Advancing Additive Manufacturing for Gas Turbine Cooling

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Additive manufacturing, or 3D printing, has experienced a rapid rise in the past few years. The choice to use advanced manufacturing has major implications not only for the design and prototyping of components, but also for the cost, material, and lead time savings. When used thoughtfully and intentionally, additive manufacturing can infiltrate and transform almost any industry. The gas turbine industry is no exception. In fact, additive manufacturing is already being implemented in the gas turbine industry. For instance, what I am showing on the slide right now is a 3D printed gas turbine blade made by Siemens and manufactured for gas turbines that are used in power generation. This additive manufactured blade shown here will lead to higher efficiencies for these gas turbines and allow Siemens to develop parts closer to customers' requirements. Siemens quoted that their choice to use additive manufacturing reduced lead time for prototype development by 90%.

These blades were installed in a Siemens SGT-400 industrial gas turbine with a capacity of 13 MW. The additive manufactured blades are made out of a powder of high performing polycrystalline nickel superalloy, allowing them to endure high pressure, hot temperatures and the rotational forces of the turbine's high-speed operation. At full load, each of these turbine blades is traveling more than 1600 km/h, carrying 11 tons (equivalent to a fully loaded London bus), is surrounded by gas at 1250° C and cooled by air at over 400° C. The advanced blade design tested in Lincoln provides cooling features that can increase overall efficiency of the Siemens gas turbines.

"This exciting technology is changing the way we manufacture by reducing the lead time for prototype development up to 90%," said Willi Meixner, who is CEO of the Power and Gas division of Siemens. "Siemens is a pioneer in additive manufacturing. We can accelerate the development of new gas turbine designs with an increased efficiency and availability, as well as bring these advancements to our customers faster. This new flexibility in manufacturing also allows Siemens to develop precise components and provide spare parts on demand."

Reference for Image

http://dieselgasturbine.com/printed-blades-siemens/#.WK-Je1UrLYR

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When the gas turbine's estimated 50 heat shields are 3D printed instead of traditionally cast, they reduce cooling flow requirements by more than 40 percent, offering operators potentially millions of dollars in fuel-cost savings per year [*Metal AM*]. The first stage vane is one of the turbine's hottest-running components and its 3D printed portion offers a 15 percent reduction in the need for cooling air, which is equivalent to approximately $3B in annual fuel savings.

