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INDUSTRIALISATION AND FIELD EXPERIENCE OF GAS TURBINE COMPONENTS MADE BY ADDITIVE MANUFACTURING

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1. Abstract

Additive manufacturing is delivering real-world benefits to the Siemens gas turbine portfolio throughout the entire product lifecycle. This game-changing technology was first introduced as a repair process in 2013, then subsequently as a spare parts and aftermarket solution in 2016. Today, Siemens in continuing to develop and adopt additive manufacturing for its portfolio of aero-derivative, industrial and heavy-duty gas turbines. In doing so, Siemens is also committed to fully industrialising the technology and bringing it into the mainstream for manufacturing and supply chains of gas turbines.

This paper will explore several different applications of additive manufacturing in Siemens gas turbine components along with the associated benefits being delivered, validation activities and challenges.

2. Introduction

Additive manufacturing (AM) is a disruptive technology with great applications for new unit as well as service offerings, enabling component performance enhancement as well as a substantial reduction in development cycle time and component lead time. Additive manufacturing is a new dimension in the integrated design and manufacturing space, introducing exciting product development opportunities. With this technology, complex components with a high degree of functional integration can be produced as one integral part with higher reliability, improved performance and lower life cycle cost. Within the context of gas turbines, this technology lends itself nicely to combustion and turbine components, as they are highly complex as a result of their functions and harsh operating conditions.

The breakthrough of AM is becoming a key enabler throughout the entire Siemens gas turbine portfolio. This paper will explore the various applications for AM, the benefits realised by Siemens with several component examples, and will also discuss the successes and challenges of fully industrialising AM.

In the context of this paper, the AM technology being discussed is Selective Laser Melting (SLM), otherwise known as Laser Powder Bed Fusion (L-PBF).

3. Applications

Throughout the entire component lifecycle, AM is enabling new benefits for OEMs and gas turbine operators alike. 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. This section will explain only a few of the completed and ongoing AM development programs. Overall, Siemens is pursuing an aggressive roadmap to deliver over 200 additive manufacturing components for gas turbines by 2025.

a. Rapid prototyping

The notion of using additive manufacturing for rapid prototyping is certainly not new. However, as the technology has matured, the usefulness of AM prototypes has increased dramatically. Not only are parts produced quickly thus shortening validation times, but they are dimensionally accurate and durable enough for full load testing. The most prominent example of this within Siemens was the full-load engine test of high-pressure turbine blades for the SGT-400. Several blade cooling designs were tested at the same time, shortening the program considerably. The blades were manufactured using Siemens' proprietary SLM process for CM247, a difficult-to-weld nickel superalloy common to gas turbines.

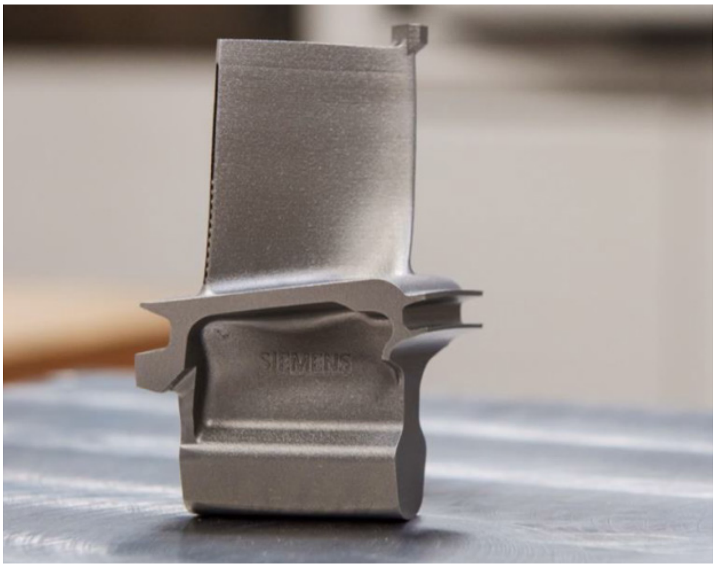

Figure 1: Prototype of additive manufactured turbine blade

Fully functional prototypes have also proven to be extremely valuable in combustion testing, where parallel development tracks can be implemented to validate several concepts in the same test campaign. This provides R&D engineers with faster feedback and better test data used to improve predictive models, especially for highly complex simulations for air-fuel mixing and combustion dynamics (acoustics).

