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WHY COMBUSTION COMPONENTS ARE PARTICULARLY SUITABLE FOR HARVESTING THE BENEFITS OF ADDITIVE MANUFACTURING

Gianni Panfili
Additive Manufacturing Manager, Aeroderivative Gas Turbines
Siemens Energy Canada Limited
Montreal, Quebec, Canada

Kevin Sheehan
Head of Design For Additive Manufacturing
Siemens Energy, Inc.
Orlando, Florida, USA

Gianni graduated with a bachelor's degree in mechanical engineering (specialization in thermo-fluids and propulsion) in 2009 from Concordia University in Montreal, Canada. He began his career with Rolls-Royce Energy in the R&D organization of the aero-derivative industrial gas turbines. Within the combustion department, he was involved in several engine and rig testing programs.

When Siemens acquired Rolls-Royce Energy in 2014, he was a combustion design team leader and became involved with applying Siemens' additive manufacturing (AM) technologies to the aero-derivative gas turbine products. In 2017 he was appointed AM Manager at Siemens Canada (Gas & Power). Gianni and his team are part of a highly focused global AM organization, delivering new additive manufactured solutions to the aero-derivative portfolio.

Kevin joined Siemens in 2000 as a materials engineer in Orlando, Florida within the fossil power generation division. Prior to his joining Siemens, he briefly worked as a materials engineer for the International Truck and Engine Company after graduating from the University of Florida with a Master's of Science degree in Materials Engineering. Since the start of his career at Siemens, he has spent the first half as an engineer providing support to the engineering community to solve issues through failure analyses as well as provide materials solutions to the new generation of industrial large gas turbines. Since 2006, Kevin led the Materials Engineering organization as well as served as Technology Owner for Materials within Large Gas Turbine Engineering. Recently, he was the Technology manager for the SGT5/6-9000HL gas turbine program whereby all developed technologies were designed into the new advanced gas turbine engine for Siemens Gas and Power. Presently, Kevin's Design for Additive Manufacturing organization is responsible for designing and implementing additively manufactured serial components into the large power generation equipment fleet for Siemens Energy.

ABSTRACT

This paper focuses the use of additive manufacturing (AM) for the production of gas turbine (GT) combustion system components. It discusses how AM methods are being employed to improve the reliability and thermo-mechanical fatigue resistance of select parts by eliminating potential crack initiation points at braze locations. The paper also discusses other capabilities and benefits that AM enables, such as rapid prototyping, reduced part lead times, and lower repair and lifecycle costs.

Several real-world use cases are presented in which AM methods have been used to fabricate parts for GT models that are currently in operation. In one example, AM burner heads were produced for a conventional dual-fuel injector on a 38-MW aeroderivative GT model. Traditionally, the burner head was considered a complex assembly that required six different brazed joints to produce the final part with small passages for air, gas, liquid fuel, and water. Siemens replaced the head portion of the burner with a single AM piece that is welded to the rest of the burner, simplifying both the manufacturing and repair processes; see Figure 1.

In another example, AM was applied to manufacture the central fuel injector of a dual-fuel, dry low emissions (DLE) variant of the 38-MW GT model, which is commonly used in offshore oil and gas applications. The development consisted of manufacturing the component as a single printed part and optimizing some of its features in order to enhance functionality, and particularly the combustion noise signature at low power. Such optimization was prevented in the conventional-made part by manufacturability constraints (e.g. wall thicknesses, casting yield, etc.).

In a third use case, serial production of a high-performance combustion fuel swirler has been achieved. The swirlers are now produced in quantities greater than 1000 per annum. These examples and more will be discussed. In all cases, extensive validation of the AM component was carried out, including matching design analysis tools to experimental results on a combustion test rig.

INTRODUCTION

Additive manufacturing is a disruptive technology that is presenting exciting product development opportunities in the integrated design and manufacturing space.

