scale, by delivering repeatedly debit-free stitching quality at highest stability: this is the future of industrialized additive manufacturing.

And that, after all, was our goal. We built the M Line to redefine L-PBF printers as a mature industrial technology that could meet the demands of aerospace, medical, and other demanding applications—at scale.

We believe the M Line's consistency makes it more than competitive on a dollar per cubic centimeter of output. It is a machine that excels at printing large, complex components with properties unmatched by other printers, and smaller parts for high-volume applications.

The M Line is, quite simply, a mature, proven technology that manufacturers can rely on to scale by delivering repeatedly debit-free stitching quality, at highest stability: this is the future of industrialized additive manufacturing.

04

Laser Anthology

Get the facts on stability

Sarah Ulbrich

Lead Engineer – Process & Materials Development, Colibrium Additive

Get the facts on stability

Sarah Ulbrich, Lead Engineer – Process & Materials Development , Colibrium Additive

Stability is something that needs to be tested at all stages of additive machine development to ensure printing success. Depending on the user's level of exposure to additive, the concept and interest in stability can range from being an unknown to being a commonly discussed factor when printing.

Maintaining a high level of stability at all stages of development ensures that you get a higher quality part that is less prone to defects and has the intended material properties.

Here, Sarah Ulbrich, lead engineer – process & materials development at Colibrium Additive, discusses how stability is being achieved on the mid-size M2 machines and on the larger M Line system.

Q: What is Stability?

There are three types of stability to consider. The first is platform stability. When we look at platform stability, we are testing across the platform and across the optical field in all dimensions. In these tests, we investigate all the different angle incidences from the lasers and test for material properties.

The second stability that we test for is the build-to-build stability. This is performed on just one machine, and we build the same print job repeatedly to confirm that we can continually reach the same stability.

The third stability that we look at is machine-to-machine stability. This is where we have different machines of the same platform, and the same build job, and we test them over and over again.

Platform stability is something that we look at from a material perspective during parameter development, then we look at it from a machine perspective. During development, we make sure that we can reach that platform stability, and during machine validation, we make sure that we can reach it across the platform repeatedly.

Q: What criteria do you use when determining stability?

We have a set build-job design for the different platforms. While they are similar, and standard specimens are used across all the platforms, the samples are arranged differently on the platform so that we can measure across the whole platform. We then measure a range of properties, including surface roughness on vertical and angled surfaces, porosity, and mechanical properties—such as tensile testing and hardness.

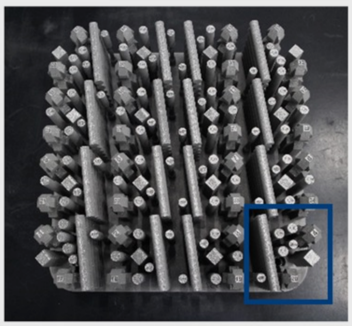
There are two groups that can be tested. These are printed parts in the as-built state or in the heat-treated state. For determining stability, we test the parts in the as-built state, because they are more prone to irregularities than parts that have been heat treated. When you heat treat the part, you change the material properties of that part, and any differences get washed out compared to an as-built part. So, if something goes wrong during the build process, it is easier to detect it in the as-built state.

M2 Series 5 Platform Stability

Machine: M2 Series 5

Parameter: Ti64 – 120 µm

16 unit cells to get information about the platform variation



UTS in MPa*

1055	1050	1054	1048
1059	1054	1056	1050
1061	1052	1053	1049
1058	1060	1049	1049

A in %*

15	14	15	14
13	14	15	15
14	14	14	15
14	14	15	15

Porosity in %

0,06	0,03	0,03	0,05
0,03	0,03	0,04	0,04
0,03	0,03	0,03	0,04
0,03	0,04	0,02	0,03

* Heat treated condition combining horizontal and vertical orientations

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Our tests have shown that we achieve very stable results across the platform. These results are also shown on our published material data sheets. We do this for all new developments. Data sheet

Q: What are we testing, and what results are we getting on the M2?

On the M2, when we test for stability, we have a standard setup where we use unit cells of specimens containing tensile, porosity and surface roughness samples in all positions of the platform and test the properties of the material. These tests are done in both the as-built and heat-treated states because the end-users are more interested in the heat-treated state, but for us, the as-built state is more interesting for the reasons previously mentioned.

Once this has been completed, we also generate and analyze a lot of data from factory acceptance tests (FATs).

From these tests, we have seen very stable machine-to-machine results. For example, we see the results of 12 different M2 Series 5 machines tested with CoCr showing a very high stability.

A key part of these tests is that we don't look only at the sweet spots of the machine be it for best gas flow location or best optic location, but we also look at worst-case spots as well. By doing this, we have been able to identify problems that existed in the past and have rectified them by making the appropriate improvements using the obtained data.

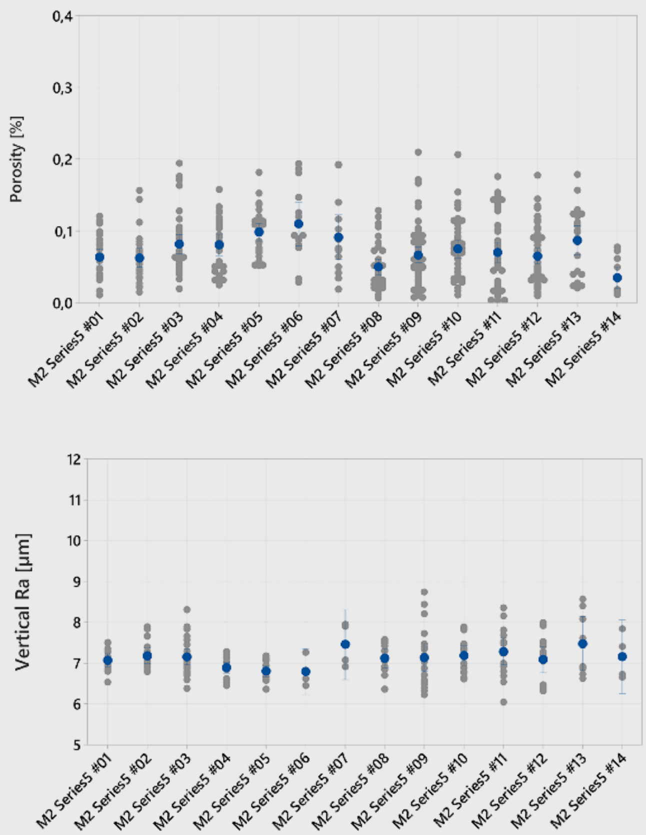


Figure 1: Graphs show repeatable results over 12 M2 Series 5 machines from the factory acceptance test (FAT) for CoCr 50 µm. *Source: Colibrium Additive*

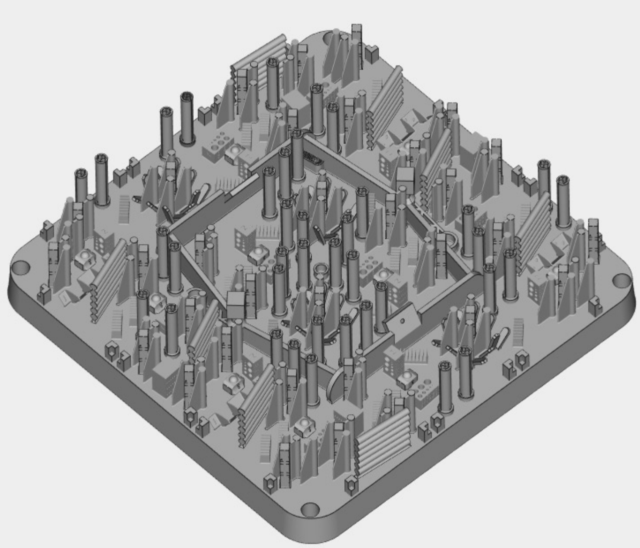


Figure 2: FAT Layout for the M Line Source: *Colibrium Additive*

Q: The M2 is a smaller build plate, but the M Line is on a whole different scale. How are you approaching stability on this larger format platform?

On the M2, we have a 245 × 245 mm build area, but we have four times the space on the M Line. To tackle the larger build plate, we quadrupled the number of samples on the plate and placed them strategically according to our laser allocation. This way, we can test all over the platform and at all angles of incidence.

This is our FAT. Additionally we run a capability and stability test to test all the laser angles. We took what we learned from the M2, quadrupled the number of samples, tested them according to our standard lab procedures, and ran the same stability and capability tests that we performed on an M2, but on a larger scale. We also tested the stitching during a standard FAT and during machine validation. This is at both the bottom of the machine and at different heights so that we know the stability over both the platform and height of the build area.

Q: What does the validation process look like for the M Line?

A lot of testing takes place during the validation process. As the M Line was being developed, we were continuously testing, working closely with our in-house laboratory and quality teams. The same is true during the parameter development stage as well. Since locking in the machine configuration and parameter sets, we have performed 443 porosity, 298 tensile measurements, 780 vertical roughness measurements, and 224 upside/downside measurements. This is in addition to all the other tests that were performed before we locked in everything on the machine.

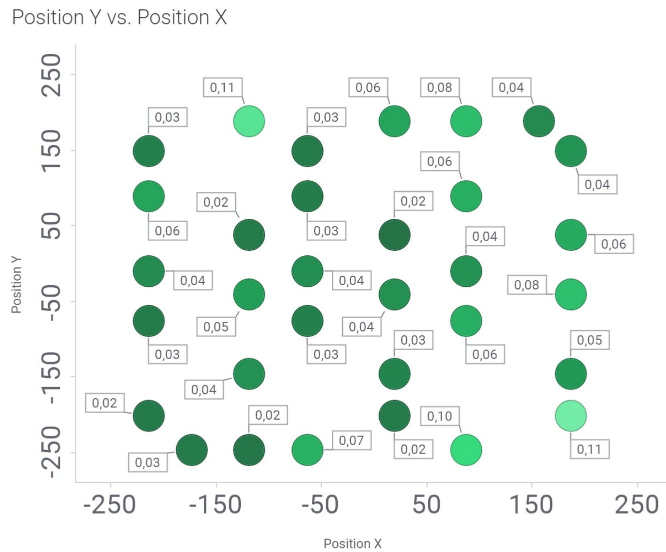
This large amount of testing has been done in the validation phase so we can reduce the number of tests required during the production stage. We always perform a range of tests on each machine before it is shipped to the customer so that we know they are capable of delivering the expected productivity levels.

Q: What are the benefits of having an on-site laboratory compared to sending the parts off for testing?

The biggest benefit is the time saved by not having to ship the samples off to be tested, losing time in both transport and receiving the results back..

Q: What's next in stability development and how do we get there?

The ideal next step–and it is still some way off–is eventually to get to a point where we don't have to do material testing anymore. This way, we will know the material results by measuring the machine and have confidence that the system will be able to get those results each time. The only way we will get to that point is by continuing to collect more data and more analytics. The next logical step is to start reducing the number of tests that we do, but because the M Line is a relatively new system, we will have to wait a while to start implementing this approach.



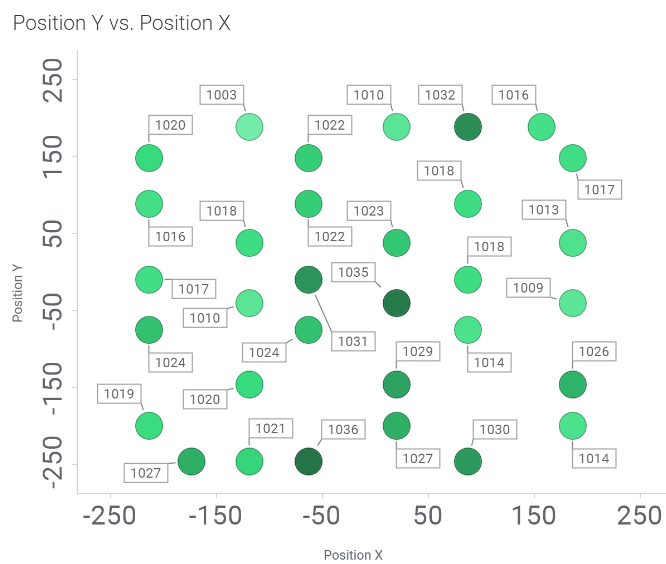


Figure 3: Platform stability of Porosity [%] over M Line 500 × 500 platform for Ni718 50 µm layer thickness; as-built. *Source: Colibrium Additive*

Overall Outlook

When it comes to stability, there are several tests that need to be performed to ensure that the machine is working as intended and that you're going to get the desired material properties in your part, regardless of where it is on the build plate. To do this, we need to make sure that the worst-case areas are also being analyzed alongside the sweet spots, as that allows you to evaluate the entire build volume. This means we can continuously make improvements to our systems and machines, but it also enables our customers to have a certain level of confidence that when they use the machine, they are going to get the intended output.