Lastly, by developing and prototyping with additive manufacturing in mind, component designers are able to realise complex and intricate designs with higher performance than conventionally made parts. In doing so, ambitious development targets can be set with a higher likelihood of being achieved. In addition, the discipline of designing for additive manufacturing (DfAM) is emerging as an important subset of the mechanical design skill. The importance of DfAM will be discussed further in Section 4.b of this paper, however it is worth noting here because during the prototyping stage, a design engineer can be granted more freedom to experiment with different concepts and quickly improve manufacturability.

b. Serial manufacturing

Despite prototyping with additive manufacturing, some components will be manufactured by conventional methods. For example, in the case of the SGT-400 turbine blade; an additively manufactured blade will not have sufficient mechanical or metallurgical properties as directionally solidified or single-crystal castings. On the other hand, there are many components whereby AM for serial production is not only viable, but it is preferred. There are many such examples within the Siemens portfolio.

SGT-A35 (Industrial RB211) Non-DLE Dual Fuel Injector

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 was the introduction of the AM burner head on the SGT-A35 Dual Fuel injectors for the non-DLE variants of the G and GT series gas turbines. The head has traditionally been a complex assembly requiring 6 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.

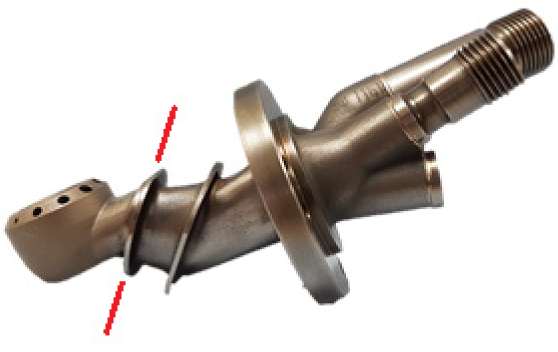

Figure 2: AM head to the left of the red line, welded into the injector assembly.

In order to validate the AM component, Siemens 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 behaviour of the whole combustion system. In addition, fuel placement within the combustor was carefully validated. In other words, not only was it important to validate how much fuel is delivered, but also how the fuel is delivered. In total, this translated to sophisticated testing using laser diagnostics to measure liquid spray droplet distribution.

In terms of component life, one of the first questions asked about AM parts is usually about material properties. Siemens has a profound understanding of the metallurgical, physical and mechanical properties of the printed material, based on extensive material qualification and testing that Siemens has done throughout its manufacturing network, namely at a production facility in Sweden, and at Materials Solutions, A Siemens Business, in England. With this data, Siemens engineers perform the typical finite-element analysis (FEA) to evaluate the thermal, stress and dynamic behaviour of the AM component. This was also verified with experimental testing. Most notably, Siemens developed a thermo-mechanical fatigue (TMF) test setup, whereby the AM and conventional components were thermally cycled in engine representative conditions thousands of times to the point of failure. This test proved that the cyclic life of the AM injector is 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.

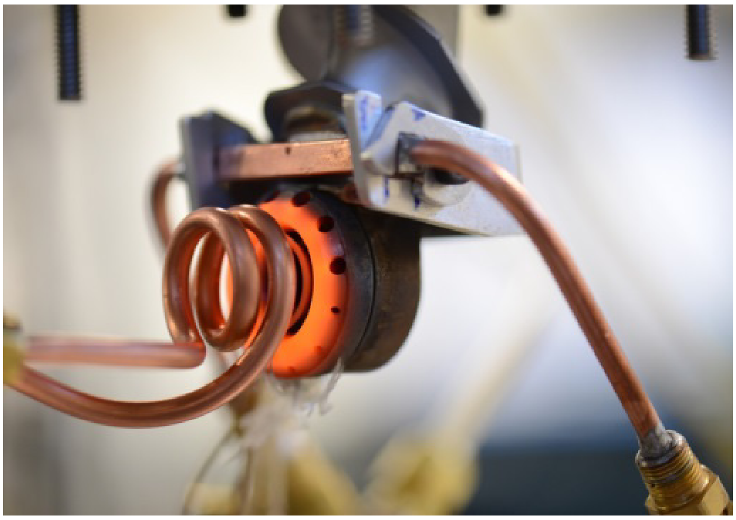

Figure 3: Conventional injector in thermo-mechanical fatigue (TMF) test apparatus.