Within the context of gas turbines, AM is enabling new benefits for original equipment manufacturers (OEMs) and operators throughout the entire component lifecycle. AM lends itself particularly well to combustion system and hot gas path components, which are highly complex and required to function in harsh operating conditions. Combustion systems in gas turbines need to provide the necessary flow dynamics and stoichiometry for efficient combustion and environmental control. These functions are accomplished by several components with complex three-dimensional (3D) shapes, characterized by small internal passages to provide appropriate flow characteristics and mixing. Traditionally, these parts required multiple brazing operations to join numerous parts. Today, AM is opening up further optimization opportunities for these parts by eliminating the constraints of conventional processes, and intrinsically enhancing the reliability and thermo-mechanical fatigue resistance by eliminating potential crack initiation points at the braze locations.

Other benefits enabled by AM include the ability to rapidly prototype and iterate upon new ideas during the design and development phase of new parts. Eventually this can turn into serial production where traditional stipulations such as production volume or long lead dies and other tooling no longer present commercial challenges. The advantages of AM also extend into the service/operation phase, where it introduces new possibilities for component repair, as well as the ability to maintain the supply of legacy spare parts. This paper will discuss real-world examples where these capabilities have been realized within Siemens gas turbine portfolio.

AM APPLICATIONS FOR GAS TURBINES

1. *Burner Heads for Conventional Dual-fuel Injectors*

One of the key benefits of AM comes from the ability to print complex shapes with small internal passages. Traditionally this required multiple brazing operations to join numerous parts, all of which can now be done with one AM printed part. This has the added benefit of reducing the risk of braze failures and inherently improving component reliability.

A tangible example of this can be seen with the introduction of the AM burner head on dual-fuel, non-DLE injectors. The head has traditionally been a complex assembly requiring six different brazed joints to produce the final part that has small passages for air, gas, liquid fuel, and water. The head portion of the burner has now been replaced by a single AM piece that is welded to the rest of the burner, simplifying the both manufacturing and repair process.

One of the fuel injectors also saw a substantial increase in cyclic life. Just as a chain is only as strong as a weakest link, a brazed assembly is usually only as strong as the brazed joints. These features are typically imperfect and can easily act as local stress concentrations. Also, the braze material will usually have mechanical properties which are quite different than the bulk material of the joined components. The effect of this is that over time, or more precisely, after many mechanical and/or thermal cycles, cracks can initiate and propagate at a brazed joint. A good design will try to locate the brazes away from high stresses to avoid these issues, but still these component failures can occur. On the other hand, additive manufacturing can produce intricate geometries without these features, and thus without any inadvertent “defects”. This was verified when the conventional and AM fuel injector were tested for thermo-mechanical fatigue (TMF) in a lab setting, as the AM component outlasted the conventional one by thousands of cycles.

Figure 1: AM head to the left of the red line, welded into the injector assembly

In order to validate the AM component, the OEM has undertaken several activities. Throughout the engineering and design phase, typical analysis methods have been combined with specific novelties to account for the AM process. Two prominent examples are flow characteristics and component life.

For flow, numerical analysis of computational fluid dynamics (CFD) must consider the surface effect of an AM part compared to a conventionally manufactured part. Extensive flow and spray tests were carried out in order to validate gas and liquid fuel flow. It was important to ensure that flow capacity for both fuels was maintained in order to preserve the behavior of the whole combustion system. In addition, fuel placement within the combustor was carefully validated. Overall, it was critical to validate how much fuel is delivered, and also how it is delivered. This resulted in sophisticated testing using laser diagnostics to measure liquid spray droplet distribution.

To validate material properties of the AM part, including component life, extensive qualification and testing was performed at a production facility in Sweden. With the data generated during this process, engineers performed finite-element analysis (FEA) to evaluate the thermal, stress and dynamic behavior. This was also verified with experimental testing. The OEM developed a TMF test setup, whereby the AM and conventional components were thermally cycled in engine representative conditions thousands of times to the point of failure, as shown in Figure 2. This test proved that the cyclic life of the AM injector was higher than that of the conventionally made part it replaces. This is because, as previously stated, the single piece head made by AM eliminates the brazed joints in the assembly. In turn, this eliminates the failure mode of the brazed joints developing cracks under thermal fatigue.

