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DEVELOPMENT AND VALIDATION UNDER ENGINE OPERATION ENVIRONMENT OF ADDTIVELY MANUFACTURED HOT TURBINE PARTS

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ABSTRACT

Additive Manufacturing (AM) has emerged as an innovative manufacturing method in comparison to traditionally subtractive method. Its unparalleled design freedom opened up the applications in gas turbine business where the efficiency improvement is consistently needed. While the AM application in combustion section has gained a lot of experience, the AM application in turbine hot gas path is still limited, e.g., most of the applications like vane 1 and vane 2 are limited to the gas turbines with relatively low operation temperatures. This paper presents the project where vane 1, heat shield 1 (HS1) and vane 2 in SGT-800 were redesigned with only AM enabled in-wall cooling schemes and these parts were tested and validated under the real engine operation environment. Through Design for Additive Manufacturing (DfAM), these parts were redesigned with lower cooling air consumption, reduced average metal temperature and more even temperature distribution. After that, these parts were additively manufactured in EOS M400-4 and post print quality checks were conducted to ensure the part quality. The quality check includes cut-up metallurgical investigation, hot air thermography test and water test, etc. All three AM parts were instrumented with thermo-couples and thermo-crystals, and tested under the full load engine operation condition. The crystal measurement results confirmed the reliability of the design tool as well as the design targets. For AM vane 1, a cooling air saving of more than 20% was achieved and the average metal temperature was reduced by 56 ºC from the baseline of the cast vane 1. For AM HS1 and AM vane 2, the cooling air saving is not significant, but the average temperature was reduced by approximately 80 ºC. This will result in significant increase in part life time, either to increase the part service interval or use it as basis for cooling air saving. With this validation under the engine environment, the implementation of these three AM parts is planned in the customer engines.

Keywords: AM, DfAM, gas turbine, vane 1, HS1, vane 2, SGT-800, thermo-crystal, validation, engine test.

NOMENCLATURE

k	Thermal conductivity, W/(m·K)
$\dot{q}$	Heat flux, W/m^2
t	Wall thickness, m
$T_{m,c}$	Temperature metal at cooled side surface, K
$T_{m,HL}$	Temperature metal at heat load surface, K
AM	Additive Manufacturing
CFD	Computational Fluid Dynamics
DfAM	Design for Additive Manufacturing
HS	Heat Shield
LPBF	Laser Powder Bed Fusion
OEM	Original Equipment Manufacturer
TMF	Thermo-Mechanical Fatigue

1. INTRODUCTION

AM refers to a production process in which components are printed layer by layer from information provided through digital 3D design data. Among various AM technologies, Laser Powder Bed Fusion (LPBF) is the most suitable one for high quality requirement, e.g., components in gas turbine applications [1, 2]. In gas turbines, Original Equipment Manufacturers (OEMs) have consistently looked for ways to have more efficient parts so that the turbines can be operated at higher firing temperatures with higher efficiency. After decades of continued improvement, this effort is often limited by the traditional manufacturing method, i.e., subtractive manufacturing technology. With AM, a completely new design space has become possible. Some of the main design benefits of metal AM, specifically the LPBF process, for gas turbine applications include improved efficiency through new design features and life cycle improvement through increased structural integrity or reduced metal temperature. This allows gas turbines to evolve beyond today's most advanced performance. For example, improved mixing in the combustion system allows for higher firing operation. Other benefits include the potential to use less resources in production processes, provide reduction in development time, and drive faster repair and manufacturing.

While the AM technology itself is revolutionary, the implementation into gas turbine applications needs to take an evolutionary and stepwise approach, i.e., thorough validation before being introduced into customer engines. While the implementation of combustion parts has been very successful in Siemens Energy, this paper will focus on the turbine hot section instead, i.e., vanes and heat shields. Over the last years, a number of AM turbine components have been validated and implemented. For example, a redesigned AM HS1 of SGT6-8000H was tested under the engine operation condition in the test bed in Berlin in 2018 to confirm the feasibility of AM components [3]. Furthermore, vane 1 and vane 2 have been used in V64.3 engine and SGT-700 in customer sites with significant operation experience, respectively [4, 5]. Currently, AM vane 1 in V64.3 has an operation experience of 25k operation hours while vane 2 of SGT-700 has generated more than 15k operations hours. Both components worked very well. However, neither V64.3 or SGT-700 engines operates in extremely high firing temperatures like SGT-800 or HL class engines.