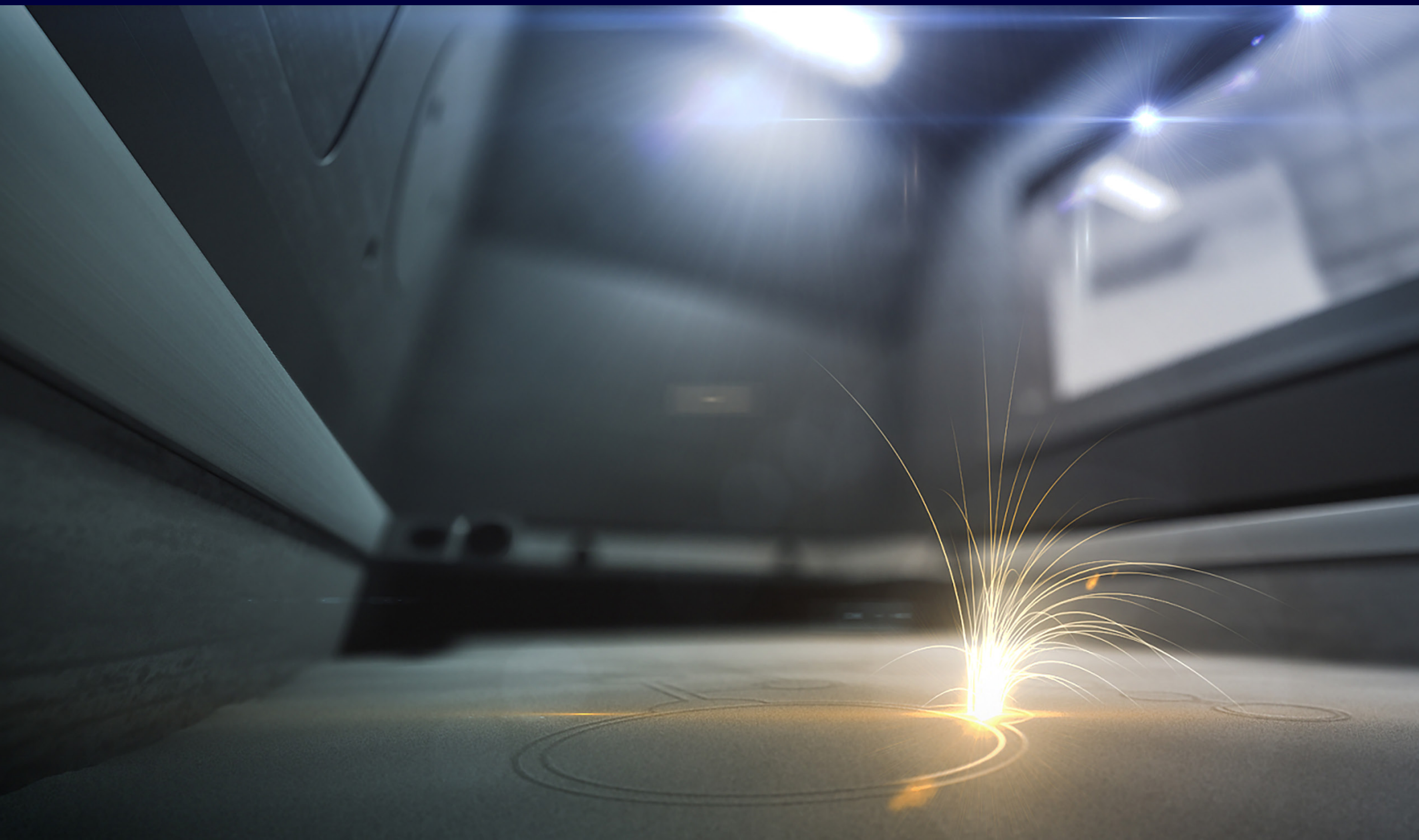
If you would like to know more about how we're committed to stability and how it impacts the other aspects of your printing approach such as the reliability of stitching in the larger M Line machine, **get in touch.**

Laser Anthology

05

Get the facts on accuracy, uniformity and continuity

Halima Iqbal
Advanced Lead Project Manager, Colibrium Additive



Get the facts on accuracy, uniformity and continuity

Halima Iqbal, Advanced Lead Project Manager, Colibrium Additive

The overall capability of a laser powder bed fusion (L-PBF) additive system is defined by its consolidation potential. The consolidation potential of an L-PBF system is a product of the machine's capability, its accuracy, the uniformity of the build, and the machine's continuity. In order to optimize the output of an L-PBF machine, that is, to ensure high-volume production of high-quality parts and minimal part-to-part deviation, these factors are critical for ensuring success.

Halima Iqbal, Advanced Lead Project Manager, Colibrium Additive, discusses the importance of accuracy, uniformity and continuity when building parts—especially in highly regulated industries—and how they can be achieved to a high standard, ensuring part build success.

Q: What do we mean by accuracy and why is it important?

With an L-PBF system, we're aiming to ensure that accuracy is well known within the industry on a couple of different points.

The aim of the game when it comes to accuracy is to ensure that, when printing a part, you are meeting the design intent per your CAD model requirements and the material properties required for your application.

Accuracy with L-PBF systems really means that you're hitting the laser on the powder bed in the exact place as intended, and with the right properties. These properties include a consistent beam spot size, shape, and quality, with the laser beam characteristics and energy input needing to be controlled and optimized. These properties drive the quality of the part and allow you to build the part to the right specifications and dimensions. You also need to minimize the variability in positional accuracy—where the laser hits the powder bed—if you want to meet the design requirements.

It is important that you have the right quality of components available to ensure that you are building the intended specifications and material properties. This is even more crucial in highly regulated industries, such as aerospace and medical where certain requirements must be met and demonstrated repeatedly. If you don't have a highly accurate system, you are going to automatically close yourself off to some of the highly regulated markets, as your parts will struggle to meet the stringent requirements set by those industries.

Q: What are some of the methods used to achieve accuracy?

Ensuring that the optical components are thermally stable and regulated, having high-quality optical components, and ensuring that there is minimal variance in our working level distance. The combination of optical component choice, set up and thermal stability drives the positional accuracy by limiting the drift of components, and positional accuracy is ever-more important when more than one laser is used.

With the improvements made in our design and methods for both spot and position accuracy, we have been able to reduce focal shift in our L-PBF systems by over 70% and demonstrate enhanced stitching capability.

Talk to us about the importance of thermal regulation in terms of accuracy.

The characteristics of the laser beam are very important as it moves from the source to hitting the powder bed. The beam needs to have the right size and energy input to be accurate. This is heavily dependent on the temperature of the different optical components in the system.

If there is a large thermal shift within the optical components, it starts to alter the characteristics of the beam. This can cause a focal shift in the optics, which changes the size or shape of the spot on the powder bed from what was intended and deduced to be optimal for a high-quality build. If you don't have the right spot characteristics, you don't achieve the desired material properties, that is, reduced quality.

Therefore, ensuring the thermal stability of the optics is one of the most critical pieces for ensuring high accuracy, and in our systems, we have optimized both water- and air-cooling systems depending on the type of optical component. This allows us to hit the narrow process windows that we want to achieve to get the right part quality.

Q: And how do you ensure a high optical component quality?

The quality of the components themselves is very important if you want to achieve the desired spot characteristics, and we make sure that we hold our suppliers to a high-quality specification. The products are tested before they leave the supplier, as well as before and after installation in the machine. Off-the-shelf components don't tend to work, so the purchasing of components requires a lot of understanding about how these components behave, undertaking a lot of in-depth analyses, as well as trial and error with different components. There's a careful selection process that goes behind obtaining the right optical components.

Q: And what's important about the working level distance?

The distance between the laser output and the powder bed is the working level distance, and is a very important factor for determining the characteristics of the beam. The shorter or longer the beam is, the different the beam characteristics will be, and this changes how the spot forms on the powder bed. So, you need to ensure that you have the same working level distance, otherwise you will also experience focal shifts within your beam. The main way to do this is through the set up of your recoater blade. The recoater blade spreads the powder across the build plate and sets the working distance. So, you need to pre-calibrate the recoater blade before you put it into the machine to ensure that there are minimal variance issues so that you get a narrow processing window.

Q: What do we mean by uniformity?

Uniformity ensures that whatever you do in one part of your build plate or powder bed can be replicated. So, you're essentially aiming for uniform operating conditions within your process chamber to ensure minimal part-to-part variation. Once you have achieved the desired spot characteristics, targeting uniformity using technical levers will allow you to achieve the same quality output, regardless of where you are on the build plate—be it from part to part or throughout one large part. It is highly critical to ensure that you achieve uniformity within regulated industries, where part one needs to equal part 10, which needs to equal part 100.

Q: How do we achieve uniformity?

There are a few technical levers that we use to ensure that we achieve uniformity across our builds. These are an efficient gas flow, an optimized recoater design, and the choice of optimal components used. If you do not achieve uniformity within your machine, you're going to have a constant struggle to try to qualify your parts because you will be scrapping half of the build plate. This is not a great business case for any user, so uniformity is key for maximising the output of any additive machine. By utilizing the different technical levers around optimizing recoater design, gas flow distribution and component choice, we have managed to significantly reduce our variation across build plates in our latest products.

Q: How does gas flow affect the ability to create uniform parts?

The gas flow across the build plate is a big factor for achieving uniformity as it allows a clean melting process to take place. A lot of soot gets generated when you laser metal powder, so you need an effective gas flow.

It is important that the flow is uniform across the powder bed and build plate so you're not getting clean and dirty regions as that will ultimately lead to differences in part quality across the build plate. Otherwise, regions of soot will remain. If you're lasing through soot, you will have a lower part quality, so a uniform gas flow is key to achieving a uniformly clean and homogenous build environment. This ultimately leads to an overall improvement in quality, density, and surface roughness of your parts.

Additionally, how the gas flow is calibrated is key to ensure uniform airflow, as it ensures that the machine is within the right tolerances before use.

Q: What effect does the recoater design have on uniformity?

Having an optimized recoater design enables you to minimize the turbulence in the build environment, allowing you to have a clean flow.

Q: And what about the impact of optical component choice on uniformity success?

The choice of optical components is a major player for minimizing the variability in the spot characteristics and how that can be demonstrated repeatedly across the build plate. The goal is to be able to hit a small enough spot size to allow for fine feature resolution in your parts, while maintaining the beam shape with minimal variation. So, as you move across the build plate, if your optical components are of a high quality, the deviation in the focal shift is going to be minimal compared to poor-quality parts, allowing you to achieve a repeatable output on the build plate.

Q: How does continuity contribute to a maximized output?

Once you've perfected the spot characteristics and you've demonstrated that you can replicate it across the build plate uniformly, you need to set the machine up for success by optimizing the output and reducing the total cost per part. An L-PBF system should be designed so that your operational effectivity is high, and any losses are kept to a minimum.

Continuity aligns with your ability to have the machine available to you as much as possible, so that you can continuously print parts without facing operational losses. One big aspect to this is powder handling, as a lot of time is spent loading and unloading the powder. We are actively trying to optimize this area so that the user can have more laser-on time and spend less time on factors that don't add value.

