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DIRECT MANUFACTURING

3D PRINTING & ADVANCED MANUFACTURING

ADVANCING THERMAL MANAGEMENT WITH ADDITIVE MANUFACTURING

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INTRODUCTION

Thermal management is an integral engineering element across a variety of major industries, including electronics, aerospace and automotive.

Maintaining acceptable temperature ranges can require complicated techniques and components, depending on the application. Additive manufacturing (AM, aka 3D printing) offers a unique solution for next-generation thermal management. With unmatched design freedom for nonlinear geometries, 3D printed parts can increase performance and reduce the size and weight of thermal control systems.

WHY CHOOSE AM FOR THERMAL MANAGEMENT?

Additive manufacturing is not as mature as casting or traditional milling operations, so why choose AM for a thermal management application? The next generation of thermal management devices across most applications needs increased performance without pressure loss. These devices also need to be affordable, and if possible, modular and scalable.

The design freedom provided by additive manufacturing, and the potential performance increase achieved through design optimization, is a major advantage. AM provides a tool-less process; the manufacturing constraints and tooling costs typical for subtractive and multi-part assembly operations are eliminated. In addition, cost does not scale with complexity with AM. Design freedom enables the implementation of nonlinear, tapered and optimized variable geometries in extended structures like fins, vanes blades, capillary wicking structures, heat pipes and conformal internal passages.

A byproduct of design freedom is part consolidation. This has been traditionally achieved through investment casting, which requires expensive tooling and can result in weaker mechanical properties. AM enables greater design freedom than casting, without tooling costs, and produces near-wrought properties. Significant weight and space savings can be realized, resistance between components eliminated, and product assembly times can be reduced. Reducing the number of parts produced can shorten product assembly time, save money, and reduce weight.

In the development cycle, AM enables easy iteration throughout the design, build and test processes. In the production stage there are significantly reduced lead times and a simplified supply chain. Additive manufacturing allows complex tools to be built on-demand, with designs based on functionality, not on cost or lead time. In addition, a digital inventory can be amassed and new tools can be printed on-demand instead of holding on to expensive, outdated parts and equipment. This digital inventory reduces physical inventory, freeing up storage space and lowering overhead costs.

AM applications for thermal management exist in various stages of the product development life cycle.

Starting in prototyping and design phases and moving into production parts, engineers can take advantage of the benefits of multiple AM technologies throughout product development.

Proof-of-concept validation is performed in the design and prototyping phases with additive plastics and metals. Concept models can be printed quickly, sometimes within hours, helping engineers validate designs quickly, and move onto new iterations within days with technologies like PolyJet, FDM, Stereolithography or Laser Sintering. Less expensive than conventional manufacturing methods, PolyJet can print in full color and high resolution. These models are a unique opportunity for visual heat flow analysis with heat maps representing directional airflow within complex geometries. The proof-of-concept models also enable effective communication of the business value and product benefits of these devices.

Proof-of-concept models 3D printed in color plastic and metals help validate designs quickly.

Direct Metal Laser Sintering (DMLS) is the type of Direct Metal Laser Melting (DMLM) technology that Stratasys Direct utilizes for metal applications. DMLS parts are strong, durable, and thermally conductive, ideal for thermal management projects in the prototyping and production phases of the life cycle. The accurate metal printing process provides tough functional prototypes quickly, as well as complex thermal management production parts. DMLS has manufactured several key thermal management applications, as detailed below.

Integral regenerative cooling of rocket engines has been standard since the 1960s and 1970s, but the ability to integrate conformal channels into a rocket nozzle and produce this as a monolithic component is impossible without an additive process. For passive heat pipes used in long-range space applications and small satellites, optimized wicking structures that cannot be made with traditional processes could be implemented with AM. Nonlinear heat pipes can also be created with the structure inside it, enabling AM to print curved and angled heat pipes. Microchannel and jet impingement strategies also are applications that can be optimized using AM for microelectronic device cooling.

Optimized heat exchanger built with DMLS technology.

Something relatively new in the industry is lattice structures and using them for integral thermal shielding within a part. Lattice structures create a passive barrier for heat conduction within a part itself. Conformal coating for injection molds is one of the archetypal examples for AM. Cooling passages can be directed along the part, providing more homogenous cooling, quicker cycle times, and less expensive parts.