While this is a very encouraging result, there is an important counter-balance to consider. The metallurgical output of the laser powder-bed fusion process is not always perfect. There are many variables which can affect the quality of the material being produced, such as alloy composition, laser and process parameters, cooling/heating rates, and many other variables specific to the particular AM machine being used. The results could be reduced density or compromised mechanical properties. Therefore, one must be mindful of the chemical and metallurgical outcome.

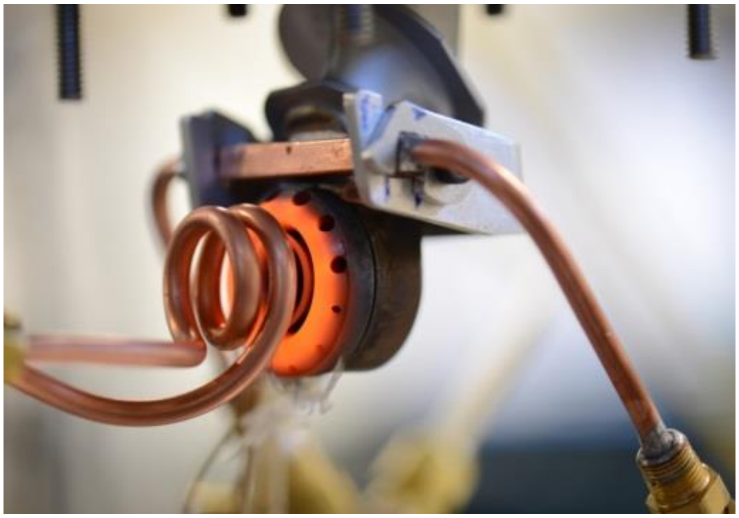

Figure 2: Conventional injector in thermo-mechanical fatigue (TMF) test apparatus

The AM burnerhead was fully validated with engine testing in early 2019 and was released into service, starting commercial operation in February 2019. It is now the new production standard for all new units. The process will also be utilized for the repair of fuel injectors in the operational fleet.

A similar program was undertaken for the gas-only legacy standard of non-DLE fuel injector, known as the Package 1 burner. Given that this injector delivers a single fuel, it has been developed as a fully additively manufactured component, requiring only some basic machining to produce the finished part. This is seen as a key enabler for existing operators, where supply chains for legacy parts can be challenging to manage. In this instance, the deterioration of castings and the dies used to produce them make this a great candidate for an aftermarket solution. The AM part eliminates the need for sourcing multiple components and greatly improves the flexibility of the supply chain; which in turn translates directly to a reduced burden of spare parts inventory for operators.

The validation for this component followed a very similar path as the dual-fuel variant described above. The gas fuel feed was carefully designed to ensure that the delivery of gas to the combustion system did not adversely affect the overall system. This was first simulated analytically and eventually validated with laboratory measurements.

In both use cases, the specific AM technology that was utilized was Selective Laser Melting (SLM), otherwise known as Laser Powder Bed Fusion (L-PBF).

2. *Central Fuel Injectors for Dry-low Emissions (DLE) Combustion Systems*

Improving product capability is another key outcome of applying AM technology. In the case of a dual-fuel DLE combustion system, the OEM has been able to eliminate an operational limitation inherent to the original design that was a symptom of conventional manufacturing constraints. As with the example above, the AM technology used in this case was L-PBF. See Figure 3 below.

When the dual-fuel variant of the DLE combustor was initially developed, the gas exit holes in the central injector needed to be moved slightly to make room for the liquid fuel injection system, which in turn changed the gas fuel placement. During prolonged operation at very low power with gas fuel, higher levels of combustion noise increase the risk of vibration damage to downstream components in the turbine section. The root cause for this issue was attributed to the new position of the gas exit holes that had been forced to shift slightly from the original gas only design because of manufacturing constraints with conventional methods.