Maximizing the laser-on time of the machine allows the user to hit the build times required to meet their part

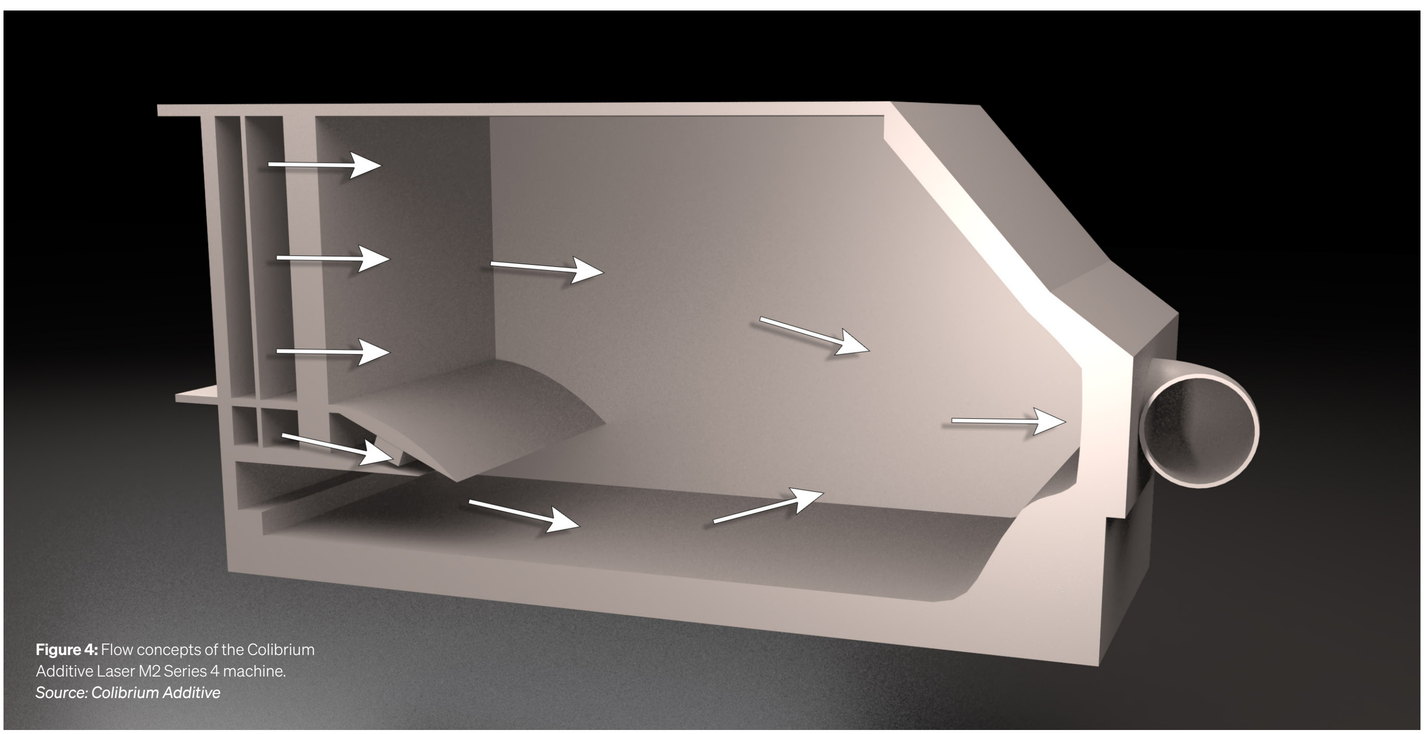


Figure 4: Flow concepts of the Colibrium Additive Laser M2 Series 4 machine.
Source: Colibrium Additive

demand schedules, while also ensuring residual stresses in the part are kept to a minimum. By doing as much of the vector calculation work (especially for complex parts) offline, on your office desktop, more time can be spent printing and delays can be kept to a minimum during the build. This maximizes the laser-on time, allows for faster builds, and reduces the amount of residual stress in the part, because you're not waiting around for the calculations to take place—which can cause some thermal differences between layers during the wait, increasing the stress on the part.

To achieve the maximum laser-on time, the machine needs to be easy to maintain and have an easy-to-handle design. In addition, implementing certain maintenance procedures to ensure minimal downtime and undertaking specific training can help any user to become self-sufficient with their machine, maximizing laser-on time, and in turn, reducing the cost per part.

Overall Outlook

Overall, you need a combination of accuracy to hit the powder bed in the right spot, a high degree of uniformity to ensure the same part quality across the whole build plate, and a high degree of continuity in your machines so that you can maximize your laser-on time and reduce the total cost per part. By ensuring these three factors are met, you will be able to create a large volume of parts that are uniform and of a high quality, which will be able to meet the most stringent of industry and regulatory requirements.

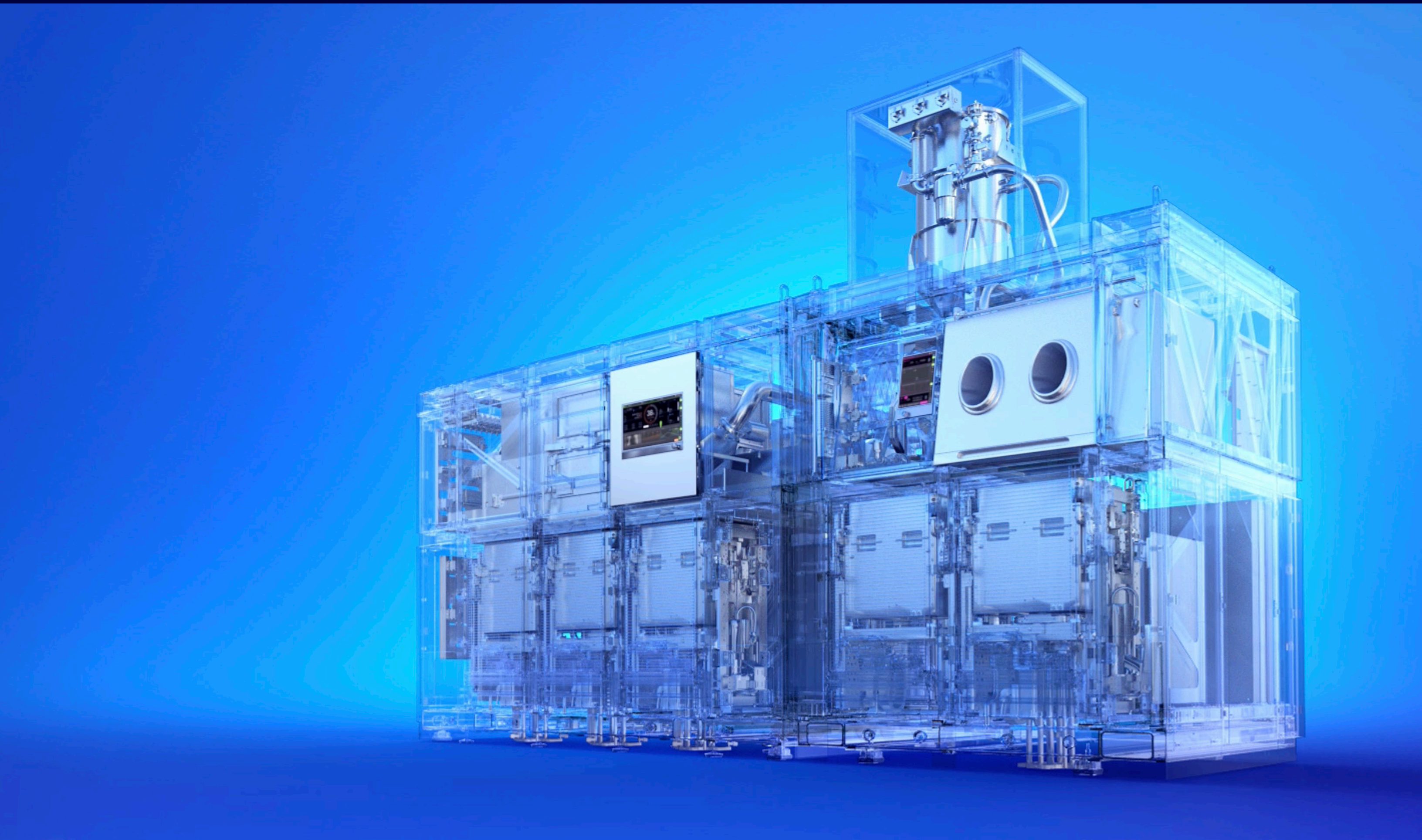
If you'd like to find out more about how our teams can support you throughout this initial optimization process, and once you start printing parts, **get in touch.**

06

Laser Anthology

Get the facts on productivity & technical availability

Viktor Kremer
Operations Leader, Colibrium Additive



Get the facts on productivity & technical availability

Viktor Kremer, Operations Leader, Colibrium Additive

Users of additive machines naturally want high productivity in their process to ensure that the machine is producing at desired cost per part. High productivity does not only mean melt rate, but also yield (ability to print good parts) and technical availability. Having a machine that is operating with minimal downtime and always available to print, combined with high yield and melt rates, is the ultimate goal.

Our M Line system has been developed with these factors in mind to ensure that the user gets consistently high output.

We caught up with Viktor Kremer, Operations Leader - M Line, Colibrium Additive, to see how the productivity of a machine is primarily governed by technical availability and discuss other factors that influence the productivity of an additive machine.

Q: What drives technical availability?

Technical availability is mostly driven by the design of the machine. So, the way the components are designed, the way the components are working together, the way the interfaces between different systems are designed and implemented, the interaction between hardware and software, and the motion systems all drive the technical availability of a machine. These are factors we can control, by design.

Another factor of technical availability is the way the customer uses a machine. Depending on how well the user follows the service schedules and service activities that we prescribe for a system, and how well the user follows the work instructions and procedures design can all have a bearing on the technical availability of an additive machine. We can control most factors of technical availability, but some are reliant on the user.

Q: Which components require specific attention?

There are several high-stress components used within an additive machine that require high durability. These carry the load of the (heavy) metal powder, so the z-axis needs to be designed to consider the different payloads used—the different materials that have different densities and weights—and the different movements that happen within the z-axis.

The M Line has been designed to carry the heaviest material, tungsten. So, all the motion systems within the M Line have been designed to be able to withstand heavy payloads.

The second area that requires specific attention in the design phase is recoating systems. You need to put a lot of thought into the guiding mechanisms, because these have traditionally been exposed to a lot of powder during printing. However, powder exposure hasn't typically been considered for the components that are used for the guide rail.

The M Line changes this dynamic. We have designed the guiding mechanism in such a way that it is placed within the machine where there is going to be as little powder contamination as possible. This helps to extend the amount of time that the machine can run without any wear effects on those rails, reducing the chance of failure occurring, which also means that you have longer service intervals than you do with other systems.

On the subject of the availability and downtime of the machine, another area that requires a lot of attention is the gas flow system. These pumps experience high rpm ranges depending on how full the filter is. So, when the filters are full, the pumps run at higher rpms, putting more stress on them. There are also restrictions to the lower-end speeds because the pumps suffer from very low rpms as well. There is an operating window where the pumps are running optimally. The M Line's systems have been designed so that all gas flow velocities fall into this optimal operating window. This means there is less stress and wear on the pumps and a lower likelihood of premature failure.

Q: How do system complexity and technical availability affect each other?

The higher the complexity of the system, the higher the probability of system failures. This is driven by the number of components that could fail and also how many other subsystems are impacted in case of failure. Even though the M Line is complex with many components and system interactions, it has been designed with a full system design approach, limiting those failure modes and probabilities as well as validating the system design to achieve the highest techncial availability.

To manually interrupt, correct and continue the print process to prevent scrapping the part, is not very productive overall . You don't want to waste your time and resources watching a machine and scrapping parts because of constant interruptions. In the end, the focus we put on the M Line is to have a reliable and highly available system so that you can have 'lights-off-manufacturing'. The next step we are taking is to increase melt rates to support productivity further.

The interfaces of the M Line, between the systems and the specific components, have been designed with reliability in mind. Users who are looking for production machines such as the M Line demand a higher reliability, so there's no reason for us concentrate on high productivity in the first place and not consider the reliability of the system. If you have a system with highest melt rates only but are not achieving the quality required (yield) or high reliability, then it isn't actually going to drive your business case for printing the parts.

Q: What's the difference between yield and technical availability?

Many people think that if you have a highly technical available product or a machine with high melt rates, then you're good to go. However, what counts is how many builds are successful and within the required specifications. There is also the possibility of you having a good-looking print, but then you take it to the lab and realize that it's full of porosity and the material parameters do not match the specifications. This then causes a lot of time, money, and material to be lost.

Our focus is around having successful prints that provide reliable, repeatable, and consistent results, not just on one machine but across several machines. It's not just about having a high melt rate. This means that build-to-build and machine-to-machine variations need to be controlled at all times. This is one of the biggest contributors to high productivity. If every single print is successful, then your overall productivity is going to be awesome.

The focus of the M Line is to have a high yield rate, that is, many successful prints. Even if you have a high technical availability, many of your builds could still be failing. On the other hand, if you have a high yield and a low technical availability, you could have a 100% print success rate. But, because you can print only periodically, your overall productivity is low. This is one of the reasons that users need to look at both yield rate and technical availability—the M Line has been designed with both factors in mind.

Our focus is around having successful prints that are providing reliable, repeatable, and consistent results not just on one machine, but across several machines.

Q: How does technical availability affect Overall Equipment Effectiveness (OEE)?

OEE is an equation that combines availability, performance, and quality. The customer has an impact on both the availability and quality of the OEE, while we as a machine manufacturer have an impact on all three. We've already covered the availability and the importance of having the machine available to the user as much as possible.