VALIDATING AM FOR THIN-FILM COOLING

Thin-film cooling involves jetting a very thin layer of a relatively cool fluid to shield a solid interface from a much hotter process. The center of a combustion liner is extremely hot, so ideally, the gas exhaust should be as hot as possible without melting the solid that's next to it. A thin film of gas was used to insulate the metal itself. This process is widely used in turbine engine combustion liners, and additive manufacturing is uniquely positioned to take thin-film cooling a step further.

Stratasys Direct Manufacturing leveraged Cincinnati Thermal Spray (CTS) to apply thermal barrier coatings to additively manufactured thin film cooling geometry. The overarching goal for this project was twofold: taking advantage of the complex internal passages that can be built using AM and creating very complex geometries of the outlets for the thin-film cooling, with the ultimate aim to hopefully increasing the efficiency of the cooling itself. Going into the project, it was uncertain whether AM could simply be used to accomplish and improve thin-film cooling. Thermal barrier coating is a very important part of turbine engines in general, and for this thin-film cooling application in particular.

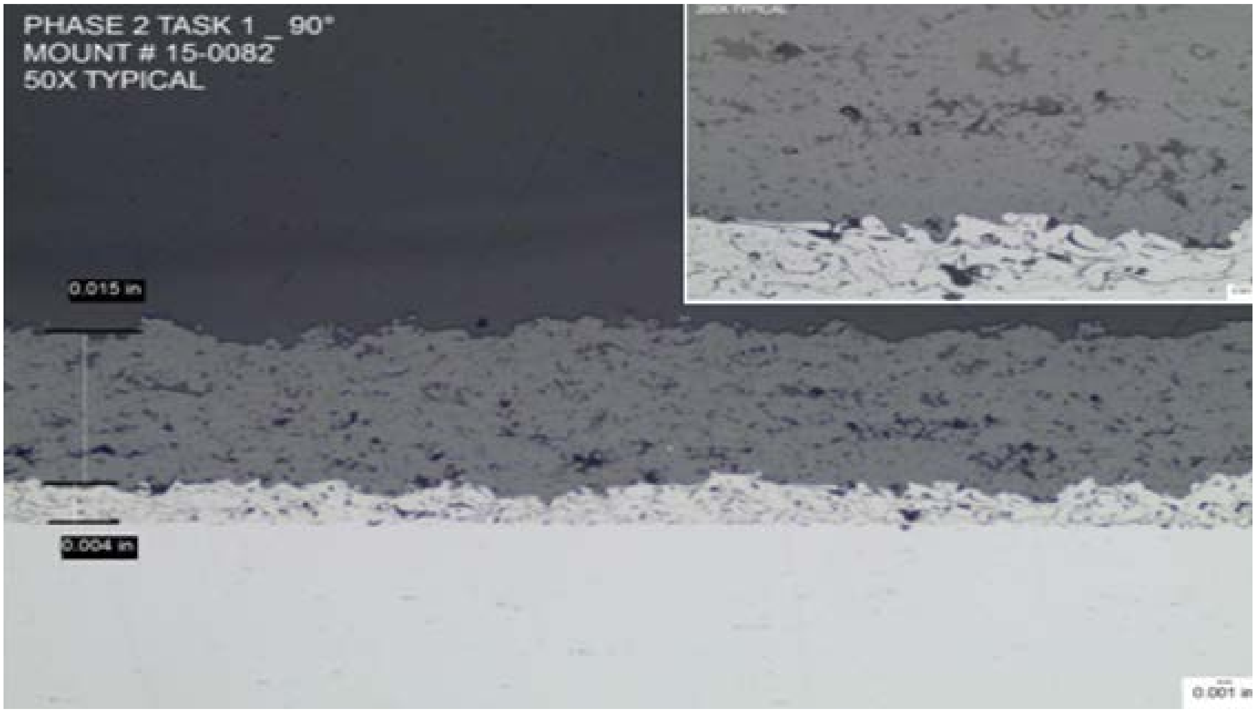


Figure 1: Micrograph cross-section of the thermal barrier coating applied to the effusion hold surfaces on top of the part.