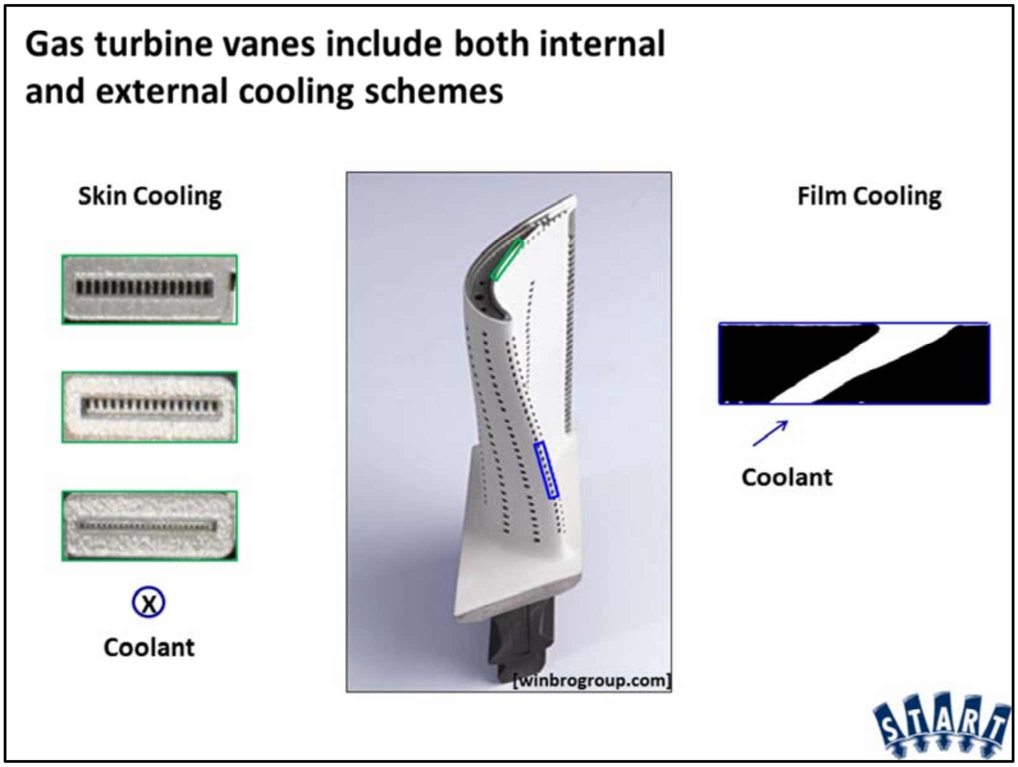
Additive manufacturing parts have also been implemented in the Berlin Mitte Power Station, where heat shields and parts of the gas turbine's first stage vane were additively manufactured. The first stage vane is one of the turbine's hottest running components and therefore requires a lot of cooling technologies both internally and externally to maintain its lifetime. The additively manufactured vane, however, reduces the amount of coolant required by 15%, which has two major implications. One implication is the heat transfer because these vanes run through the airfoils which are located in some of the hottest parts of the engine over 1000 ° C above the melting temperature of the material used to make the airfoils. Therefore, needing 15% less cooling flow means that the heat exchanger technology within these vanes is much more efficient. The second implication linked to the reduction in cooling flow is an increase in the overall efficiency of the turbine engine. This increase in efficiency is due to redirecting less air to the cooling system which allows more air to reach the combustor and create more energy. At this point, however, the technology is being developed so rapidly that gas turbine designers are only scratching the surface of the seemingly infinite possibilities offered by additive manufacturing. Keeping abreast of the developments in manufacturing technology is key to furthering its impact in various industries. At the START Lab, we are working to advance the applications of additive manufacturing as they relate to the gas turbine industry by investigating the influence the manufacturing process has on the cooling technologies in gas turbine airfoils.

References for Content

Metal AM, http://www.metal-am.com/german-power-plant-uses-metal-am-heat-shields-vanes-natural-gas-turbine/

Reference for Image

https://powerplants.vattenfall.com/en/mitte



Gas turbine vanes include both internal and external cooling schemes

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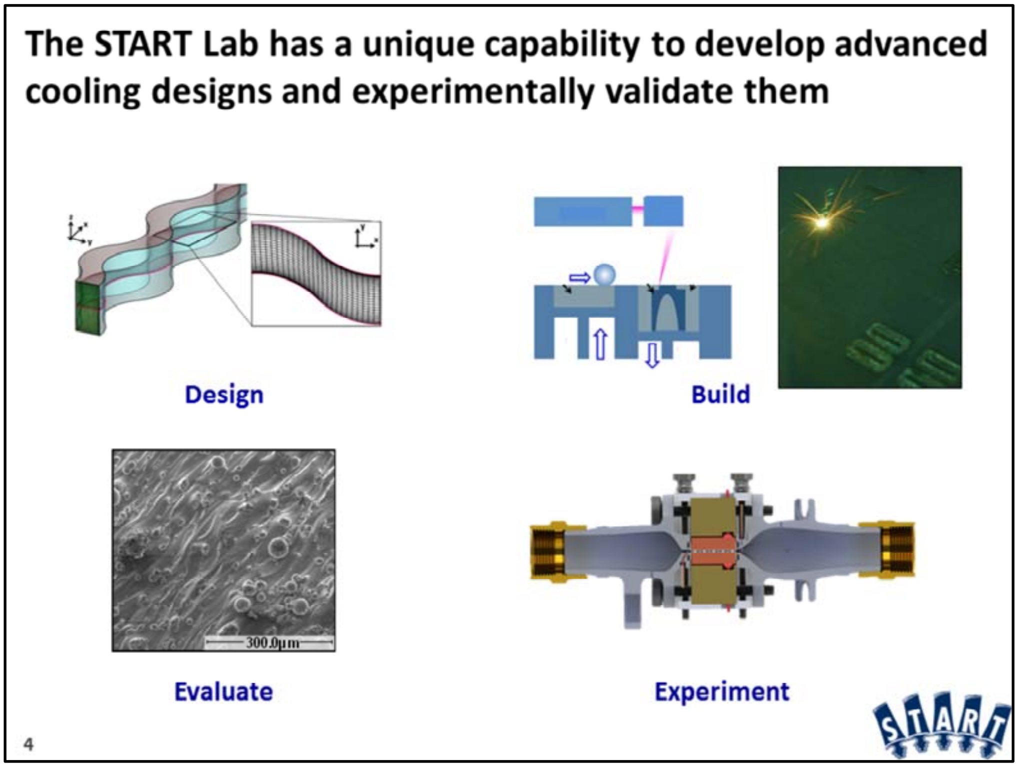
As I have mentioned, airfoils are currently cooled both internally and externally. Advanced internal cooling schemes can be found in what is known as skin cooling. These internal cooling mechanisms must be extremely small so that they can be manufactured into the skin of the airfoil, and therefore be placed closest to the hot combustion gases that travel over the surfaces of these airfoils. In the three images on the left, we are looking at examples of micro-sized cooling channels that were additively manufactured. These microchannels would be implemented in the turbine airfoil with the length of the channels spanning the vertical dimension of the airfoil—coolant is routed up through the bottom of the airfoil, through these channels and then out through what are called film cooling holes, a cross section of which is shown on the right. Coolant comes out the film cooling holes and spreads a thin film of air on the surface of the airfoil to prevent the hot combustion gases from actually coming in contact with the airfoil surface.