While the performance is centered around the melt rate, the OEE of the machine is the calculation that people need to care about the most. Productivity influences OEE.. The combination of availability and quality are highly important, because it is not good for a machine to always be available if the parts don't meet the specifications, or vice versa.

The performance and melt rate do need attention, and this is something that we are actively working on. The M Line has a flexible architecture that will enable us to develop these capabilities further in the future, allowing for an increased in performance.

Q: What can customers do to achieve good technical availability?

Customers should continue to invest in training their teams as much as possible, and as precisely as possible. The attitude and working effort that a worker puts in is going to have an impact on the technical availability of the machine. The additive process requires a lot of attention to detail, and without proper training and focus, there is the risk of a lower technical availability or a lower yield.

Availability is a big contributor to OEE. So, if you are not treating the machine with care, you cannot expect a satisfying technical availability. The biggest factors that affect the technical ability come from us as the machine manufacturer, but the user also needs to maintain a sense of ownership and train their teams well—and sometimes opt for additional training packages to keep their knowledge up to date.

Overall Outlook

Anyone who is looking to scale their additive printing to production levels requires machines and systems that have a high technical availability. Without it you won't have productivity, reliability, or predictability in your supply chain. The M Line was designed to avoid the many potential failure modes that can manifest at these machine sizes through a high degree of technical availability and quality.

Technical availability is one of the many factors that can contribute to OEE, and when combined with high quality and performance, you will be able to print parts regularly and with a high success rate.

OEE is the driving factor for large-scale printing success—and it is not only governed by the melt rate—and this will become ever more important as the additive industry continues to mature in the coming years.

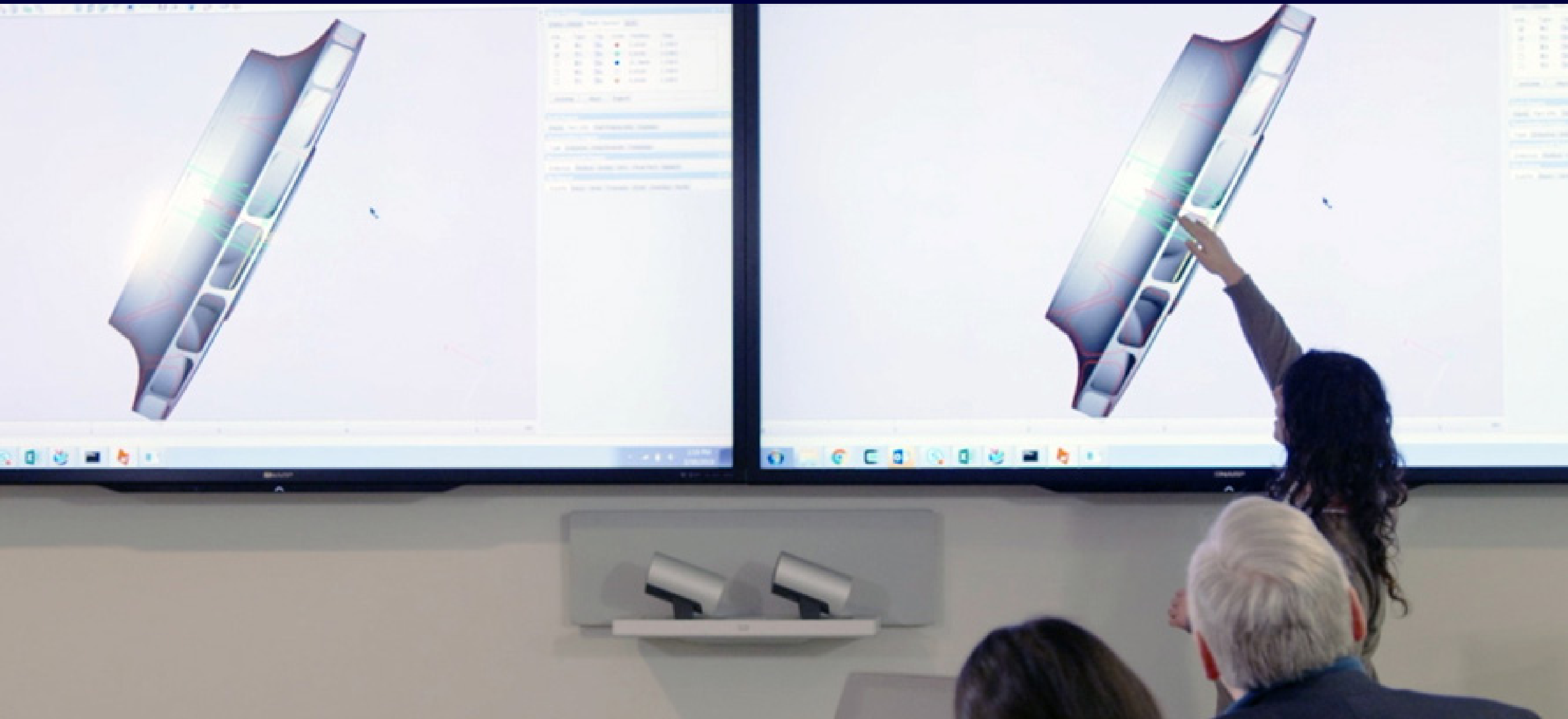
If you'd like to find out more about how the different factors can be optimized in your build, or more information about how the M Line has been designed with the user in mind, **get in touch**.

Laser Anthology

Get the facts on multi-laser stitching validation and performance

Kevin Menger
Additive Process & Materials Engineer, Colibrium Additive

Dr. Benedikt Roidl
Colibrium Additive



Get the facts on multi-laser stitching validation and performance

Kevin Menger, Additive Process & Materials Engineer, Colibrium Additive and Dr. Benedikt Roidl, Colibrium Additive

Stitching, otherwise known as multi-laser processing, is a key piece of the additive puzzle when printing larger-scale parts.

While the concept of stitching different sections of a material together might seem daunting to some from a mechanical property point of view, there should be no need for concern as long as your machine manufacturer can provide you the right mechanical data to show that the part behaves as it would if it were being produced with a single laser.

We caught up with Kevin Menger, Additive Process & Materials Engineer, Colibrium Additive and Dr. Benedikt Roidl, Senior Engineer, Colibrium Additive, to discuss stitching and how, with the right kind of preparation and know-how, it is possible to anticipate, avoid and mitigate any issues.

Q: A basic question, but why do we use the word "stitching"?

It goes back to the interlocking of melt pools, which is now an outdated strategy. When you looked at how the two melt pools meet at the point where two lasers meet, it looked like the sections were sewn together like a suture.

Q: Why do we stitch?

There are two reasons that we stitch parts. The first is for a higher productivity and the second is for building large additive parts beyond the build area of a single laser.

On productivity, if we want to build parts quickly, we can use several lasers to reduce the build time of the part. When several lasers are used, we have stitching in regions where the lasers meet to improve the mechanical properties of the part. We can also improve the productivity further with good gas flow—enabling more efficient local exposure regions—and knowing how the soot will behave in the machine.

For producing large-scale parts, users may also need to stitch if the build plate is larger than the optical field size. For example, the M Line has a build area of 500 × 500 mm, but our optical systems have a field size of 400 × 400 mm. So, when building large parts, more than one optical system is required. So, this automatically requires the part to be stitched.

Q: Why is it so difficult to stitch properly?

It's not hard to just stitch, as you only need to let two or more lasers work in the same place, but it's difficult to do stitching well. This is because, from a parameter development point of view, we're dealing with multiple exposure elements at once. On one hand, you have the bulk area, which is quite simple to stitch as there is an overlap area, so it's pretty forgiving . As well, the lasers don't need to be aligned perfectly. The lasers dont't get good mechanical results, when surfaces are machined properly and the part is not used in as-built condition.

On the other hand, it gets difficult when you start to stitch the contour—the outside surface of the part—because you need to balance obtaining a high level of surface finish with little to no sub-surface porosity to avoid costly post-processing steps whenever it is possible.

Stitching in the contour region is unforgiving with respect to the alignment of the melt pools that need to meet each other. It's hard to align these melt pools to achieve acceptable levels of both surface finish and sub-surface properties. If your melt pools are misaligned by more than, say, 50 microns, then you're going to get issues with sub-surface porosity and a bad surface finish locally.

Without any additional control mechanism, it is hard to keep the optical systems aligned within 50 microns over the duration of a build. If the system drifts above this threshold, you start to get surface discontinuities that can cause problems, especially regarding fatigue.

Q: What are some of the factors that can influence stitching quality?

One of the factors that indirectly influence the quality of our stitching is gas flow. If too much soot is deposited on the laser window and not efficiently transported out of the process chamber, it can cause a thermal lensing effect. This causes the laser window to heat up, resulting in a shift in the focal plane, distortion of the laser, and a misalignment of the optical systems.

Another factor might be the recoater blade leveling. So, the way the build is set up can affect the optical alignment. The blade needs to be set up so that it's aligned to the optical plane. The temperature and thermal behavior of the machine can also have a big impact on the optical alignment. A lot of power goes into the machine, so we need to dissipate the generated heat.

We use a cooling system to keep our thermal influences low on the misalignment. It is important that you control this; otherwise, you'll have thermal drift of your components, for example, in the recoater, recoater rail, build level, optics, optics frame, process chamber.

The final main factor is the initial optical system calibration. If a lot of effort is put in to calibrate the optical systems properly before use, there is going to be a solid baseline of alignment in the machine, that is, below the 50-micron threshold, before printing.

Q: Why are recoater leveling and alignment particularly important?

The recoater alignment to the optical calibration plane is important because the optics are set to a certain height where the alignment is perfect. The recoated blade needs to be set up parallel and to the same height as the optical plane so that there is no misalignment. For example, if the recoater is set up higher than the optical plane, it leads to a gap in alignment between the optical systems.

Also, if there is a tilt in the recoater blade relative to the optical plane, it could lead to one side of the part having perfect stitching, while the other side is full of defects. If the user of the machine can set up the recoater blade correctly during the initial set up of the machine, as well as follow the developed process given to them, they can have a positive influence on the stitching quality, as well as ensure a high level of stitching consistency between builds.

Q: How does stitching calibration and performance affect the optics?

One of the most important ingredients for good stitching is the initial calibration. First, the individual optical components and their optical fields need to be calibrated, so that they point in the right direction from a single laser perspective.

The second calibration step looks at the calibration of relevant optical system combinations and ensures that each system is perfectly aligned with all the others. You have to bring these interactions within a certain threshold of alignment, the 50-micron threshold that was mentioned earlier. This is the global misalignment across the whole build plate. This is a solid baseline for a good stitching result.

As the optics drift over time, they need to be recalibrated every six months. This is the current guideline, but it is subject to change as it's currently under investigation. We also advise our customers on the software countermeasures that are available to them and how the software is key to obtaining good stitching. With these countermeasures it is possible to go up to a 100-micron threshold and still achieve a good level of stitching results.

Q: So, what does good stitching look like?

If you have good stitching, you hardly see anything on the surface, including any surface discontinuities or different coloring from the thermal behavior of the material during the melting process. Additionally, below the surface, having a level of porosity that is consistent with your single-laser machine behavior is a sign of good stitching.

Overall, a good a stitch will ultimately be showcased if the microstructure of the part is consistent, regardless of whether a single or multiple lasers were used. It is also possible to have something that is discolored, so it looks like bad stitching, but the stitching is actually good and the mechanical properties are sound. From a datasheet point of view, if the part behaves in the same way as a single-laser part (in terms of tensile and fatigue properties) then you have a well-stitched part.

Q: And how about bad stitching?

Whatever is different from a single-laser exposure can be interpreted as bad stitching. For example, if you have visible contour ends sticking out from the surface, any surface discontinuities, sub-surface porosity, or even bulk porosity—in extreme cases that cannot be attributed to the single-laser parameter—then you have bad stitching. In areas where there is a deviation from a smooth surface, the surface discontinuities can also cause cracks to form, depending on the load applied to it, which is critical to fatigue-relevant parts.

Q: Why is validation important when it comes to stitching?

There are two types of validation that we do at Colibrium Additive, validation of the machine and validation of the process.

We set up design of experiments (DOEs) for the many possible scenarios involving stitched and non-stitched parts at different build plate locations. This way, we have all the possible inputs that can influence the stitch part in the DOE. This is done over several builds and several materials and uses coupons and bars and subsections of actual parts to test the material properties.