On the right side of Figure 1 is a micrograph cross-section of the thermal barrier coating applied to the effusion hole surfaces on top of the part. Successful adhesion and accessible porosity were achieved in the thermal barrier coating. In the lower left photo is the geometry of one of the fusion nozzles with the thermal barrier coating applied; on the right is a photo of one of the test samples. This was experimentally tested at Baylor University.

Once it was demonstrated that the thermal barrier coating could be applied successfully, the geometry of the effusion holes was addressed. These holes output the fluid that creates the thin film. This was jointly developed with a large aircraft manufacturer and Stratasys Direct Manufacturing working together on the impingement and the film cooling. Nine different tests were conducted, which demonstrated that at multiple different flow velocities and mass flow rates, similar levels of fluid flow and similar consistency in fluid flow between the holes is achieved.

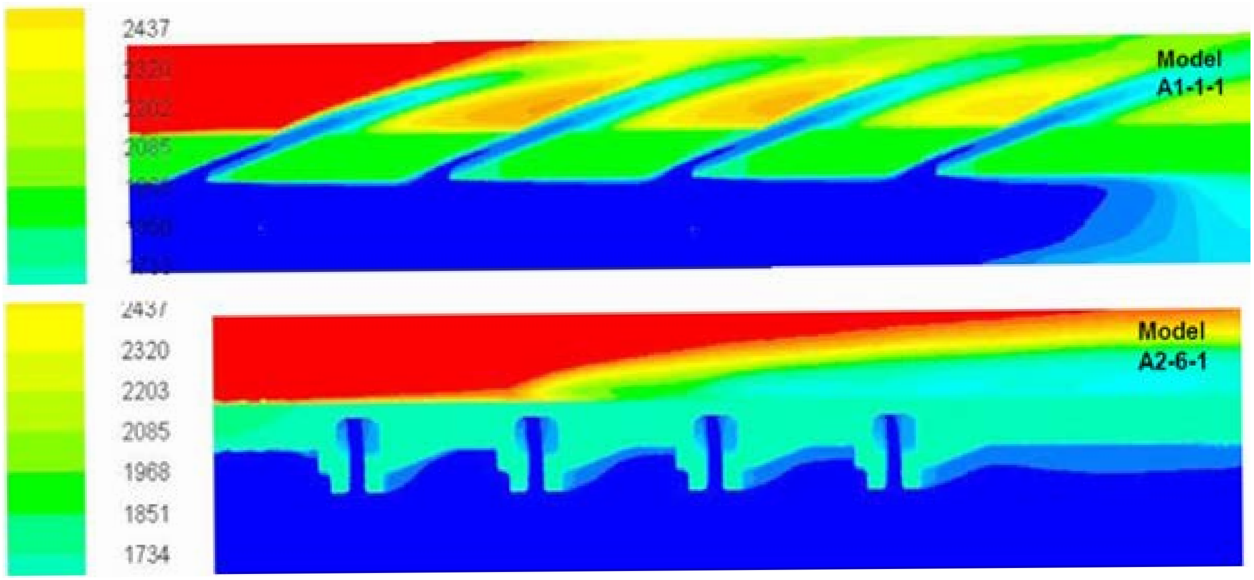


Figure 2: Film effectiveness is drastically increased over additively manufactured holes.

The question arises: why is cooling improvement with additive metals desirable versus the traditional means of thin-film cooling – conventionally CNC-drilled or EDM wire-popped holes? The answer: There is quicker development of steady-state thin film. This is evident in the top right image of Figure 2 where the liner is still fairly hot after a number of effusion holes. The bottom right image shows how the steady-state condition develops quickly with additive-manufactured holes. Hot spots in the thin film are also reduced. The lower right image shows the traditional holes on top with red rectangles in between the holes; the bottom right shows the AM effusion holes very quickly creating a homogeneous thin-film layer. The bottom left image shows the geometry details with the INKL625 effusion hole and thermal barrier coating on top. This was proven to reduce the liner temperature by up to 250°F (121°C), which is significant in this process.

Stratasys Direct Manufacturing successfully manufactured novel shaped effusion holes for this thin-film cooling application. The increased film coverage and effectiveness were experimentally and numerically validated with performance enhancements to be gained through further testing. Future work will include testing, the assembly of multiple liners, and hot fire testing of these parts.