By adopting additive manufacturing methods, a revised design of the injector was possible which maintained the liquid fuel capability, while also restoring the gas fuel capability and noise characteristics to that of the proven gas-only version. This solution has now successfully completed multiple combustion rig tests to validate the required dual fuel operating range and confirm combustion dynamics in line with the proven gas-only variant (over 9 million hours in service). After full validation and testing similar to the non-DLE injector, it has now been released as a production standard.

Figure 3: Additive manufactured dual fuel injector

3. *Serial Production of Main Swirlers*

One of the most recent examples of how the OEM is leveraging AM can be seen with the production of the main fuel swirler for yet another product which is primarily used in combined cycle power generation applications. The swirlers main function is to mix air and fuel prior to combustion by the burner. Market demand for the swirler exceeds 1,000 units per year.

The conventionally-produced swirler is comprised of ten cast and machined parts welded together. The OEM redesigned the swirler assembly using AM. This enabled integration of vanes, a shroud, and mounts into a single part, which is approximately 250 mm in length. The swirlers are produced from a proprietary Inconel alloy. The entire AM process has chain has been developed specifically for the swirler. This includes the powder and machine parameters, to post-processing and heat treatment.

Figure 4: Additive manufactured swirlers

As is the case with many non-AM parts, the conventional swirler design required numerous machining and welding steps to produce. Not including the time for casting, the processing time for each swirler was approximately six hours. AM has enabled the OEM to reduce this by more than 80% to just one hour. The process consists of depowdering, part removal via wire electrical discharge machining (EDM), removal of support structures, and bead blasting. CNC machining is also required at the base of the part where it will be welded to the larger burner assembly. The swirler is then measured and marked for serialization.

Sixteen swirlers can be printed at one time on EOS M 400-4 quad-laser Powder Bed Fusion systems. The components in the AM build plate is shown above in Figure 4. Since starting production, the OEM has been able to reduce overall print time by 33% by adjusting build parameters at individual regions of the part. Currently, the OEM operates 40 L-PBF machines across its locations and is able to produce more than 1,000 main swirlers per annum to meet market demand.

4. *Burner Tip Repair*

Component repair is also as an interesting application for AM. For decades, repair of burner tips had always been done by conventional methods – i.e. cutting off the tip and replacing it with a pre-manufactured one. However, in 2013 the OEM launched the first burner repaired by SLM technology. This was the first instance of this new technology being brought out from the laboratory into an industrial production environment.

Two types of repairs are enabled by L-PBF. The most obvious is when repair parts are made by AM. Recall the non-DLE injector in Figure 1. Conventional repairs sometimes call for the brazed head assembly to be broken down to individual sub-components for the damaged areas to be replaced, and then re-brazed back into the final assembly. By replacing the entire head assembly with an AM head, fewer operations are required and fewer repair parts are needed which means a smaller inventory burden.

The other repair method is whereby damaged areas of material can be removed and rebuilt directly onto the part. Similar to serial manufactured parts, lead time reduction is expected to be significant, especially for complex structures or raw materials with long lead time. The OEM has developed a burner tip repair procedure by SLM for several gas turbine variants. This repair process is ten times faster than the conventional method because it eliminates several intermediate manufacturing and inspection processes. Additionally, the SLM repair process gives operators the opportunity to upgrade repaired components to the latest design rather than replace the full set (Navrotsky, Graichin 2015).

Figure 5: Burner and combustor configuration

The burner tip face is directed into the combustion chamber and exposed to the hot gas and heat radiation from the flame (see Figure 5), causing thermo-mechanical fatigue and oxidation damages to the outermost 10mm of the tip. The rest of the burner is protected by the combustion chamber and, in general, exposed to low thermal and mechanical loads. However, the conventional repair process used to remove approximately 120mm of the burner due to the complex internal passages, as indicated by the red line in Figure 6 below. This also required the external fuel pipe and instrumentation to be replaced.