Figure 1: Good stitching: 150-micron misalignment between lasers, special contour countermeasures.
Source: Colibrium Additive

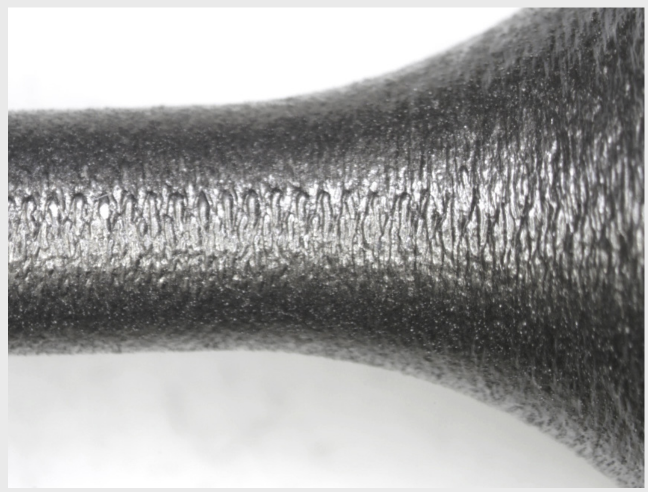


Figure 2: Bad stitching: 150-micron misalignment between lasers, no contour countermeasures.
Source: Colibrium Additive

We also create parts using certain misalignments to see how different misalignments affect the part quality. The DOE setups also allow us to see what the thresholds are for each part without using countermeasures so that we get the mechanical properties that are statistically the same as a single laser. This then allows us to understand what the machine misalignment capability is so that we can ensure that the customer gets a safely stitched part.

The second type of validation is for large parts, where coupons and bar results are not enough. In these scenarios, large parts are printed several times on the M Line with different configurations and settings, followed by heat-treated and non-heat-treated analyses. This allows us to see if the stitched regions come out in a satisfactory manner on a big-part level in terms of porosity and surface finish. This is typically a big endeavor and much harder than validating at the coupon/bar level.

Q: Should additive users be concerned about stitching?

It's a perfectly valid response to be concerned, because there's a lot that can go wrong if the right protocols are not in place. However, if your machine manufacturer can provide you with data and results about the mechanical properties of the part, including machine-to-machine and build-to-build variations, and show that there's no difference between a single-laser-exposed part and a multi-laser-exposed part, then there should be no issues, as long as the machine is calibrated within the acceptable threshold levels.

In general, customers should pay attention to the smaller features in their parts. Stitching gets more and more complicated the smaller the features and the thinner the walls. For example, on a heat exchanger, multi-exposure on very small areas, including misalignments, can lead to critical porosity.

Overall Outlook on Stitching

While stitching can be a hard process to do well, with the right care, protocols, and calibration efforts, the stitching is not as scary as many people think. Additive users do need to make sure that their machines are running optimally and are calibrated every 3-6 months, and by employing software countermeasures, can have a larger margin of error when it comes to the alignment of the optical systems.

Working directly with the machine manufacturer to ensure that all systems are running as intended, and before starting printing, additive users should ensure they have been presented with all the correct mechanical data that shows the stitched part has the same performance as a non-stitched part. With all this in place, there should be no worries regarding the mechanical properties of your printed parts.

If you'd like to find out more about how you can work with Colibrium Additive's engineers to ensure that you get the right stitching advice and data that fits your needs, **get in touch.**

Laser Anthology

08

Get the facts on optics

Maik Zimmermann

Senior Engineer, Colibrium Additive

Get the facts on optics

Maik Zimmermann, Senior Engineer, Colibrium Additive

There are many components within an additive manufacturing system that are critically important to ensure the printing of a high-quality part every time the machine is used. When it comes to laser powder bed fusion (L-PBF), optics are essential for ensuring the quality of the build.

We caught up with Maik Zimmermann, Senior Engineer, Colibrium Additive, to discuss the importance of optics within laser-based additive methods and how these systems are calibrated to ensure that a high level of part consistency is achieved, across the build plate, between batches and across different machines, when using high throughput systems such as the M Line.

Q: What is a typical optical setup for laser-based additive processes?

The energy source for the metal 3D-printing process is a single-mode fiber laser. The laser radiation is transported using an optical fiber, and the emitted cone is transformed to a low-diverging beam using a collimator. The key system of the optical train is the high-performance 3D scanner, which is used to steer the laser power across the build plate using a high-resolution, advanced full digtal motor control technology. The specific optical configuration depends on the product line, as each machine has a different setup and a various number of scanners. For example, on the M Line, we have four lasers and four scanners with 400W power level and ranging up to 1kW in future releases.

Optical components are very sensitive to dust and contamination, so the 3D scanners are located within an air-conditioned enclosure to prevent any level of particle build-up in the optical train. This is crucial to protect optical systems against harsh production environments to avoid degradation or damage of our high-quality components over time. Additionally, we spend a lot of time performing quality control inspections and measurements on all our optical components.

Q: What's the approach for calibrating multiple lasers, such as those in the M Line?

We have a special automated calibration process in the M Line and use a calibration plate that contains dozens of photodiodes and pinholes. Each of these pinholes has a microns-size diameter. The pinholes are arranged in pre-determined order with a very high precision, so they act as a reference for the calibration process. Using this process, we can calibrate single scan fields as well as multiple scanners —calibrating each scanner against each other.

The process is automated and the machine switches between the scanners during the calibration process, so the operator needs to start the calibration process only once. Using this calibration process and special scanpath strategies on the M Line creates a stable system that is very repeatable and enables debit-free stitching, even in terms of low-cycle fatigue properties.

Q: Which laser beam parameters can affect the build quality?

In L-PBF systems, the laser beam quality is very important for the lasing process. The laser quality factor characterizes the laser beam and how well you can focus the laser to a certain diameter. We typically have laser beam quality factors (also known as M^2 or "M squared) that are way smaller than 1.3. This allows for a focus diameter in the powder bed of 50 microns.

Another critical parameter is the spot size diameter control in the powder bed. The spot size accuracy is especially important if you want to process different materials, as each material will have its own set of parameters to work with, and the spot size required will be different depending on material selection and printed features. We usually use spot size diameters between 50 and 350 microns, with very small deviations when we digitally call different diameters during the build process to print various features.

When talking about the spot diameter control, the thermal focus shift must also be considered, since thermal lensing results in deviations in the focus position and the spot diameter depending on laser power. In our optical system a low thermal focus shift is guaranteed by the selection and quality control of the optical components.

The next influencing factor is the ellipticity of the beam, as you usually want a symmetrical, round spot and power density distribution. This way we avoid variation in line thickness at edges and ensure orientation agnostics of parts on the build plate.

Q: How is build quality influenced?

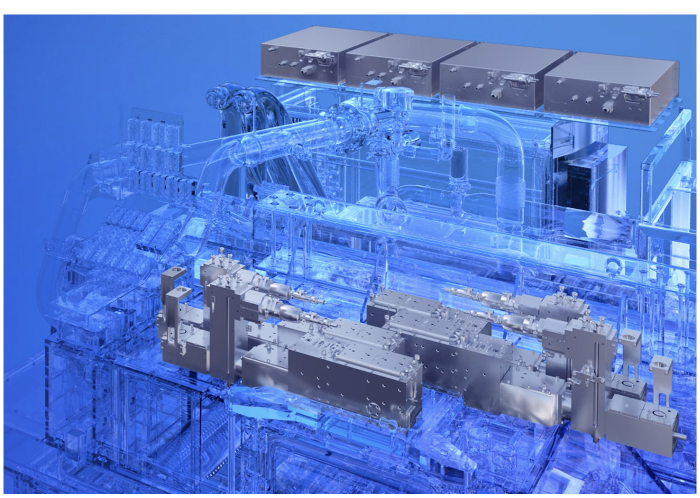
The stability of the laser intensity over time and the calibration of the scanners directly influence the quality and dimensional accuracy of the parts that we print. In addition, constant laser parameters must be provided at every point on the build plate. This is extremely important for the quality of the stitched zones in multi-laser processing, as you can easily see the effects of poor stitching on the part, such as a lot of surface roughness or poor dimensional accuracy. The laser beam quality and intensity directly influence the surface finish of the part. In addition, the mechanical stability of the part is of course very important. Pores negatively affect the mechanical stability, especially the fatigue behaviour. In order to ensure low porosity, a stable process control and constant laser parameters are necessary.

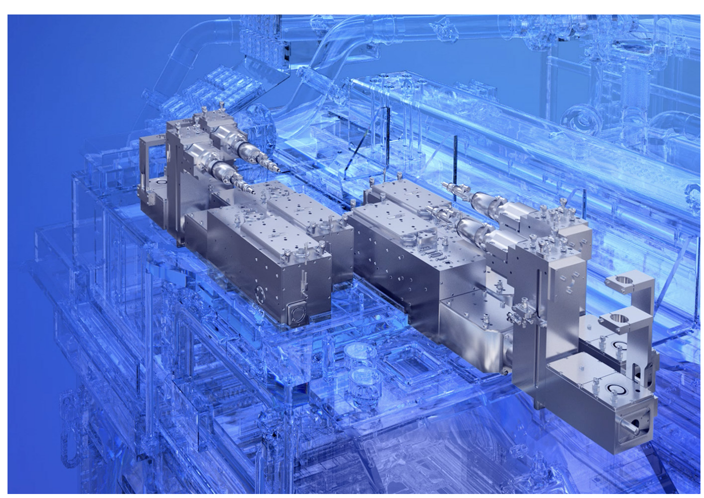
Q: How are these process parameters controlled to optimize the build quality?

The quality of the optical components is vitally important. Our optical systems are specially engineered for use in laser powder bed melting additive processes. So, we use specially designed high-power coatings and high-quality glass materials in our systems to guarantee that we can use a high laser power without debit in optical performance caused by thermal influences such as thermal lensing.

The cleanliness of the optical components is important, so we need to implement quality control measures to guarantee that we have no dust, contamination, or damage on our optical components. This ensures that we can achieve and maintain a good beam quality. On a system level, we need to implement a high level of thermal stability in our optical components. Our optics are usually cooled using either water-cooled or air-cooled systems so that we can guarantee a high stability over time.

Finally, we need to ensure that our optical components have good alignment with other sub-systems, because it’s not only the optics that are responsible for creating a high-quality part. We need good alignment with the thermal management, with the gas flow management, the recoater system, and finally the mechanical design and PLC/software that connects all sub-systems of the machine. The gas flow, for example is particularly important for





ensuring that the laser radiation is coupled properly to the metal powder and the process chamber window is protected from soot and other contamination. So, it is another key factor to guarantee a good build quality.

Q: How do we go about measuring and testing those key quality parameters?

Measuring and testing are some of the main tasks that are performed by the interdisciplinary engineering team during the development of a machine. We are very data driven, so we measure all the key parameters, and the system parameters (such as temperature and pressure) are monitored over time to learn about the machine's behavior.

We evaluate all our testing equipment using a Gage repeatability and reproducibility (GR&R) process. With this, we control and validate our measurement systems across multiple quantitative measurements, with one or more operators on multiple parts and on multiple machines. This is the first step to certify that our measurement process is stable and accurate.

For the M Line, for example, we are verifying our calibration process on a special pattern. We perform an exposure on a validation plate containing a pattern of concentric circles.

This pattern is measured with a coordinate measurement machine (CMM) to identify the single-laser and multi-laser mismatch. We then perform additional measurements at different power levels—from low to maximum power levels—to identify power stability, as well as the power stability over time. We also measure the caustic, spot size, and ellipticity using camera-based measurements systems for all power levels of the machine.

The approach we take allows us to obtain a very deep system knowledge of our machines and enables us to monitor the machines and their performance over time. We collect a large number of data points to ensure that the build quality and critical process or environmental parameters—such as the temperature of the optical components—are monitored and logged in our machines. Therefore, if we see any issues, we can go back into the log files and identify if there are any issues with the cooling or other system parameters. During the validation of the M Line, we collected, analyzed, and connected more than nine million data points from all the sub systems. This was a huge amount of data, but it was necessary to get to a deep system understanding of the machine.

Conclusion

Additive machines can create high-quality parts, thanks to the use of properly calibrated, contamination-free, and highly-quality optical components. For the M Line specifically, it utilizes fully digital, high-performance 3D scanners alongside a special motor control with a high spatial resolution that facilitates a high laser beam quality, high scan speeds, and a low drift.

As the metal additive industry scales and starts to look towards greater levels of industrialization and production scale-up, reliable and repeatable optical systems are going to play a key role in enabling additive high-volume manufacturing. Beyond this, another key aspect for ensuring a wider adoption of additive is going to rely on having a deep understanding of the machine itself (obtained through data, continuous monitoring, and statistical process control) and knowing a lot about the routine behavior of the machine, as well as what factors are going to impact the quality of the critical parameters.