To bring AM components to another level, a project was set to apply AM components into a high temperature operation product SGT-800. For this, three turbine hot gas path components, vane 1, HS1 and vane 2 in SGT-800 were redesigned, additively manufactured, and validated via thermo-crystals under full load engine operation condition. This paper covers the design change, design procedure, quality check, crystal validation and the comparison against the conventionally cast parts. The results will contribute to the next step of full implementation in the future.

2. AM COMPONENT DESIGN AND GAS TURBINE APPLICATION

In this part, details will be laid out for how AM parts can be used in SGT-800 with benefits. AM vane 1 will be used to illustrate the DfAM work.

2.1 AM benefits via DfAM

One benefit from AM is its short lead time in manufacturing as it does not need tooling. This results in a lot of applications like rapid prototyping, rapid tooling and rapid repair. The other benefit is that it can create high performance components with its only AM enabled features. This requires major redesign effort called DfAM. For hot gas path turbine components, DFAM provides at least three different benefits.

(1) Aero performance improvement

Aerodynamic profile has an effect on gas turbine efficiency directly. The traditional airfoil shape manufactured by precision casting is typically not bowed due to manufacturing constraints, e.g., casting limitations and the need to place the insert or impingement plate in the cavity to cool down the airfoil. This manufacturing constraint can be eliminated by AM as the impingement plate is no longer needed due to the AM in-wall cooling feature. With this design freedom provided by AM, any new type of airfoil shape and contoured platform becomes possible with today's highly powerful design tool, CFD. One schematic example is in Figure 1 where a new possible airfoil shape and the current vane 1 shape are compared. The new optimized airfoil shape and platform can minimize the aerodynamic loss due to secondary flows. The other aspect of aerodynamic improvement is in trailing edge. With AM, it is possible to have a very thin Trailing Edge (TE), for either center line ejection or cut-back design. In both cases, AM in-wall cooling design can cool down the part more as opposed to sufficiently while it is always challenging in the traditional cast design.

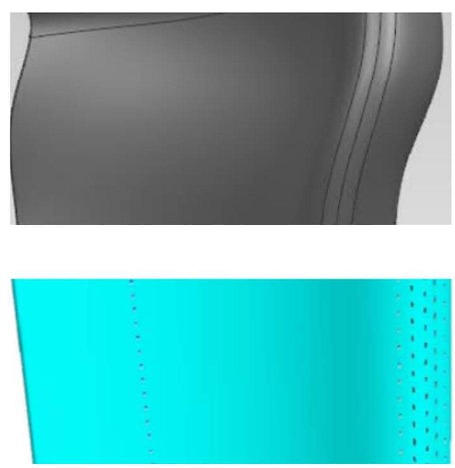

Figure 1: Possible AM airfoil (above) and the traditionaly cast airfoil (below) of vane 1 SGT-800

To validate the aerodynamic performance under the engine operation condition, a full set of components would be needed. Having a few parts with different aerodynamic shapes will not show the design benefit. It also creates issues in engine operation.

(2) Cooling air saving

The main focus while designing the cooling scheme was to reduce temperature gradients in the part and reduce coolant consumption. To achieve these goals, an in-wall cooling scheme was chosen. The cooling channels are placed as close to the hot gas path surface as possible, while the mechanical requirement is met.

Assuming a constant heat flux boundary condition on the hot gas path surface and constant maximum metal temperature in the part, such reduction in wall thickness increases the surface temperature for internal heat transfer. This can be shown in Figure 2 and the 1D heat conduction equation (Eq. 1):

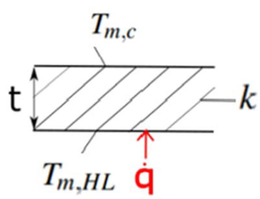

Figure 2: Heat conduction through wall

$$T_{m,c} = T_{m,HL} - \frac{\dot{q}t}{k} \qquad (1)$$

In the above equation, $\dot{q}$ is the specific heat flux, k is the thermal conductivity of the material, t is the wall thickness, Tm,hl is material temperature on the heat loaded surface and Tm,c is the surface temperature on the cooled side. Eqn. 1 shows that the cooled surface temperature will increase with a reduction in wall thickness. Therefore, the coolant can also reach higher exit temperatures which would typically mean an increase in cooling efficiency. With this, the AM parts can achieve cooling air saving via AM in-wall cooling scheme.

(3) Reduced metal temperature for longer component life time

Under certain conditions, some gas turbine customers may prefer longer service intervals instead of high turbine efficiency. In this case, DfAM can keep the same cooling air consumption while reducing the metal temperature significantly. Due to the flexibility of AM cooling channel placement, the metal temperature distribution can be more even as well. With the combined effect of these two, the AM components can operate for longer periods of time. It is certainly possible to achieve both cooling air saving and temperature reduction together, depending on the application.