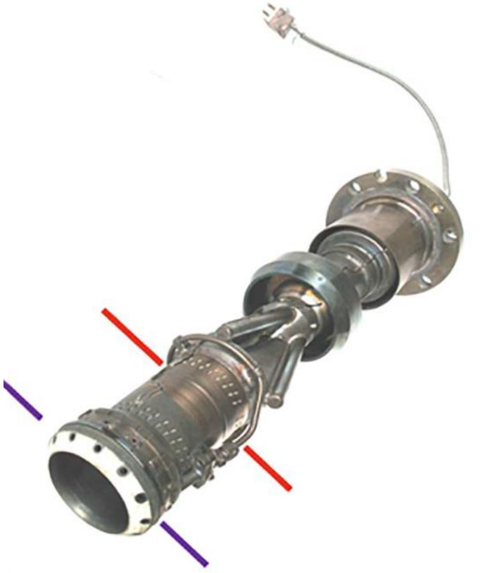

Figure 6: Burner repairs in the traditional fashion (red line) and the described novel repair process (purple line)

The traditional repair method was replaced with an innovative AM repair process based on SLM in a customized AM machine. With the AM repair technique, the cut is made only 20mm upstream, indicated by the purple line in Figure 6. The system uses a sophisticated imaging system to accurately position the CAD-model that is to be printed onto the burner substrate. From the camera images, the substrate's edges are identified, and the software adjusts the position of the CAD-model in X, Y and tangential direction.

Since the introduction in 2013, the OEM has successfully repaired and put in operation over 2,000 SLM repaired burners. During the repair older variants have been modified and updated to the latest standard and several have been laboratory examined after operation and shown to be in excellent condition which was confirmed by metallurgical investigations.

The SLM repair method is now the first choice when repairing burners and is considered to be a mature process. By 2019, the fleet leader had accumulated more than 35,000 equivalent operation hours (EOH) and the unit with most start / stop cycles has recorded more than 500 starts.

5. *Spare Parts on Demand*

There are many legacy components and products which are no longer offered in new applications. Components of these combustion systems are especially attractive for AM due to the moderate temperature regime governed by the compressor cooling air and the high complexity of the parts.

The head of the pilot burner is a fuel-air-mixer for the pilot flame and conventionally sourced as an investment cast part made from a Ni-based alloy. This was the OEM's first "spare part on demand" as an AM component, shown in Figure 7 below.

Figure 7: Additive manufactured pilot burner head

In order to geometrically inspect the AM parts, they were scanned along with the original cast part. The initial results were concerning; the deviation between the AM and the cast part was almost 1mm on some surfaces. It was not until both sets of scans were compared to the nominal CAD geometry that engineers understood the data. As it turns out, the printed part was well within a maximum of 0.2 mm deviation compared to the nominal, which demonstrated far better accuracy than the cast part which was over three times worse, shown in Figure 8 below. In the end, the engineering team decided to match the AM design to the engine-proven cast geometry to avoid any possible risk to the function and performance of the component. Of course, this was done with minimal effort and did not require any tooling changes (Navrotsky, Piegert 2018).

Prior to delivery and installation, an inspection schedule was agreed with the customer so that field feedback could be gathered. Hence, a well-maintained engine was picked to install the first burner heads. This particular machine does not only act as a validation site but is also the fleet leader for this particular component which can only be ordered as an additive manufactured part. Meanwhile, the engine has reached its first minor hot gas path inspection, surpassing more than 12,000 operating hours, without any issues or signs of any damage.

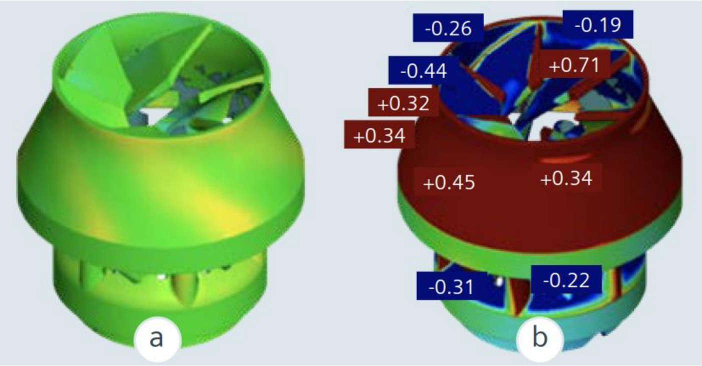

Figure 8: Geometric comparison between 3D-model and (a) SLM component as well as (b) investment cast component; red – positive deviation / blue – negative deviation