To find out more how the M Line has been specially designed for larger scale production, or for more information about how high-quality optical systems can be utilized to create high quality parts for your application and industry, **get in touch.**

Laser Anthology

09

Get the facts on critical sub-systems

Mack Redding

Engineering Leader - M Line, Colibrium Additive

Jon Ortner

Senior Manufacturing Engineer, Colibrium Additive

Get the facts on critical sub-systems

Mack Reddingm, Engineering Leader - M Line, Colibrium Additive and Jon Ortner, Senior Manufacturing Engineer, Colibrium Additive

When it comes to additive manufacturing and printing a functional part, many people are still led to believe that you simply plug in the machine and away you go. But that is not the case, and there is an entire ecosystem behind the machine that comes together to work in unison. It is this coming together of critical sub-systems behind the machine that really enables high part quality consistently.

Understanding how an additive machine works requires a good understanding of fundamental physics. But beyond that, it is the validation of different systems, the collection of large amounts of data, and the interdisciplinary nature of the work that goes on behind the scenes of machine development that really enable an additive machine to be developed to its fullest. Mack Redding, Engineering Leader - M Line, Colibrium Additive, and Jon Ortner, Senior Manufacturing Engineer, Colibrium Additive, discuss the role that the different critical sub-systems play in additive to ensure that the machines are designed to be as reliable as possible.

Q: How do we define critical sub-systems and what are they?

One way to define which sub-systems are critical (and which are not) is by leveraging years of experience using the machines. Teams across GE are not just building additive machines and systems, but our businesses are also using them on a regular basis. This has given us a deep insight into which sub-systems affect the quality of the parts. There are some obvious areas—such as z-axis, recoater and optics—that were identified early on, and you really need those three to work together to get a high part quality.

There are also less obvious sub-systems—including the gas flow, software and parameter sets—that have now been defined as a part of the critical sub-systems but are not a part of the machine itself. These three areas also need to work closely together, because you need to ensure that you get a good gas flow, your software is controlling all the other systems together properly and that you're thermally controlling the process via the thermal control sub-system. You can design the other sub-systems to get a good part quality, but you need that thermal control on top to make sure all the critical sub-systems are working together as they should.

Beyond having years of experience, if you can understand the fundamental physics of the solidification process of the material and what you need to enable that, then you can define which sub-systems are critical. The years of knowledge that you gain are based on a good understanding of the fundamental physics of the problems, and this in turn translates to better understanding the sub-system design and sub-system control.

Q: How do we ensure that we have the correct machine design for each of those critical sub-systems?

When you understand the physics of what is going on, you can better leverage all the tools you have at your disposal. For example, we took this approach to make sure that our gas flow is consistent across the full platform and the complete build height. Before we went and produced the M Line, for example, we undertook a considerable amount of computational modeling of the gas flow. We then modified the machine and design space multiple times, so we really optimized the inlet/outlet design and the shape of the process chamber to obtain a good physics-based gas flow system design. Once we had a good design of the gas flow, we tested it on a test rig and verified the models before we integrated and tested on a full machine.

Computational fluid dynamics (CFD) modeling allows us to conceptualize different ideas quickly about how we want the gas flow to look, which for us, is avoiding any recirculation zones in the process chamber and achieving a high-speed flow across the top of the powder bed. It also goes beyond this, as well, into regulation validation, sub-system validation and full machine validation, as well as the validation of third-party suppliers' components. All the components we use are validated in both our new machine validation process and in the production process of every machine. We focus on designing the right machine to ISO and ANSI standards, even if it might take a little bit longer.

Q: How do you verify that the machine is within those specifications?

At the end of the whole process. You perform your initial modeling design and that determines how you will build your test rig. You then test the sub-systems and the modules, and you test the z-axis and recoater by themselves. This is the first step for collecting the data to show that the sub-system design is what it's expected to be. After that you move onto validating the full system.

We learned a lot from the M2 machine and took a learning-based approach to the M Line. We made sure that we consistently tracked all the critical measurements from all the critical sub-systems over a defined test plan. The test plan lasted a year and we tested multiple machines. This resulted in over 9.3 million data points, which allowed us to adopt a Six Sigma-driven approach when checking our capability limits.

We perform due diligence across the validation and testing protocols, and this continues long after a product is launched. We also test every machine before it leaves the factory. Once it's in the field, there are elements that are re-verified as part of the installation process.

Q: How do you verify the corner case of the sub-systems when they're at the edge of their limits?

It is something that you do within the general testing to make sure that the machine is within specification. There is always going to be some degree of manufacturing variability, and there is the potential that all your sub-systems are going to be at the edge of what is acceptable. So, we ensure that even when all the sub-systems are at the worst-case scenario, users will still be able to get good results.

One of the main ways this is achieved is during the parameter development process. When we develop the parameters (be it spot size, laser speed or laser power), we not only develop them at nominal conditions, but we also test at boundaries outside of the ideal conditions. So, we check the parameters at increased and decreased spot sizes, various layer thicknesses and various gas flows. When we develop a parameter set, we want to make sure that it is still stable, near a boundary edge of the machine, and it can withstand the variations that the machine could throw at it because of manufacturing tolerances.

> The work we do is possible only because of the interdisciplinary approach across the sub-systems and with teamwork across all functions of our business.

Q: So, after all this, are the results worth it?

Yes. It's a lot of work to do the due diligence up front, but then we saw from those 9.3 million data points that you could put two machines next to each other and make them do the same print and get the same high-quality results. Many of the test engineers' comment on the quality of the parts that come out of the machines as well as the reliability from machine to machine and build to build on the same machine.

For multi-laser machines like the M Line, we're seeing great stitched regions. With all the sub-systems working together as we've designed them, coupled with the stability of that thermal system and good parameters, we're getting extremely high-quality material results and geometry results in that stitched region, and in single laser results. That quality is worth the effort we put in. The ability to see the quality parts that we can do on the M2, and then seeing that level of equivalency or better on the larger format size, is something that you don't see on other larger formats on the market.

The M Line has already been a success with our early customers, such as Erofio. They now have the ability to deploy their system quickly and drive production outcomes, thanks to the validation process in place. Erofio has already been able to do great production work with their 500 builds. They've been able to come up to speed without any significant challenges or the need to contact the services/engineering teams for support. This is where the proof is, and it is worth it.

Q: What are you and the team most proud of?

All the leaders of the critical sub-systems and ourselves agree that the ability to get a beautiful part as the end product and the interdisciplinary approach at Colibrium Additive are the two things that we are most proud of. The work we do is possible only because of the interdisciplinary approach across the sub-systems and with teamwork across all functions of our business. The results we get are not achieved by just obtaining a good z-axis. You do this by making sure that your software, parameters and machine all work together with the customer in mind.

Another proud moment is the response that we've heard from our colleagues at GE Aviation. GE Aviation has experience in running different large-format machines and the response that we received about the M Line's ability to produce high-quality parts on the first try has been excellent. The initial thought was that some of their parts couldn't be printed at all, never mind to such a high specification. Beyond aerospace, our work with Erofio is another source of pride. We were able to transfer a parameter set from the M2 Series 5 onto the M Line relatively easily—which is what we designed the machine to do.

Overall Outlook

Additive technologies are rooted in the fundamental physics of the process, regardless of whether the method is laser-based, electron beam-based or binder jet. The ability to understand the physics behind the process enables us to control the manufacturing environment of the print, including controlling the machine over time (between calibrations) and determining which sub-systems are critical for designing a machine that consistently produces high-quality parts.

The validation of the machine, its processes and the sub-systems in use doesn't end with the design. Machines undergo continuous testing and validations, allowing us to make more iterations to machines, as well take our learnings to continuously improve and create better machines. The validation of our machines continues once they are out in the field, and we use this constant flow of data to build the next generation of additive machines.

If you'd like to find out more about how our different sub-system teams work together to deliver results to our customers, or how the M Line can support you in scaling up your manufacturing processes, **get in touch**.

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Laser Anthology

Get the facts on material performance

Dr. Johannes Stroessner

Principal Engineer & Sub Section Manager, Colibrium Additive

Get the facts on material performance

Dr. Johannes Stroessner, Colibrium Additive

Material performance is a broad term that means a lot of things to a lot of different people. No matter how it is interpreted, we work with our customers (additive technology end users) to ensure that they are getting the right level of material performance for their intended part and application—regardless of whether that is porosity, a high surface finish, or specific mechanical properties.

The mechanical and technological needs of a part differ from application to application. So, a customized and tailored approach to the material performance of a part is needed for every customer at Colibrium Additive. We caught up with Johannes Stroessner, Principal Engineer & Sub Section Manager - Process & Application Development, Colibrium Additive, to discuss what material performance means to different users.

Q: What do our customers understand by the term 'material performance'?

I hate to use the standard engineer response, but it really does depend, as material performance is a broad and diverse term. Each customer has its own application in mind and a part performance that they want to achieve. We have more advanced additive customers, such as GE Aviation, which has established design curves with very clear and measurable requirements with a strong focus on the mechanical properties, so that they can operate their parts in a safe manner.

We have other customers that are using additive for applications for which they are less concerned about mechanical properties and more focused on the productivity and availability of the printing process. Others might be primarily concerned about surface finish – they just don't want to spend a long time post-processing the part to get a shiny surface.

So, it's dependent on the customer. To develop a parameter with the suitable material properties, it's important to listen to the needs of each customer. Some customers still need guidance on what they want and need—they have an idea or application in mind, but they can't give a specific property level that they want to achieve. It's our job to translate their needs and what they understand as material performance into requirements for the printing process and actual values that we can measure.

Q: Why does Colibrium Additive care about the performance of materials?

Because it's the material performance that often drives the decisions of the customer. We have some customers who don't ask for specifics about the machine, such as how the optics and gas flow are set up, and they would rather ask 'Can I process and manufacture my part successfully?' It's not typical that a competitive assessment of the achievable material properties is a major factor in the decision-making process for a machine purchase.

In these cases, we need to ensure that we have the ability to understand and show customers what we are able to achieve and can offer to the market. Therefore, it is important that we run parameter development programs and extensive material characterization programs.

By doing this, we also learn about the gaps and needs in our systems, and this information can be fed back to the hardware development team. This is essentially the driver for how we develop the machine hardware, as well as understand where we can continuously improve the hardware to obtain an improved material outcome.

Q: There's an intersection between stability and material performance. Can you go into a bit more detail about that?

When you start to move from successfully printing a prototype part one time to the point where you are scaling production and need to process the same part hundreds of times, stability and robustness become very important factors.

Stability can be thought of in many ways. On one hand, you have the machine side of things with the gas flow, optics, and components that come with certain manufacturing variations and influence the part quality in the end. On the other hand, you have the platform, where factors like the gas flow, recoating direction or the position of the scanners are potential sources for variation across the platform. You need to ensure that the parameters you are operating the machine with are robust enough to handle those factors so that we can guarantee the same level of performance across the whole platform.

If we can guarantee performance for one machine, the next step is to ensure the quality level for multiple machines and multiple builds. This is when we need to be able to exactly understand how hardware component variation is influencing material performance and how to deal with it, as well as other influencing factors, so that the performance in the end is in line with customer expectations and requirements. We have multiple approaches to ensure that the parameter sets created during the development process are able to withstand those variations.

Q: What approaches for parameter development do we have in place?

For developing a successful and robust parameter set, the first thing we need to do is understand the requirements of the customer. This involves translating those general requirements into actual values you can measure. We then start our development process by performing design of experiments (DOE) while considering the variation of the machine and other influencing factors.

Colibrium Additive has extensive knowledge about the influencing factors and how much they could affect the print, so during the development process, we not only develop the parameters to a certain nominal point, but we also go beyond to understand the wider process windows. By doing this, we understand at which calibration point or parameter adjustment we will see a significant drop in material performance.

At the end of a parameter development, we do confirmation builds during which we check the performance of the parameter one more time. In those tests, we check to see if the properties of the parts are still good across the whole platform if we misalign the parameter set or machine within certain ranges. If this is the case, then we release the parameter set and make it officially available for that machine. We have recently added the results of platform stability builds (one part of the confirmation checks) to our data sheets, so anyone can see the amount of expected variation across the platform of our machines.

Q: How do you deal with data in respect to parameter development? How important is that data?

Data is important, as it guides us to make a decision to ascertain whether a parameter set is robust enough.