Transition

At the START Lab, we are investigating the use and applicability of additive manufacturing for both internal and external cooling schemes.

Reference for Image

http://www.winbrogroup.com/applications/turbineblades/



The START Lab has a unique capability to develop advanced cooling designs and experimentally validate them

Design

Build

Evaluate

Experiment

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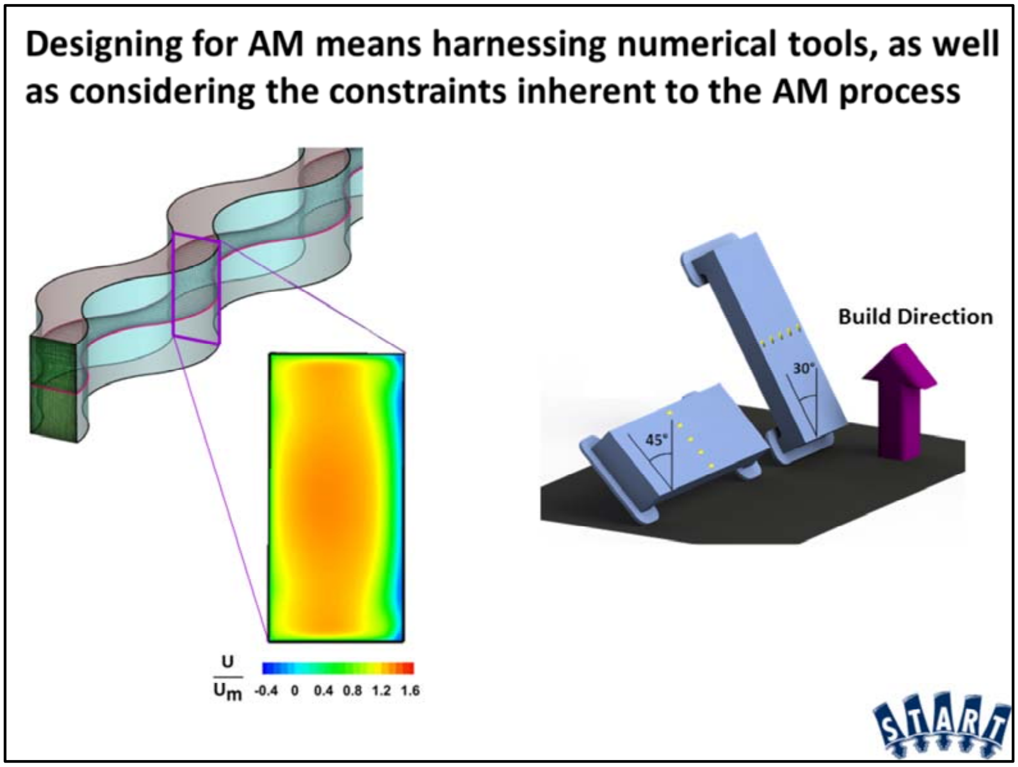
We have the unique capability to experimentally validate our designs for additive manufacturing. One tool that we used to develop novel designs is numerical optimization, which produces geometries that would be impossible to manufacture with any other method. We have additive manufacturing capabilities on Penn State’s campus, which is a huge boom to our work. Once we have our designs, it’s a simple task to send them to the other side of campus to be printed. Also at Penn State, we have the capabilities to evaluate what the additive manufacturing process has produced. Rarely, if ever, does the final part exactly match its intended design, especially at the micro-scale of our designs. Finally, housed in the START Lab are test facilities which we use to experimentally validate our internal and external cooling designs.