DETERMING WHICH COMPONENTS ARE SUITABLE FOR AM

The common characteristic of all of the components described in the above sections is that they are related to the combustion system, and for good reason. Combustion components are typically quite small, even on very large gas turbines. The enclosures of L-PBF machines are finite, in the approximate range of about 0.5m x 0.5m x 0.5m. Therefore, one must consider components which fit inside these enclosures. Another reason that combustion components are attractive for additive manufacturing is that they are typically high-value. The cost of additive manufacturing has been decreasing over the years, but compared to very mature processes like forging, casting or fabricating, it remains relatively expensive for a given volume or mass of material.

This also goes hand in hand with another characteristic which favors combustion components, and that is high complexity. Intricate assemblies are very common. For example, components with internal passages for delivering fuel, water or cooling air can be very tedious to manufacture conventionally. These types of components can be very costly and also require a very long time to produce. One final consideration is the material properties of the component itself. As an example, critical rotating components such as turbine blades or discs are under extreme mechanical loads which are not well-suited for AM.

Overall, AM is well-suited for combustion system components. However, it could also be applied to other static, hot-end components as well. A good example is turbine vanes. In cooled vanes, the intricate air passages can be optimized with AM in order to increase cooling effectiveness or make meaningful improvements to cycle efficiency.

Regardless of the type of component, the mechanical design skill must evolve -- sometimes referred to as Design for Additive Manufacturing (DfAM). As with any manufacturing process, a good designer must consider the limitations of the process and also the opportunities that arise from leveraging AM. Consider the example of the Central Fuel Injector. The internal passages which bring gas and liquid fuel from the inlets to the exit holes are carefully designed and optimized in ways not possible by conventional methods.

Unfortunately, the internal geometry cannot be shown, but this is where the DfAM skill becomes crucial. Combined with analysts and other engineers, flow optimizations can be made all while confined within a very tight space. The skills to do this work (fluids analyses, mechanical and stress analyses, etc.) already exist within R&D organizations. However, given that AM is a digitalized manufacturing technology, this opens to the door to new simulation and optimization tools that engineers can employ – for example, to model the AM process to predict mechanical properties and residual stress. Another salient example is topology optimization tools, which account for the AM process and manufacturing constraints, overlapped with physics models for flow, or thermal stress. These new tools can shorten development times significantly and be transferred directly to an AM component.

CONSIDERATIONS FOR INDUSTRIALIZING AM

As the above subsections have outlined, there are numerous commercial and functional benefits that can be realized by leveraging AM. However, it is equally true that the infrastructure supporting AM for gas turbine manufacturing has plenty of room to improve. Everything from material properties and AM process development, engineering and design practices, component inspection and quality assurance must be re-thought to accommodate additive manufacturing and make it as safe, easy and economically viable as paper printing. The sub-sections below discuss some of the efforts the OEM is undertaking to achieve that objective.

Material and Process Development

The material produced by L-PBF is inherently different than forged or cast material because of the laser process building up the material, layer by layer. In order to produce functional components, these differences must be very well understood; some properties can improve with AM, while for others a debit is observed. The powder chemistry, particle size and the hundreds of machine parameters that influence the laser behavior, melt pool and heat dissipation will have varying effects on the outcome of the material. Moreover, microstructure must be studied to ensure that defects like voids and microcracks do not compromise the printed material.

At present, the OEM maintains a robust material database for certain alloys, giving engineers the ingredients needed. In addition, material and process development continue for known alloys, new alloys being developed and new machine types, which continue to enhance the design options for AM engineers. Specifically, the OEM is investing in new combustion and turbine alloy development in order to fulfil future component requirements.