You also need to test in a way that the results are significant and that you can easily tell from the data if your assumptions are correct or not. Then there is the variation to account for. For example, powder is a source of variation, where the powder size distribution (PSD) and the chemical composition of the powder slightly differs. This will affect some of the properties of the part even though this variation does not affect the machine in any way and the parameters remain unchanged.

By capturing the data in a strategic way, and by understanding how different factors drive variation, we can understand what kind of non-machine variation parts can be expected and how we can accommodate that variation during the parameter development.

Q: Could you talk about variation in the context of stitching?

Stitching is important. Stitching is when multiple lasers come together and expose one part. So, when you have a region in the part where both lasers come together, you get stitching. From a dimensional, surface, and mechanical property perspective, it's important that the lasers work together in an accurate manner. The machine hardware can help to guarantee seamless stitching by making sure that the optical systems are well aligned.

However, as I mentioned, there is always some variation within a machine. So, you also need to understand the material answer to a potential misalignment—that is, what happens to the mechanical properties or the porosity of the part when there's a misalignment. If you can understand both sides—the material answer to a misalignment and what the machine can deliver—then you bring both pieces together to achieve a good stitching outcome that fulfills the customer's requirements.

There are also some mitigation techniques that can be employed during parameter development to reduce the effects of misalignment and achieve a better part performance. For example, measures can be taken to achieve a better surface quality in the stitched zone. Of course, outputs that we generate on the material side also feed into the solutions on the hardware and software side of things.

Q: What are some of the typical performance criteria and/or properties that you measure?

The properties that we typically measure and analyze for are porosity, mechanical properties, tensile, elevated temperature tensile properties, and surface quality. For enhanced applications, we also look at dynamic mechanical properties, such as fatigue testing. We also characterize the microstructure, analyzing the morphology of the defects, grain size evolution and the isotropic behavior of the material.

Q: What's the basic level of material characterization that you perform at the end of the parameter development?

Whenever we release a parameter set, we have static mechanical property data across the whole platform, as well as the surface roughness properties (upside, downside, vertical wall, various geometric features), the porosity of the part and etched micrographs of the part's microstructure. This data is not only on the nominal parameter set, but the whole parameter window. This is the standard and is what every customer can expect from a Colibrium Additive parameter set.

Q: Can you describe a more complex scenario when it comes to material performance?

The more complex a requirement set becomes, the more chance you have of getting conflicting requirements. For example, there is no parameter set that will deliver a super-high productivity and the best material performance. So, it is important to stay in close contact with the customer and include them in the development process so that they are made aware of any potential trade-offs that they may have to make.

So long as the trade-offs are based on data and that there is no other viable solution from an engineering perspective, then we can work together with the customer to find the optimum parameter combination and the best trade-off which still fulfills their requirements.

Our work together with GE Aviation on their applications is increasingly complex. To manage that complexity, Colibrium Additive developers both in Lichtenfels and in the US work alongside developers from GE Aviation. We review the results together at least once a week, make the decisions together and decide on the best outcome.

Material properties are one piece of the puzzle. You are working with complex parts, and we do not necessarily know which of the features within the parts are the most important ones. So, it's beneficial to have customer input so we can determine on which coupons and segments we should print on a small level before printing on a larger scale and ensure we are headed in the right direction.

Overall Outlook

Material performance means different things to different people, and there is no one set answer for what material performance is. For one additive user, it might be a high surface finish; for another, it might be a high fatigue strength. So, we cannot underestimate the importance of listening to customers to find out what material requirements they need for their intended application.

Developers and users should always understand material performance from a broader lens to ensure the parts you are printing are able to deliver material performance in a robust and stable manner.

Therefore, the machine and material performance shouldn't be differentiated as they link together. Understanding this link during process development is key to understanding how you can improve material performance by adjusting the machine by changing the hardware.

If you'd like to know more about material performance or find out how one of material science experts can help to find the best solutions for your application, **get in touch.**

Laser Anthology

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Get the facts on the mechanics, geometries and physics of large additive parts

Rob Dean
AddWorks Leader in EMEA, Colibrium Additive

Get the facts on the mechanics, geometries and physics of large additive parts

Rob Dean, AddWorks Leader in EMEA, Colibrium Additive

Metal additive parts for commercial applications come in all shapes and sizes, and since the introduction of our M Line system, critical parts can now be made accurately on a much larger scale. One of the lesser talked about technical areas within additive is how the mechanics, geometries and physics of the build can affect the outcome of the part.

From a purely physics standpoint, there is no technical difference in the effects that are observed during a build based on if the part is small or large, but there can be visual and geometric differences with larger parts because the dimensions can make the differences more significant.

Rob Dean, AddWorks Leader in EMEA, Colibrium Additive, discusses the role fundamental principles play when making a part, how these are manifested in larger parts, and how any potential issues can be tackled.

Q: What's different when printing a large part? Are the physics the same?

The physics are identical regardless of whether a large or small part is being printed, and the terms large and small are subjective anyway. The physics are also the same if you're using one laser or four or if you're using a 100 mm or 500 mm build platform. Similarly, the layer-by-layer physics and the scan- path physics are also identical. There are no new skills that one needs to acquire to be successful when printing large parts.

Q: Why is noise made about large parts?

It is because when you have larger parts, they are dimensionally bigger. So, a relative movement and growth of 1% when something is 10 times longer equals a 10 times absolute difference.

Accuracy is an absolute measurement, so you may have the same measurable movement on a large and small part, but the absolute movement will be much greater on the large part. You also need to control the large parts to a smaller relative movement to achieve the desired result.

While the physics are the same, you do need tighter controls for larger parts. The small percentage deviations that you might be able to get away with on mid-size machines, you can't get away with on the larger machines, and these can become problems if you're not aware of them.

It is worth mentioning that these larger absolute differences are not machine driven; they are driven by the part itself. If you put a small part on a larger machine, you will get the exact same result as on the smaller machine.

The larger movements come from the mechanics of the part itself. So, as the part gets very hot, layer by layer, it grows in size. Similarly, as you cool it, it shrinks a little. This is not linear and the amount the part changes differs from part to part. We can apply linear scaling on the machines used, but any non-linearities that cannot be dealt with at a machine level are driven by the part and need consideration by the component or build job designer.

Q: How do we help our customers to scale up from the mid-size machines to the larger platforms, while ensuring that the physics of the new printing scale aren't causing issues?

Our M Line build platform is essentially four of our mid-sized M2s. So, if you put the same part four times on an M Line, you can expect nothing to be different. If you're trying to make a part that is four times bigger, that is where the absolute values will make a difference.

The forces that come from the process - such as heat input and cooling during the process - can cause it to grow non-uniformly, so they need to be considered. As larger parts attempt to distort, the greater forces that arise from this process in the part can also cause cracks—in the part or the build plate—causing the parts to pull off the build plate, or pull up during the printing process and hit the recoater blade. So, it is not just the distortion of the final, cooled part the build job designer must consider.

However, those users who are looking to deploy the M Line tend to be experienced users of additive and already have an application in mind. We can look at their parts ahead of any issue manifesting itself and help them understand where the focus should be in terms of preventing the issue. We can also help to develop appropriate solutions—all before the machine leaves our factory.

In this process, we look at the root causes of any issues in their part or build job—be it heat build-up, stiffness of the part, or non-linearity of shrinkage—and explain how we can mitigate these effects. This fundamentally boils down to managing the heat during manufacturing or physically constraining the movement during either heating or cooling.

We work directly with our customers to find the best solutions for them. There are several tools they can use—such as adding supports, tuning the heat input, or compensating the geometry—none of which are new concepts, and a solution typically involves utilizing several of these tools. This involves finding the best mix between addressing root cause and treating the symptom, depending on the part's technical, quality and business-case requirements.

Q: Are we applying our learning from the aerospace sector to ensure that the M Line is ready for widespread commercial use?

Our machine development team, design engineers and the simulation team at Colibrium Additive have been working closely with the GE Aviation product and manufacturing teams to deliver user-driven developments and solutions for the M Line. In conjunction with our colleagues at GE Aviation, we use common tools to understand the challenges and mitigate them.

Working with the GE Aviation team has allowed us to talk a lot more about the process, because they have significant experience on mid-sized platforms, as well as component and product functional requirements. Bringing this directly into our working relationships has ensured the M Line can target real-world requirements.

For example, working with the simulation team, we can look at how the heat comes in during the process and adjust the parameters and supports and adjust the build job to ensure we get the results the part needs. This has driven us to develop a machine platform that enables the end results to land within the required quality window.

Many additive users still develop their production process by printing parts to see what happens. While that trial-and-error approach is fine on a mid-size platform, it is too costly and time consuming on a large platform. However, because our platform is designed to operate in a specific way, and to control the process to the same part requirements we previously developed for our M2 platform, we can realize much of the development work on the smaller, faster, and lower-cost M2 machine. On the M2, we can validate any issues and their root causes and introduce any corrective actions. Once a solution is in place, we then print the part on the M Line.

This is important as the M Line is not a development machine, it's a production-focused system and you want to bring mature work to it.

Working with our colleagues at GE Aviation, and having that very strict user-driven view of machine development rather than the machine developer's view has helped us deliver a consistent user experience between our platforms. The ability to transfer between platforms hasn't been possible before, and because the development is user-driven, we can transfer the parameters from an M2 to an M Line without having an enormous transfer exercise.

Q: There are comments around that a thicker build plate (10 cm or more) ensures better part geometry at large scale. Is there any merit in this?

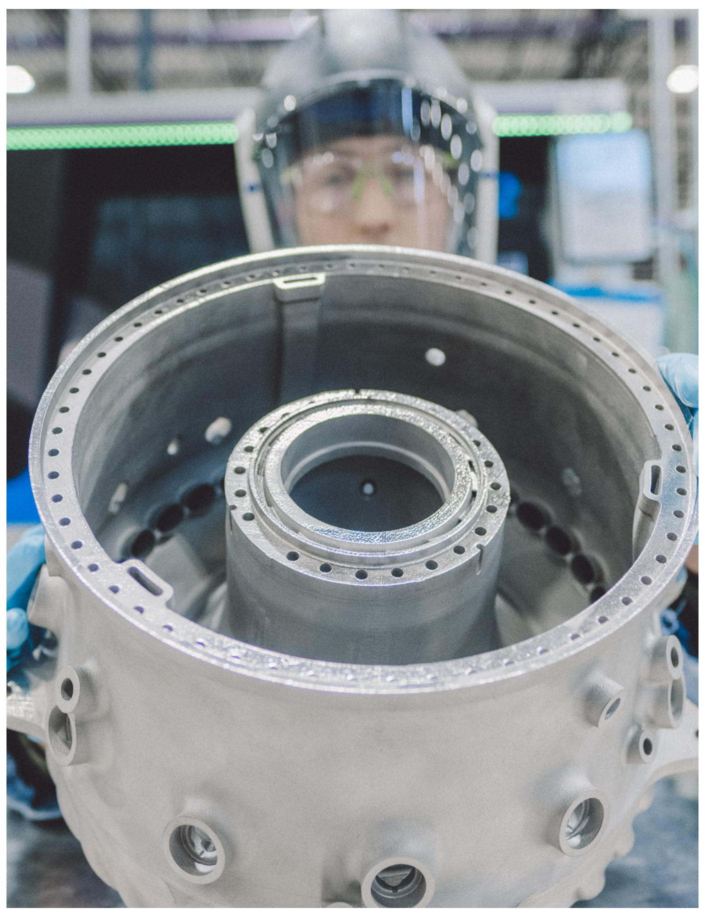
There is some merit in it. We know from our X Line and some mid-size platforms that if you put a big part on the build plate (relatively speaking) and increase the relative stiffness of the part versus the stiffness of the build plate, then it can pull up the build plate if you do not manage the heat build-up in, and residual stresses from, the part.

The build plate is essentially stiff but still has some flexibility. As the forces increase with the increase in part size, if you don't manage those forces, you can end up with forces that want to cause a certain distortion and a part stiffness much greater than your build plate stiffness. This can subsequently distort the build plate. One solution is to increase the thickness of the build plate to 10 cm or more. However, this a very costly solution and not sustainable for commercial manufacturing. While valid, we have never had to resort to this solution and do not expect to in the future.

A better, more cost-effective solution is to use simulation software to understand where the distortion forces are coming from, understand their root causes, and subsequently mitigate them.

Plate distortions are something to be aware of and exist just as much in mid-sized and small format platforms, but it doesn't stop us making parts. In some cases, you adjust the build job design to manage and control the heat. In other cases you change the geometry of the part. It is something that we work with our customers on to find out the exact needs to stop it from happening during their build, without the need to buy a costly build plate.