PIN FIN GEOMETRY RESEARCH

Stratasys Direct Manufacturing supported a research project at the University of Texas at Austin that focused on how to utilize additive manufacturing capabilities to push the state of the art in pin fin heat exchanger design. Optimized geometries were developed to tailor the fluid dynamics such that heat transfer versus pressure loss was minimized.

Pin fins are patterned in arrays within closed tubes to enhance heat transfer of a working fluid. There are some public domain studies of advanced cross-sectional shapes – elliptical, square and triangular – and a few studies of nonlinear or tapered fins. However, before this work there were no studies of tapered, non-circular pin fin geometries. These are prohibitively expensive to manufacture using traditional methods.

The question was how to combine tapered with complex shapes to determine if the overall efficiency of these components can be increased. These were area-normalized cross-sections in straight low-taper and high-taper variants, with 21 different arrays in eight geometry families (see Figure 3.)

This project used coupled computational fluid dynamics (CFD) simulation to analyze these geometries for their efficiency in four inlet velocities per design. The computational studies were validated with experimental studies of the pressure drop over these arrays printed in plastic for the reduced expense and ease of manufacture. An open loop wind tunnel was designed and built to do this, and each array was tested at ten inlet velocities.

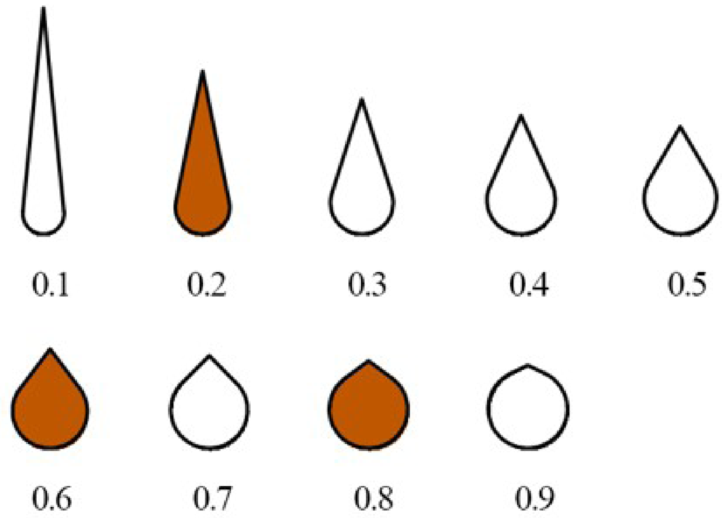


Figure 3: Cross-sections of pin fins in straight low-taper and high-taper

The combined specific friction loss parameter was used to compare each design. This is a unit-less parameter that defines how much pressure drop occurs to get a certain amount of heat exchange; lower is better. The more complex and highly-tapered fin geometries are, the most efficient and the most effective for heat exchange. Moving from straight to low taper to high taper decreases the friction loss, and therefore increases the effectiveness of these pin fins.