Engineering and Design

The best AM designs are those which unlock previously unattainable results by challenging design practices and taking advantage of the AM process. Often, existing design rules are decades old and based off of limitations in conventional manufacturing methods. However, it does not come easily or quickly for an engineer to begin making these changes, and it is even slower for entire organizations. Organizations are faced with the challenge of wanting to adopt a new, promising manufacturing technology while maintaining a safe and responsible approach which does not jeopardize their products or their customers.

One strategic approach that the OEM has employed is to form a dedicated global AM organization, focused on design, manufacturing and technology development. In this way, all the necessary engineering disciplines are working together and incubate the adoption of AM. Most importantly, this gives engineers the crucial time to practice and gain experience. By developing and improving internal specifications and guidelines, the entire process from design through to component validation is put through the same rigor as any other conventionally-produced engineering work.

Inspection and Quality Assurance

By introducing this new technology, there has also been a need to review and develop additional supporting quality assurance steps to ensure a reliable process chain. During the manufacturing process, imaging techniques are used to collect information on the laser's melt pool in order to identify a defect in real-time. This opens the door correcting issues in-situ before they are buried under subsequent layers and embedded within the printed material.

In terms of quality assurance, it must be possible to trace a component back to the powder batch and its properties for each build job. This is especially true when powder is being recycled and reused. To keep track of this data, the OEM uses a digital solution by introducing a manufacturing execution system (Navrotsky, Piegert 2018).

Another aspect of industrializing AM within a quality context is to adapt the internal Product Development Process (PDP). This is the gated engineering process which monitors a design, from concept through to production, to ensure adequate engineering quality. As components are manufactured, the Process and Product Qualification (PPQ) process is also adapted to prove that a robust and repeatable process is in place in order to qualify a part by AM. This is done for "as-printed" components, as well as the finished parts or assemblies that eventually get fitted onto an engine.

Digitalization

The backbone to the industrialization of additive manufacturing is digitalization. The entire process chain, from component design through to inspection and post-processing is all driven by digital solutions. As a result, design and CAD software must interact with product life-cycle management (PLM) tools. These tools must also interface directly with the AM machines, regardless of the machine type.

Within the AM machines, some fundamental elements of process monitoring remain within the domain of AM equipment manufacturers; off-limits to users due to IP-protected systems. The vision for the future is an Open Platform Communication, utilizing industrial standards while still ensuring data security. By combining in-situ monitoring with big-data solutions, the goal is to predict material characteristics and guarantee material quality without the need for test bars and witness coupons, along with their respective destructive and non-destructive tests required today, which are both costly and time-consuming (Navrotsky, Piegert 2018).

Finally, within the AM production facilities, workflow and production routers, as well as inspection and post-processing must all be digitalized and linked together, providing an end-to-end "digital twin" of each part made by AM.

CONCLUSION

Gas turbines play a critical role in addressing the evolving needs of oil and gas and power generation applications. The drive to continuously reduce costs often translates into increased production requirements, as well as improved operational efficiencies. In addition, the environmental footprint of operations is increasingly an area of focus, with more stringent regulatory limits being applied. Gas turbine OEMs are therefore encouraged to develop solutions which provide value to existing equipment fleets, as well as upgrades to new units within the portfolio.

Additive manufacturing is a disruptive technology that lends itself particularly well to the production of combustion and hot gas path components in gas turbines. As this paper outlined, in the design and development phase, AM provides the ability to rapidly prototype and iterate upon new ideas. Eventually this can turn into serial production where traditional stipulations such as production volume or long lead dies and other tooling no longer present commercial challenges. And finally, in service, AM introduces new possibilities for component repair as well as the ability to maintain the supply of legacy spare parts.

NOMENCLATURE

AM = Additive Manufacturing
CAD = Computer-aided Design
CFD = Computational Fluid Dynamics
DLE = Dry Low Emissions
EDM = Electrical Discharge Machining
EOH = Equivalent Operating Hours
FEA = Finite Element Analysis
GT = Gas Turbine
L-PBF = Laser Powder Bed Fusion
OEM = Original Equipment Manufacturer
PLM = Product Lifecycle Management
PPQ = Process and Product Qualification

SLM = Selective Laser Melting
TMF = Thermo-mechanical Fatigue

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