By working with our colleagues at GE Aviation and having that very strict user-driven view of machine development, rather than machine developer view, has helped us deliver a consistent user experience between our platforms.



Q: How do we ensure that larger parts aren't affected by the larger absolute physics values?

You need to be aware of the physics going on when you make your part, such as how the heat is coming in during the build and how you're managing that with the supports. If you can keep it uniform throughout the build, there will be no major issues beyond those that have been acceptable on a mid-size platform. But it does need consideration and thought.

The difference between the M Line and the M2 is that you need to consider the physics all the time. For example, in large builds, supports play a larger role than just manufacturability, as you can use them to manage any thermal gradients in the part where the hot and cold regions meet.

The main point is that it's not the machine that can cause issues, it is the part itself. The M Line is easy to use, because it builds large parts in a predictable and repeatable way—due to its uniform gas flow—so any simulation solutions can be integrated easily.

Overall Outlook

While the mechanics, geometries and physics of larger parts need to be considered to ensure that you don't run into unexpected issues, they are not driven by the machine but by the part itself. Each part will behave differently. The best solution to tackle any issues is on a case-by-case basis using a combination of technical results and a business case that is unique to your part and application.

One of the key things to note is that there is nothing new here, and these are phenomena that we see at all build scales. We see it, understand it, and control it on the M2 and because the M Line is a user-driven extrapolation of the same requirements that drove the development of our M2, we can do the same at larger scales. We're just working with larger absolute magnitudes.

If would like to know more about how our technical teams can support as you scale up on your additive journey? Get in touch.

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Laser Anthology

EROFIO Group prints first part on Laser M Line system

Shaun Wootton,
External Communications Leader, Colibrium Additive

EROFIO Group prints first part on Laser M Line system

Shaun Wootton, External Communications Leader, Colibrium Additive

EROFIO Group – an industrial molding sector company and long-standing user of Colibrium Additive's DMLM laser technology - was selected to test and put Colibrium Additive's Laser M Line through its paces ahead of its commercial readiness later this year.

Less than three months since receiving and installing an M Line system at its 6,500 sqm mold-making facility in Batalha, central Portugal, a team led by EROFIO Group's metal additive manufacturing leader, Luís Santos, has successfully 3D-printed its first mold core.

The core was manufactured using M300 hot work tool steel – a material often used for the production of injection molding and die-casting tool inserts with conformal cooling, as well as functional components. The core contains more than eight independent, internal conformal cooling channels, stretching over eight meters in length and between five to eight-millimeters in diameter.

Additively manufacturing the part affords the team the design freedom to enable conformal cooling to create a more efficient heat exchange. This improved cooling will increase the overall plastic injection process productivity through decreased cooling cycle time and warpage, and the improvement of the injected plastic part aesthetics.

In addition to the benefits of geometric freedom on the design of inner channels, using additive manufacturing has reduced finishing requirements by 90%.

90% reduction in finishing requirements

Another advantage identified, when compared with conventional manufacturing processes, was a reduction in the total manufacturing time -- from powder to mold assembly -- by 30%.

Three months from installation to first print

Santos and his team, already experienced users of Colibrium Additive's Laser M2 system, opted for an existing parameter – developed for the Laser M2 Series 5 – and made only very minimal changes in order to adapt it for the M Line system.

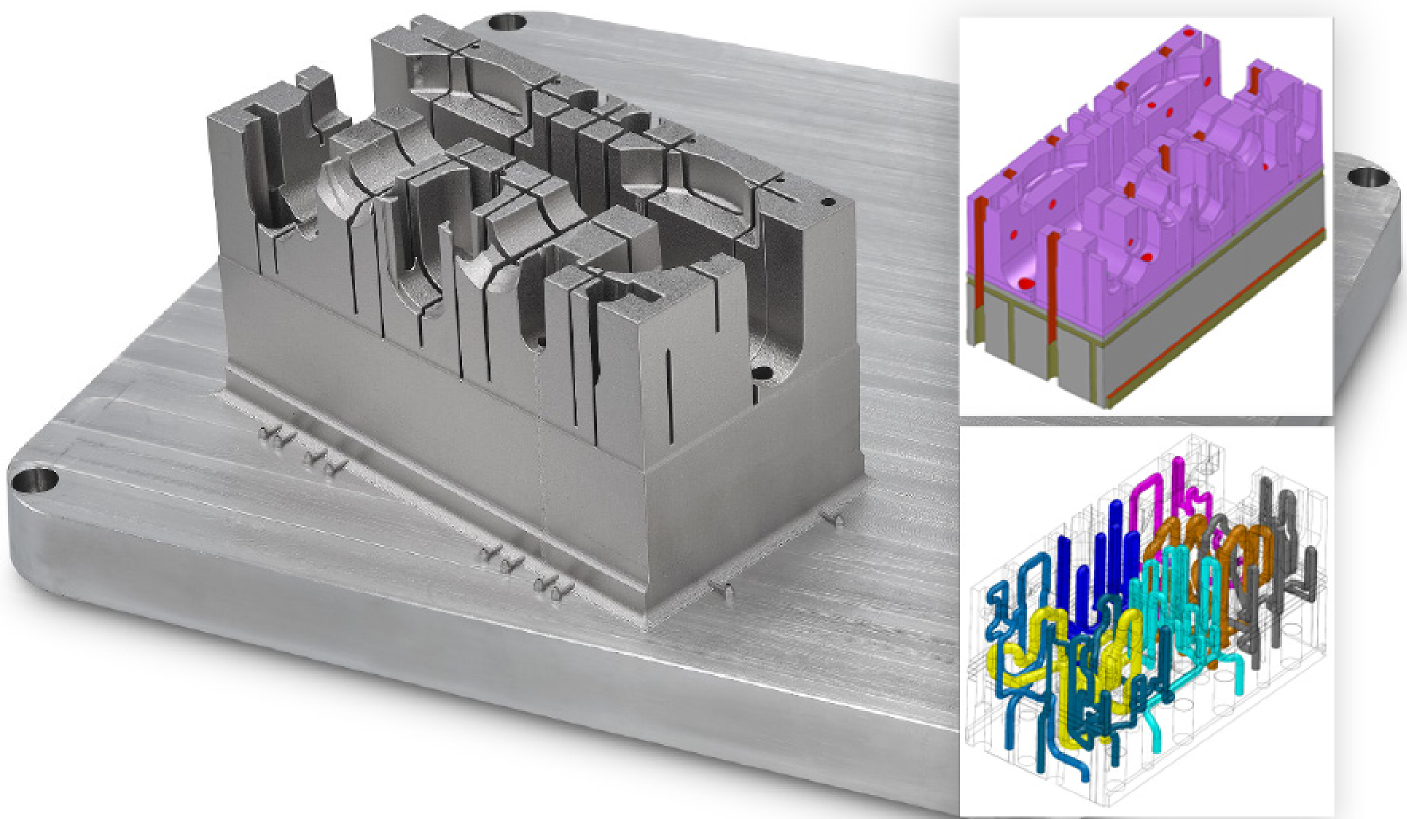
Following remote optimization support from the Colibrium Additive team in Lichtenfels, the part was successfully printed on its first attempt, over a six-day period in May 2021.

"We are honored to be part of Colibrium Additive's thorough commercial readiness process. We're learning a lot from them and I think it's safe to say they are learning a lot from us and our first impressions working with the M Line. Having the first part come off our system is great a milestone and we're looking forward to supporting the wider team as the solution comes to market and beyond," said Luís Santos, EROFIO Group.

"We have a solid working relationship with the team at EROFIO that goes back well over a decade. As we near a critical phase in commercializing the M Line system, we specifically sought out a trusted partner to gain early installation experience, data and honest customer feedback," said Wolfgang Lauer, Laser M Line Product Manager, Colibrium Additive.

“We fully expected the first part to be printed on the M Line to go well. And when it did there was a rush of excitement felt across the entire team here in Lichtenfels. Work continues here in Germany on the M Line, ahead of the launch, and we will factor in additional feedback from the team at EROFIO,” said Jan Siebert, General Manager, laser technologies, Colibrium Additive.

“It is critically important that when Colibrium Additive brings new solutions to market, it can tangibly and immediately demonstrate business impact. Our M Line system operates at higher levels of reliability and repeatability, meeting customers’ needs from day one. This is not a science experiment and we are not developing laboratory equipment. Overly ambitious claims and incomplete specifications in other vendors’ product launch announcements only serve to undermine the trust that our wider industry has collectively built in metal additive technology in recent years,” he added.



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Laser Anthology

US Air Force and GE reach next milestone in Pacer Edge Program

Shaun Wootton,
External Communications Leader, Colibrium Additive

US Air Force and GE reach next milestone in Pacer Edge Program

Shaun Wootton, External Communications Leader, Colibrium Additive

Building on the earlier success and momentum of the Pacer Edge program, the US Air Force (USAF) and GE have entered Phase III of its metal additive manufacturing pathfinder. This phase tackles the USAF's sustainment behemoth of 'cold starts' head-on.

Aircraft engine components that are considered 'cold starts' are parts that take over 300 days to procure. It is estimated that the USAF has over 800 engine 'cold starts' each year.

"The first priority, for the USAF and GE team has been to create digital 3D technical data packages (TDPs) for hard-to-procure, obsolete 'cold start' parts and deliver four airworthy, near-net castings. These TDPs will eventually mean that part obsolescence will be a thing of the past," said Alexa Polites, USAF Pacer Edge program manager, Colibrium Additive.

Over the coming years, the joint USAF and GE team plans to create at least five TDPs, increasing in technical complexity, across the USAF's sustainment platforms.

"The teaming of GE and the USAF legitimizes utilization of additive manufacturing to address critical needs of the aging aircraft that are currently unsupported within the existing supply chain," said Zack Miller, Chief, Advanced Manufacturing Program Office, Air Force Rapid Sustainment Office.

"Pacer Edge is accelerating the USAF's widespread adoption of 3D metal printing to organically solve supply chain shortages and realize its promise to improve warfighter support by drastically reducing lead times and creating additional sourcing options," Beth Dittmer, Chief, Propulsion Integration Division, Tinker Air Force Base.

Phase III has already successfully printed two components, a bellcrank and a cross shaft arm, in cobalt-chrome on a Laser M2 Series 5, located at Colibrium Additive's facility in Cincinnati, Ohio. Work has also progressed on additional components using Alloy 718.

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The cornerstone of the USAF / GE Pacer Edge program is the creation of organic capabilities at Tinker Air Force Base (AFB). One way to achieve that is by ensuring that intellectual property generated within the Pacer Edge program is owned by the US Government. This will enable the USAF and Department of Defense to print these parts themselves in the future. The program remains on schedule with the goal to have airworthy production castings delivered to the USAF in Spring 2022.

"In parallel to the TDP creation, Colibrium Additive is working closely with our USAF peers to transfer the production capability to the Tinker AFB Depot. This will establish an organic, airworthy, metal 3D printing capability for the USAF," said Joe Franzen Jr., technical account manager, Colibrium Additive.

Laser Anthology

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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

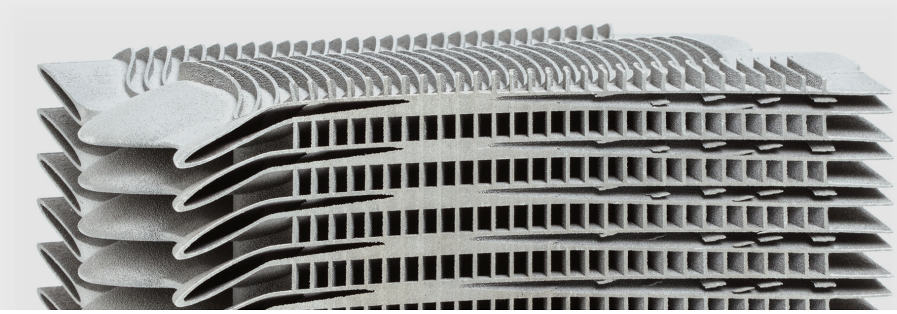
Determine the ROI
Based on your business goals and in-depth cost, performance and supply chain data you gathered, run a final ROI analysis using a spreadsheet and data for your company. Does additive make sense for this business case?

- 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 hit the production floor running.
To turn complex into a competitive advantage.
To turn a business case into a full-scale production at the speed of today.
To look forward, not back.

When you're ready to revolutionize your business with metal additive, the people who pioneered its full production are ready to help.

Let's go. Talk to Colibrium Additive today.
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