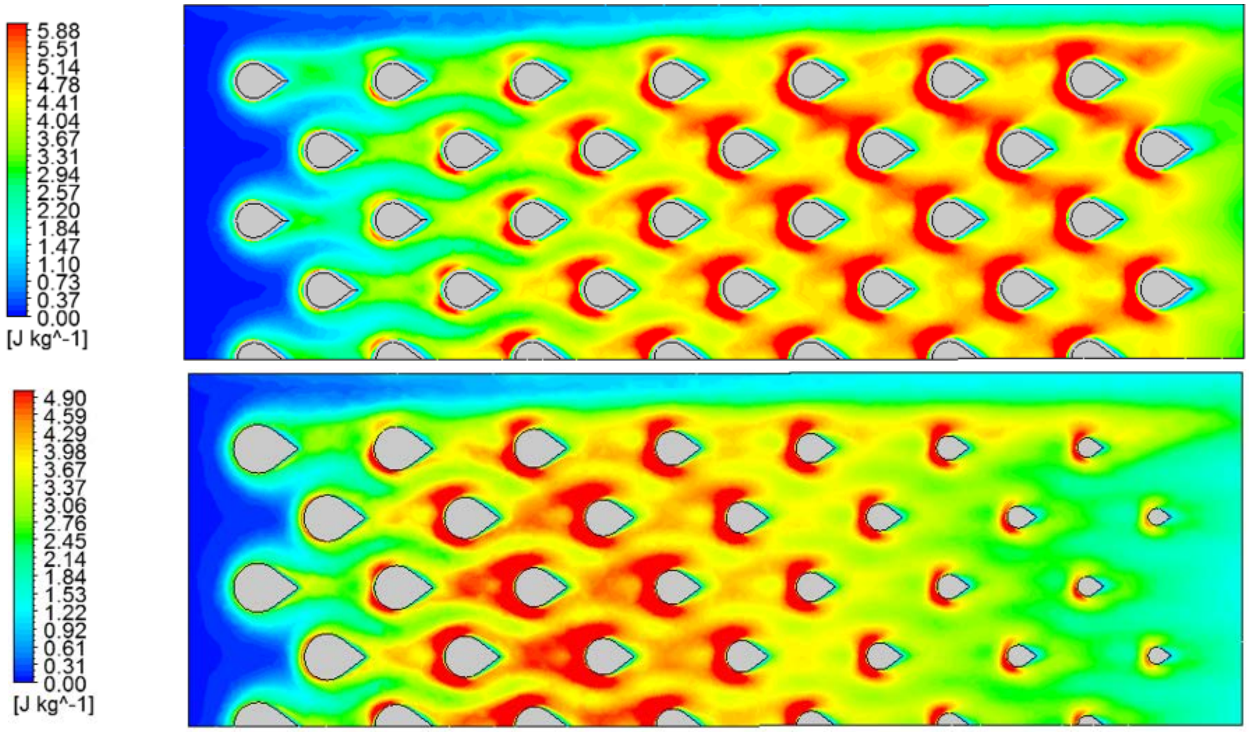


Figure 4: The size of pin fins changes in a stream-wise direction.

Fluid flow through these pin fins is highlighted in Figure 4. The top image depicts the same pin fin throughout the array. The result is slow development of a steady state of turbulence in the fluid flow, which will then exist for as long as these pins are in the passage. The bottom image shows that the size of the pin fins changes in a stream-wise direction, and therefore, the steady state behavior can be tailored to optimize heat exchange at every stream-wise location in the passage. If a passage must be variably cooled at different areas, or cooled to a specific level, these batches can be designed, built and tested quickly using AM, and in production, manufactured cheaply and efficiently.

For the pin fin project, additive capabilities can be used to manufacture more effective pin fins; a number of different parameters in these pin fins were highlighted for performance gains. Among those were the teardrop shapes tested, high-aspect-ratio tapers, varying the fin dimension along the stream-wise direction, and linear and nonlinear tapers. Future needs include experimental measurements of heat transfer, varying fin diameters, analytical computation of the optimal taper profiles, and further investigation of array layouts, as well as thermal topology optimization.

MATERIAL CAPABILITIES AND DEVELOPMENT

The available additive metal materials are driven by industry demand. Materials for AM are gas-atomized, usually within an inert gas like argon or nitrogen. This is an expensive process and is slowly coming online in large quantities as the AM industry continues to grow. While material selection for metal AM is limited, aluminum and copper are available to meet most part requirements for thermal management applications. Stratasys Direct Manufacturing offers aluminum and copper alloys that exhibit high-thermal-conductivity and high-specific-heat. The mechanical properties of these materials are similar to wrought after processing and heat treatments. These materials were developed for aerospace applications but have been used by multiple industries, including energy and automotive.

Stratasys Direct Manufacturing is actively evaluating further aluminum and copper alloys, different alloy blends and other materials, and characterizing their geometry capabilities on a per-material basis.

DESIGN CONSIDERATIONS WITH DMLS

What are the challenges and the future work to be done for thermal management with metal additive manufacturing? AM is still in the early adoption phase for thermal management applications, but as shown in the above projects, there are a number of cases in which AM provides preferable performance and efficiency gains.

With DMLS there are limits on the wall thickness and featured detail. The surface finish out of the machine is not ideal for many fluid flow applications, although post-processing offers significant surface improvements. Geometries must take into account support design and powder removal. For instance, a closed sphere can't be printed because it will be filled with powder during build.

3D printing allows for complex geometries with internal features.