The other benefit of DfAM is the reduced cost, e.g., part consolidation by eliminating impingement plates in vanes or heat shields. However, there is still much work to do to further lower the cost for AM components.

2.2 AM applications in SGT-800

Launched in 1997 as a 43 MW machine under the name GTX100 [6-8], the SGT-800 had been updated several times under the stepwise evolutionary development based on experience and proven design solutions so that high reliability can always be assured. Currently, the simple cycle power generation (ISO) is up to 62 MW and the combined cycle efficiency is above 60%. With more than 7 million equivalent operation hours of fleet experience and the overall fleet reliability of 99.8%, SGT-800 has become the flagship product in Siemens Energy’s gas turbine portfolio. More than 370 units have been sold worldwide.

To continue the successful journey of SGT-800, effort has been carried out to check how AM technology can be utilized in SGT-800. For combustion, several AM applications have already been implemented, e.g., burner repair [2]. For turbine section, a brainstorming session was carried out and different options were explored. In consideration of benefit, cost, technology challenge, and risk, three components have been chosen for AM applications: vane 1, HS1 and vane 2 as shown in Figure 3. A technology project was set up to redesign these three parts by using AM with the goal to either reduce cooling air consumption or reduce metal temperature for longer life time. In comparison to previous applications like V64.3 and SGT-700, this application will bring the AM technology into even higher operation condition in SGT-800.

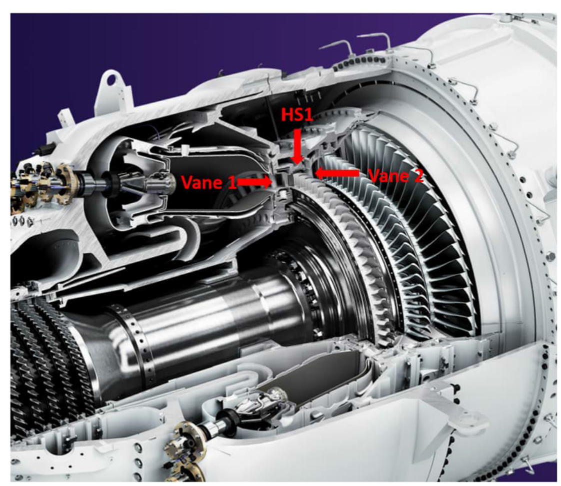

Figure 3: Vane 1, HS1 and vane 2 in SGT-800 turbine section

Even though AM design can result in aerodynamic improvement, it was not in the scope of this study. As mentioned, a full set of the components in one stage is needed to demonstrate the aerodynamic benefit under engine operation condition. That will increase the project cost, time and complexity significantly.

Therefore, the decision was made to keep the existing aerodynamic shape, and only cooling features were changed for vane 1, HS1 and vane 2. The project goal was to save the cooling air or reduce the metal temperature for longer a life time or both. With that, only a limited number of AM components needed to be manufactured and tested, which is called rainbow test.

2.3 AM Design for vane 1

For all three AM components: vane 1, HS1 and vane 2, the aforementioned AM in-wall cooling was used. Depending on the local boundary conditions, the placement of the cooling channels was optimized, e.g., pitch and channel size. Due to the limited space in this paper, only AM vane 1 will be discussed here in detail as an example.

(1) Geometry and cooling channel placement

The cast vane 1 in SGT-800 uses impingement cooling and convective channel cooling for airfoil and platforms. To do this, an impingement plate is needed. For AM, the cooling channels can be printed inside the wall which is called in-wall cooling. Figure 4 illustrates the change of cooling scheme from the impingement cooling for outer platform of the cast vane 1 to the in-wall cooling scheme in the new AM vane 1. One can see that impingement plate is no longer needed in the AM design which reduces the cost and the manufacturing complexity. In addition, one can see the distribution of the cooling channels in AM vane 1 is locally optimized, depending on the external boundary condition. This will result in more uniform temperature distribution.