Transition

I will be discussing some of the design procedures that we use, build process, evaluation of additive manufactured parts, and experiments that we can perform to validate our designs.



Designing for AM means harnessing numerical tools, as well as considering the constraints inherent to the AM process

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As I mentioned, the first step is to design one tool that we use to generate complex designs is numerical optimization procedures. Using these procedures, we can optimize for various characteristics such as heat transfer or pressure loss. The open design space offered by additive manufacturing is an incredible advantage inherent to the process, but it can be daunting—how do you know the best design for a given application? At the START Lab, we turn to numerical optimization tools. On the left of the screen is an example of a computational domain that we created for an internal cooling design. The changes in wall shape that were generated by the optimization process are incredibly complex, as you can see. However, such a complex design is not a problem for the additive manufacturing process.

In addition to designing unique shapes, we are interested in understanding the differences between additively manufactured and conventionally-manufactured designs, as well as the limitations of the additive manufacturing processes. The build direction has a strong influence on how the final part comes out and you can see on the right hand side of the slide, we manufactured the same design—you can see the film cooling holes here in yellow—in two different build orientations. In a gas turbine airfoil, you may not always have the option to build all the features in an advantageous build direction. We have the capabilities to test both build directions and report to our industry sponsors on how the performance of film cooling holes changes, despite the fact that they are the same exact design.

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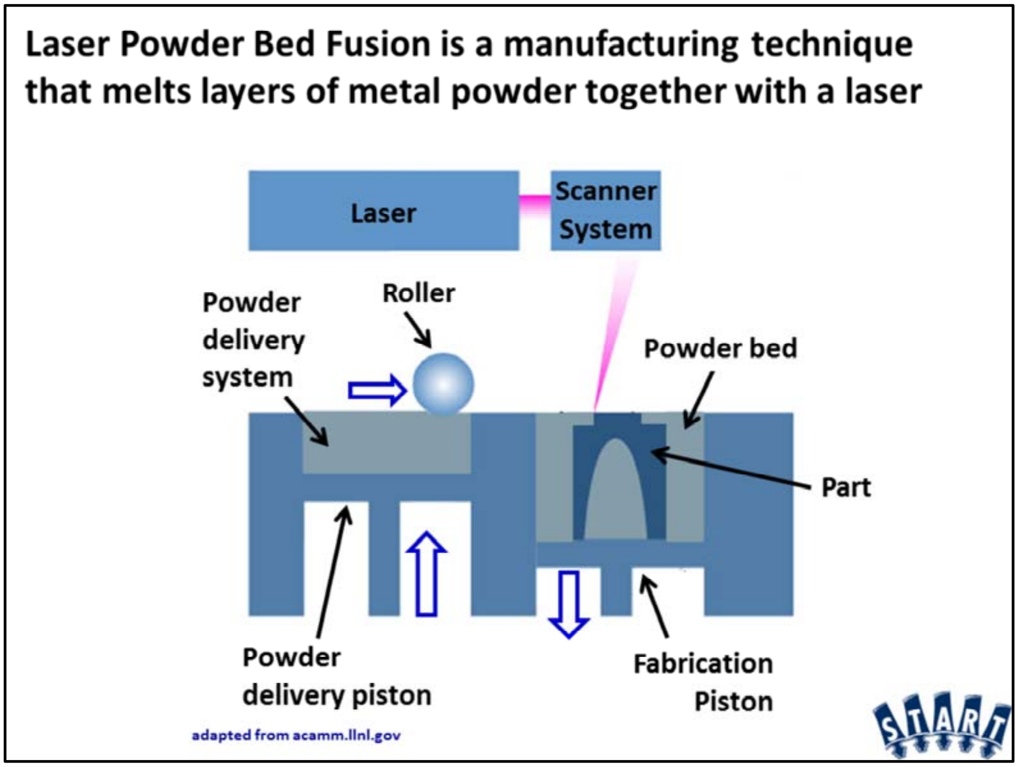
Now, we will take a look at the additive manufacturing process we used to build our microchannel coupons.