This solution was fully validated with engine testing in early 2019 and was released into service, starting commercial operation in February 2019. The AM component is now the new production standard for all SGT-A35 non-DLE units. The process will also be utilized for the repair of fuel injectors in the operational fleet.

SGT-A35 (Industrial RB211) DLE Dual-Fuel Central Injector

Improving product capability is another key outcome of applying AM technology. In the case of the SGT-A35 Dual Fuel DLE combustion system, Siemens has been able to eliminate an operational limitation inherent to the original design that was a symptom of conventional manufacturing constraints. 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 hrs in service).

After full validation and testing similar to the non-DLE injector, it has now been released as a production standard.

Figure 4: Additive manufactured dual fuel injector for SGT-A35 Dry-Low Emissions (DLE)

c. Repair

Component repair is also as an interesting application for AM. Two types of repairs are enabled by L-PBF. The most obvious is when repair parts are made by AM. Recall the SGT-A35 non-DLE dual fuel injector explained in Section 3.b. 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. Siemens has developed a burner tip repair procedure by SLM for the SGT-700 and SGT-800. 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 [1].

Details of SGT-700 and SGT-800 Burner Tip Repair

Burner tip repair had always been done by conventional methods – i.e. cutting off the tip and replacing it with a pre-manufactured one. However, in 2013 Siemens launched the first burner repaired by SLM technology [1]. This was the first step Siemens took to bring this new technology out from the laboratory into an industrial production environment.

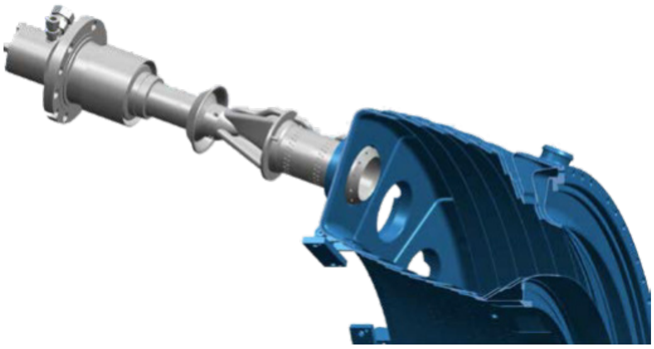

Figure 5: Burner and combustor configuration for SGT-700 and SGT-800.

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 thermomechanical 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: SGT-700 and SGT-800 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 [2].

The new SLM repair process consists of the following major steps:

a) Remove the damaged tip by machining
b) Position the burner in a special fixture
c) Position the CAD model on the substrate burner face with the help of a position-finding camera system
d) "3D-print" a new tip in place
e) Remove powder particles from cavities
f) Disassemble the fixture

Machine Customisation

The DLE (Dry Low Emission) burners of the SGT-700 and SGT-800 are approximately 720 mm tall. To accommodate an entire burner, the AM machine was re-designed in critical areas such as the z-axis responsible for the precise downward movement of the powder bed and the burner substrate during the layer-by-layer manufacturing. A unique holder-lifter device had to be designed in order to guarantee an ergonomically acceptable work position for the operator when loading and unloading the burner from the machine as Figure 7 reveals. This re-design also impacts the powder handling and gas flow characteristics in the process chamber of AM machine. These customisations were done in conjunction with the AM machine OEM (EOS GmbH).