Figure 5 looks at the actual capabilities of the powder bed process. Not just holes and thin walls, but conformal cooling, complex internal passages. 1 to 5mm-diameter holes can be printed in any orientation with no support. Between 6 and 9mm-diameter holes, if they are unsupported, the top of the holes will have some burn, which is an increased surface roughness. There is an increase in energy deposited by the laser where the hole closes.

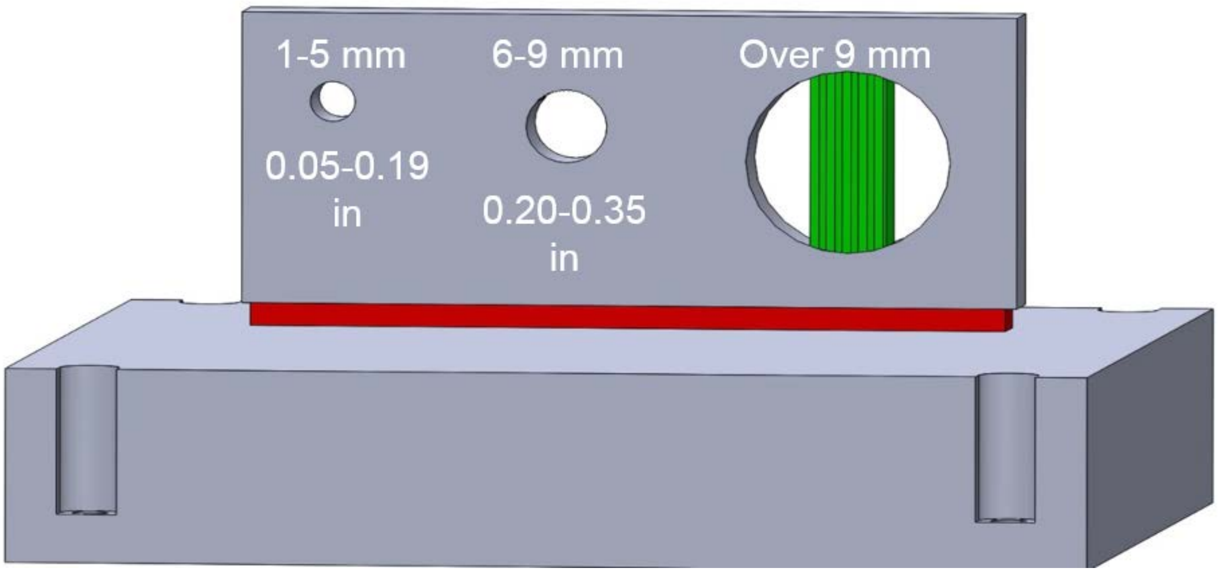


Figure 5: Size of holes determine needs for supports.