Laser Powder Bed Fusion is a manufacturing technique that melts layers of metal powder together with a laser

adapted from acamm.llnl.gov

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We used a metal additive manufacturing process called Laser Powder Bed Fusion. You may have heard this process called by a few different names—DMLS, DMLM, SLM, DMP, and so forth–but they are all the same process. The different names are just given by different companies to distinguish their machines. However, the basic concept is the same.

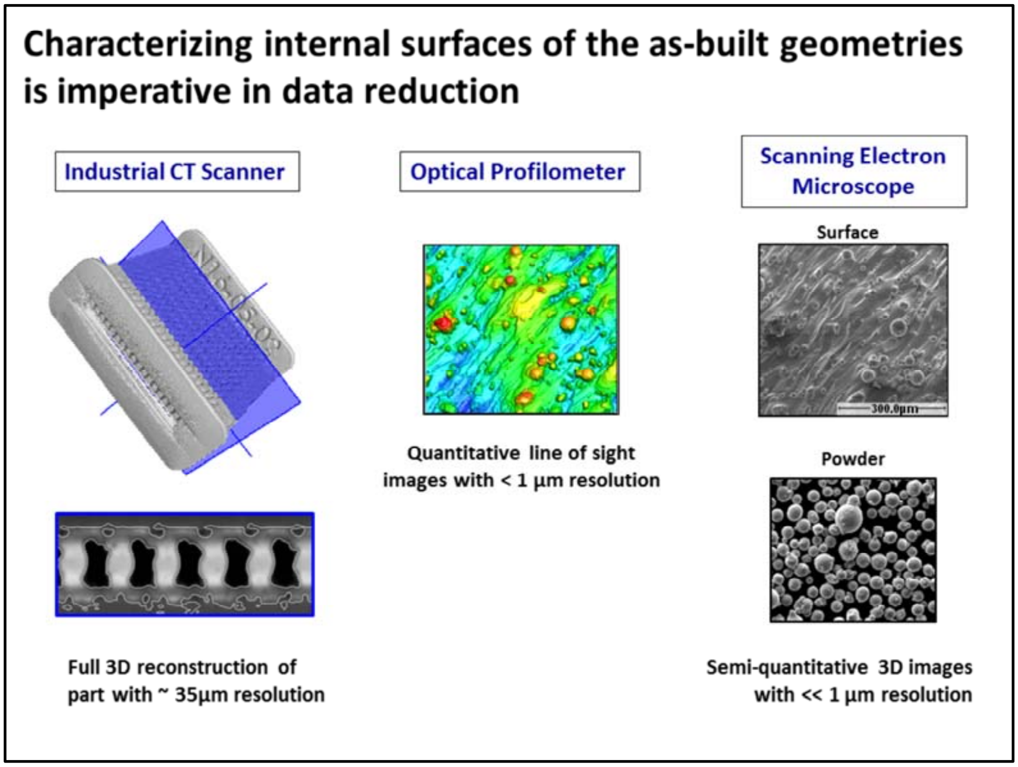
Laser Powder Bed Fusion involves a bed of metal powder that is melted together via a high power laser. This process begins with the powder delivery piston which pushes the powder up to the roller. The roller then pushes the material to the powder bed where the scanner uses the laser to melt the new layer of powder, thus adding it to the part. The fabrication piston then moves down, and the process repeats layer by layer until the part is complete.