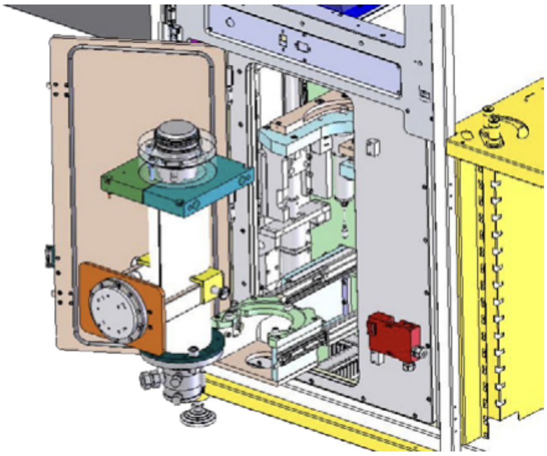

Figure 7: New machine design with novel z-axis configuration and process chamber design (courtesy of EOS GmbH)

Field Validation and Inspection

Since the introduction in 2013, several burner sets have been put in operation and there has not been any reported faults related to any AM repaired burner. There has also been detailed inspections of burners at a Siemens material laboratory, both by destructive and non-destructive testing (NDT). NDT has been carried out via ultrasonic (immersion technique) and penetrant (fluorescent dye) testing prior to destructive examination of the burner tips. The burner tip areas subject to examination are shown in Figure 6.

The inspections showed that all tested burners were in serviceable condition. The penetrant testing did not reveal any defects on the surface. Oxidation could be seen up to 50 µm into the material. Some areas revealed grain boundary attack as well as light surface oxidation. The bond coat appeared to be in good condition with aluminum-rich phases still present, and finally the hardness of the printed material between the pilot holes and the burner tips exhibited little change [2].

Current status and accumulated operation experience

Since the introduction in 2013, Siemens has successfully repaired and put in operation well over 1000 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. In 2017 the fleet leader has accumulated more than 30,000 EOH (equivalent operation hours) and the unit with most start / stop cycles has recorded more than 500 starts [2].

d. Additive Manufacturing for spare parts on demand

The on-time availability of spare parts for maintenance and repair purposes is crucial for any gas turbine operator. Siemens as an OEM and experienced MRO company is therefore looking for concepts to improve the up time of their gas turbines through innovative service concepts, and additive manufacturing is playing an important role in this.

Through AM parts can be manufactured on demand with shortened lead times. This can be especially beneficial when replacing investment cast products because AM renders expensive casting dies obsolete. Not only are production costs and lead times shortened, but this also gives flexibility to the supply chain and gives Siemens the ability to upgrade component designs. Additionally, AM can be very cost effective in particular for smaller lot sizes where conventional manufacturing suffers from the ability to streamline production. All these criteria apply directly to spare parts, especially on legacy parts for retired engine variants. For Canadian operators specifically, this can be very important for the ageing fleet of Siemens' aero-derivative gas turbines (former Rolls-Royce Energy products).

SGT-1000F Pilot Burner Head

The SGT-1000F is a mature engine no longer offered in production. With its 24 burners in an annular combustion chamber, it is set-up similar to the well-known SGT5-4000F. Components of the combustion systems are especially attractive for additive manufacturing 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 Siemens' first "spare part on demand" as an AM component, shown in Figure 8.

Figure 8: Additive manufactured pilot burner head for SGT-1000F

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 3 times worse, shown in Figure 9 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 [2].

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 part from Siemens. Meanwhile, the engine has reached its first minor hot gas path inspection, surpassing more than 8,000 operating hours, without any issues or signs of any damage.

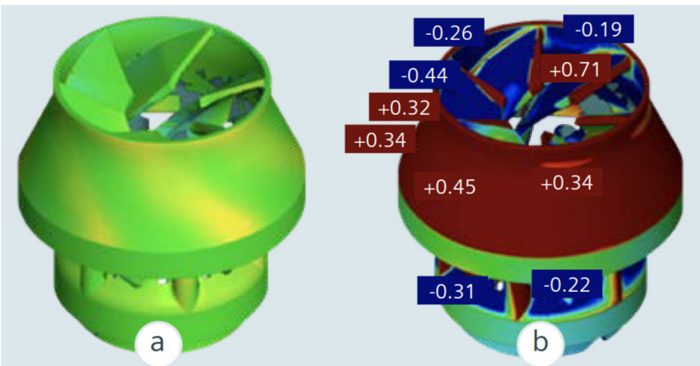

Figure 9: Geometric comparison between 3D-model and (a) SLM component as well as (b) investment cast component; red – positive deviation / blue – negative deviation