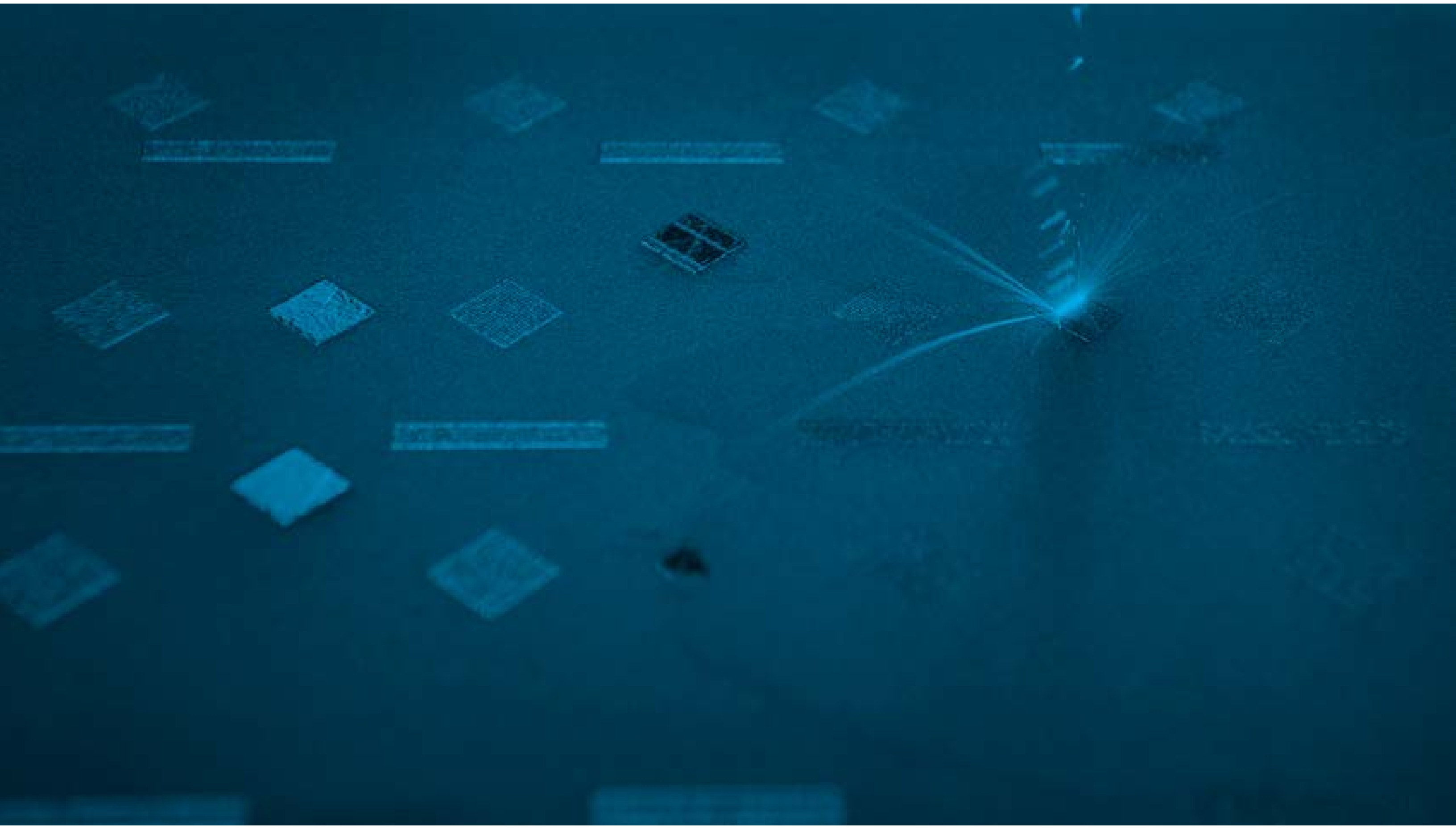
At more than 9 mm, that burn would turn into a failure if the hole is not supported. Shown in green are supports that mitigate warpage of the part that is induced by thermal stress. Any hole of more than 9 mm in diameter or any horizontal surfaces will need some type of support. For extremely complex, large internal geometries, it becomes an issue of whether they can be supported. In these cases, non-circular passage cross-sections can be used.

Wall thickness is an important consideration for thermal management, especially with heat exchangers. Ideally, a thinner wall is better, depending on the application. For this process, there are limits on the lower end by laser spot size, which is roughly 100 micrometers or 0.004”. There is the potential to go slightly lower, but the practical lower limit is slightly higher than that and dependent on geometry and material. The equipment manufacturer, EOS in this case, has a general rule of thumb that is an 8:1 ratio of height to wall thickness. If there is a .0010-thick wall building that is unsupported up to more than that 8:1 ratio, it can cause failure. This is only true for straight-ways. When printing a circle or anything with multiple walls that support each other, it can be built successfully, depending on the geometry.

Basically, short thin walls are always good, tall thin walls can be difficult, and tall thin walls with larger thermal bulks on top can cause issues with stress and warpage. These design challenges are mitigated by careful design and attention to the technology’s capabilities. The designs possible with DMLS can inspire new systems for thermal management not previously attainable with other manufacturing methods.

CONCLUSION

Additive manufacturing empowers engineers and designers to create novel geometries for thermal management systems, improving functionality, heat exchange and all parameters of a system. AM provides unparalleled geometric freedom, without the tooling costs of traditional processes, and a reduction in overall cost, lead time and assembly time. In addition, multiple components can be integrated into more efficient, modular, scalable systems, while maintaining digital inventories and iterating quickly through the design process. The embrace of AM in this sector will result in development of next-generation thermal management systems.



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