Transition

Next, I will discuss the evaluation process for the finished part.

Reference for Image

Adapted from - https://acamm.llnl.gov/am-technology/powder-bed-am



Characterizing internal surfaces of the as-built geometries is imperative in data reduction

Industrial CT Scanner

Optical Profilometer

Scanning Electron Microscope

Surface

Powder

Quantitative line of sight images with < 1 µm resolution

Full 3D reconstruction of part with ~ 35µm resolution

Semi-quantitative 3D images with << 1 µm resolution

Content

Once the parts are finished, we are interested in characterizing exactly what came out of the process. As I mentioned, at the scale at which we work, the parts will deviate from our design slightly and identifying the proper length scales for our experiments is critical. We typically use three different characterization processes, depending on the precision required. The first method that we use is a commercial CT scanner. This characterization method is important because it is nondestructive, we can get resolutions of around 35 microns which is sufficient for characterizing some of the large roughness features, and we can also see the internal surfaces of our parts.

If we need a higher resolution, we can use either an optical profilometer or a Scanning Electron Microscope. Because both of these methods require line of sight, we can use them only on exterior surfaces or if we have cut the part open. The optical profilometer offers resolution less than a micron and quantitative data, but provides data only in 2D. A Scanning Electron Microscope (SEM), however, can show the morphology of our parts, which is an advantage for us in characterizing the surface finish that comes from the additive manufacturing process. A disadvantage of the SEM is that the images are not quantitative; that is, we cannot calculate sphericity, height, or depth, for example, of particles in the image.

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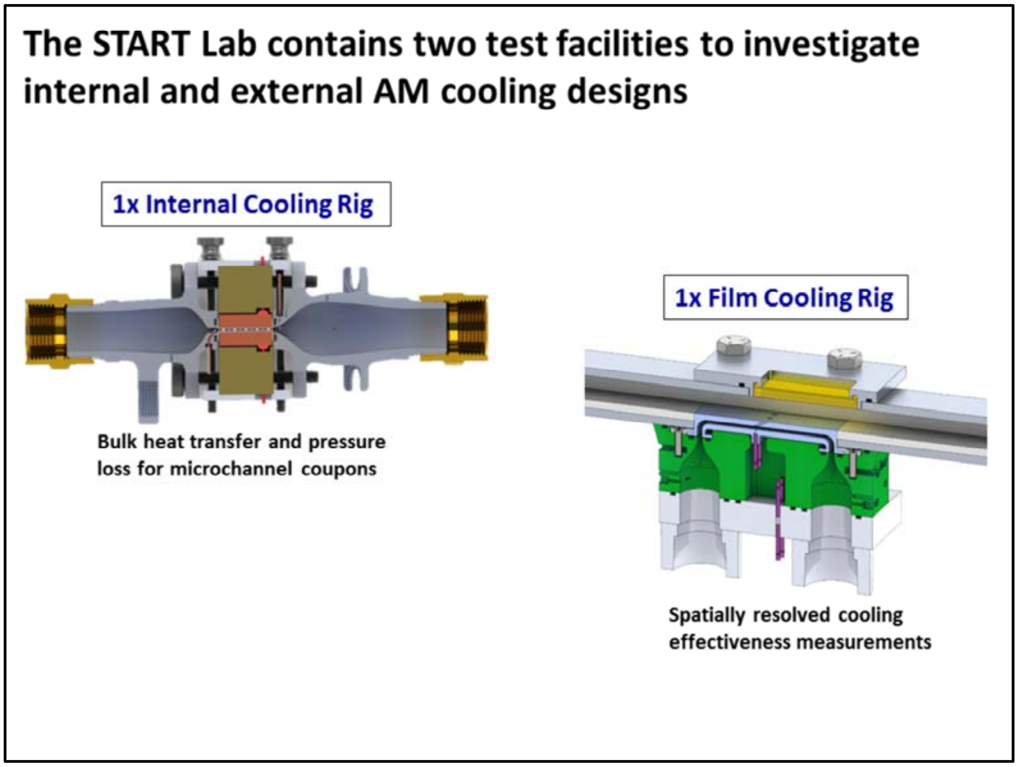
Finally, we have the capabilities to test our microchannel coupons.