SGT-A35 Non-DLE Gas-Only Injector (Package 1)

A similar program is being completed for the gas-only legacy standard of SGT-A35 fuel injector, also known as the Package 1, where it has been developed as a fully additively manufactured component, requiring only some conventional subtractive machining to produce the finished part. This is a key enabler for customers operating a large fleet of legacy variants of the SGT-A35 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 a spare part on demand, like the burner head of the SGT-1000F. In addition, this component has suffered from manufacturing quality defects as a result of the difficult brazing assembly, which unfortunately has affected some operators. The AM solution 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. And similar to the SGT-A35 dual fuel injector, a one-piece solution instead of a brazed assembly eliminates a key failure mode which increases engine reliability.

4. Industrialising Additive Manufacturing

There is plenty of hype and attention surrounding additive manufacturing. It is true that there are numerous commercial or functional benefits that can be leveraged because of AM, as demonstrated by the many examples above. However, it is equally true that the infrastructure supporting AM for gas turbine manufacturing is in its infancy. Everything from material properties, engineering and design practices, component inspection and quality assurance must be re-thought to accommodate additive manufacturing. Siemens is at the forefront of AM industrialisation, with the long-term goal of making metal additive manufacturing as safe, easy and economically viable as paper printing. This section will only briefly introduce some of these efforts, as each sub-section represents a very profound field of study.

a. 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 AM can improve with AM, while for others a debit is observed. The powder chemistry, particle size and the hundreds of machine parameters will have varying effects on the outcome of the material. Moreover, microstructure must be studied to ensure that density and defects do not compromise the printed material.

At present, a robust material database exists for certain alloys, giving engineers the ingredients needed. In parallel, material and process development continue for new alloys, which will enhance component performance. Specifically, Siemens is investing in new combustion and turbine alloy development in order to fulfil future component requirements.

b. Engineering and Design for Additive Manufacturing

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 organisations.

Siemens' approach to this has been to form a dedicated global AM organisation, 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.

c. 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.

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 because Siemens is recycling and reusing powder, sieving and rejuvenating powder after several uses. To keep track of this data Siemens is using a digital solution by introducing a manufacturing execution system (MES) based on the latest standard of the Siemens SIMATIC IT [2].

Another aspect of industrialising AM within a quality context is to adapt the internal Siemens Product Develop 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.

d. Digitalisation

The backbone to the industrialisation of additive manufacturing is digitalisation. The entire process chain, from component design through to inspection and post-processing is all driven by digital solutions. Design and CAD software must interact with product life-cycle management tools, like Siemens NX and TeamCenter. 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, utilising 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 [2].

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

5. Conclusion

The advantages of additive manufacturing are enriching the Siemens gas turbines portfolio. From the early concept phase through to the in-service support of retired products, Siemens is finding creative and effective solutions. This manufacturing technology is yielding important benefits such as:

- Shorter development cycles;
- Functional and performance improvements;
- Component reliability;
- Simplified supply chain solutions;
- New and exciting repair and aftermarket solutions.

Moreover, Siemens is committed to bringing additive manufacturing into the mainstream and is working to industrialise AM for reliable, widespread use. This is being done by deploying a global organisation to develop the necessary sub-disciplines, most notably, the digital infrastructure necessary to drive this technology firmly into the fourth industrial revolution.

6. References

[1] Navrotsky, V., Graichen A., Brodin, H., Industrialization of 3D-printing for gas turbine components repair and manufacturing, VGB Conference “Gas Turbines and Operation of Gas Turbines 2015”, 06/07 May 2015, Lübeck / Germany

[2] Navrotsky, V., Piegert, S., Andersson, O., Graichen, A., Avdovic, P., Industrialization and current field experience of additively manufactured gas turbine components, The Future of Gas Turbine Technology, 9th International Gas Turbine Conference, 10-11 October 2018, Brussels, Belgium