The START Lab contains two test facilities to investigate internal and external AM cooling designs

1x Internal Cooling Rig

Bulk heat transfer and pressure loss for microchannel coupons

1x Film Cooling Rig

Spatially resolved cooling effectiveness measurements

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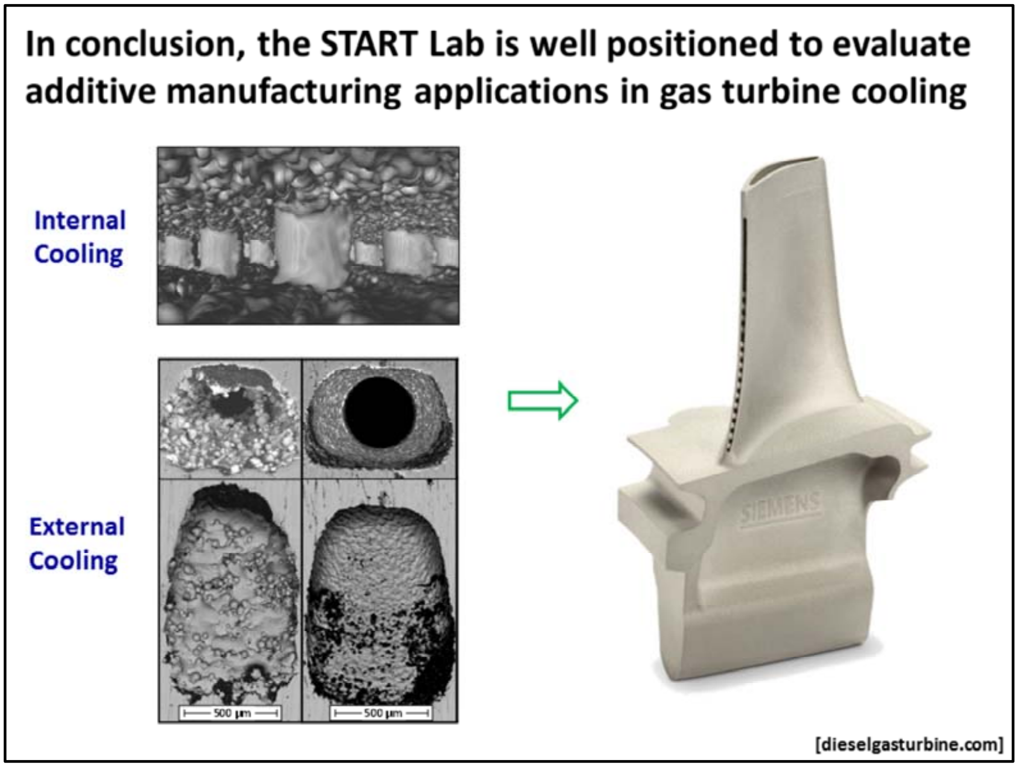
Finally, we have the capabilities to test our microchannel coupons. We have two test facilities—one for internal cooling and one for external cooling. For the internal cooling rig, we take global measurements to measure the frictional losses and the heat transfer performance of our channel designs allowing us to compare them with previous designs. On the external cooling side, we have our film cooling rig, which takes IR images of the surface as your running an experiment. These images allow you to see the temperature of the surface and how well the film cooling holes are performing.



In conclusion, the START Lab is well positioned to evaluate additive manufacturing applications in gas turbine cooling

Internal Cooling

External Cooling

[dieselgasturbine.com]

Conclusion

What we are trying to do at the START laboratory is advance additive manufacturing technology specifically for the gas turbine industry. We are looking at both internal cooling schemes and external cooling schemes, as well as different design methodologies which fuse the capabilities of additive manufacturing with numerical optimization to create more organic shapes here on campus. Also, we are trying to find the limitations of the additive manufacturing process as they relate to external cooling. Our goal is to better the internal cooling, better the external cooling, and put these together to create the next generation of gas turbine blades thus improving the overall efficiency of our jet turbine engines. Thank you.

References for Images

http://dieselgasturbine.com/printed-blades-siemens/#.WK-Je1UrLYR