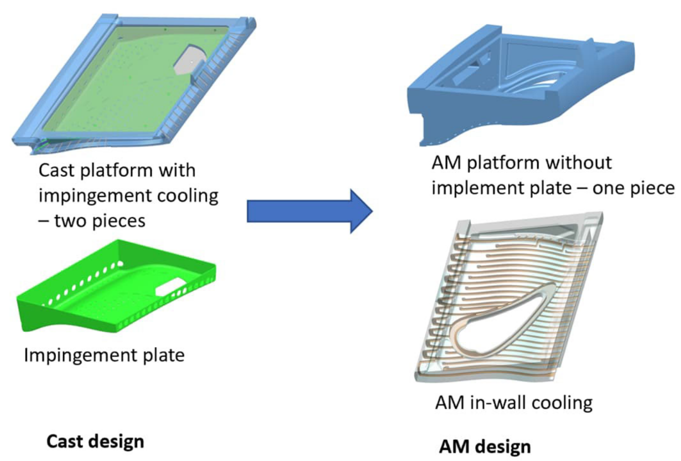

Figure 4: From impingement cooling in cast design to AM in-wall cooling for outer platform of vane 1 of SGT-800

(2) Thermal calculation

The heat transfer design was conducted by using an internal design tool which can handle the AM in-wall cooling features easily. For the boundary condition on the hot gas side, it is the same procedure as the traditional cast vane design. The critical point in AM heat transfer design is how to predict the friction factor and heat transfer coefficient in AM channels. Those channels have a higher surface roughness than the ones manufactured by Electrical Discharge Machining (EDM) or precision cast. Siemens Energy has spent a lot of effort in understanding the effect from a variety of parameters, e.g., diameter, build angle, build plate position, etc. The experimental tests were conducted in the internal fluid lab in Finspang [9], Sweden as well as the external partner Penn State University in the US [10, 11]. From these research results, design correlations were developed and used in this project. Based on the boundary conditions from internal and external surfaces, the metal temperatures can be predicted. The results from the thermal calculations will be used to predict the component's life time.

The same design procedure was carried out for HS1 and vane 2. All these will be validated by the thermo-crystal test under engine operation condition.

3. MANUFACTURING AND QUALITY CHECK

The redesigned parts were additively manufactured. The post-print quality checks were developed to ensure part quality.

3.1 Manufacturing process

After the thermal design and life time calculations are finished, a 3D CAD model of the component will be created. In addition to that, material, process- and machine-specific data are needed to manufacture a part by LPBF. Prior to the build process some information not contained in the CAD dataset must be added. For example, the positioning and orientation of the part in the build space as well as process-specific features like support structures. Furthermore, in a step called slicing, the CAD model is divided into layers of the same thickness. With this data, the part can be manufactured additively in a print machine. All AM vane 1, HS1 and vane 2 of SGT-800 were additively manufactured in EOS M400-4 printers.

The previous experience showed that the part distortion becomes bigger when the part size increases. To minimize print distortion, the following procedure was used for these three parts: Firstly, the nominal geometry is used for print simulation by using a commercial tool. The predicted distortion is used to adjust the nominal print model. Secondly, the adjusted print model is used to make print trial. After printing, the part is scanned with white light optical scanning. The scan results were used to validate and adjust the print model further. With this, it became the final print model for this test project. In case of production project, it is the final production print model. With this approach, the part distortion is minimized. With this, AM typically results in smaller part dimension distortion as well as more consistent distortion than the traditional casting manufacturing.

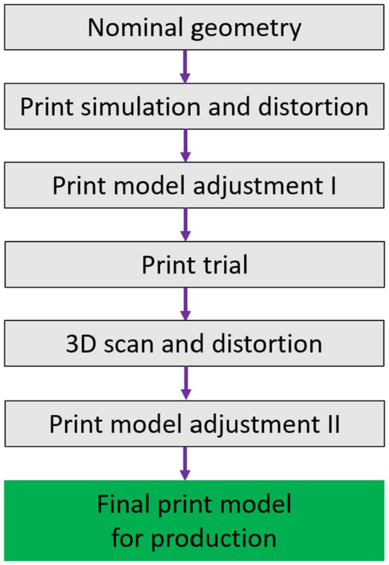

Figure 5: Print preparation process

3.2 Quality check

The introduction of the AM in-wall cooling concept has made the parts more efficient, but the complex cooling channels result in big challenges in the manufacturing quality check process. In addition to the standard cold flow tests for turbine components, a few other tests were also used, e.g., thermal image test and water test for these AM parts. The residual powders in these channels must be emptied during the depowdering process. To guarantee this, two individual tests were used to make sure the channels are powder free: thermal image test, also called hot air thermography test and water test. Thermography test uses infrared camera to record the temperature change of the vane which is suddenly heated with hot air via its cooling channel system. Any channels blocked by powder will not be heated so that it is visible in the image captured by infrared camera. For water test, any blocked channels will not see water out at the outlet. Figure 6 clearly shows the internal cooling channels are open for the AM vane 1 outer platform from the thermography test, while Figure 7 shows the water jets from the exit holes for this part. All test parts have passed both thermal image and water visualization tests.

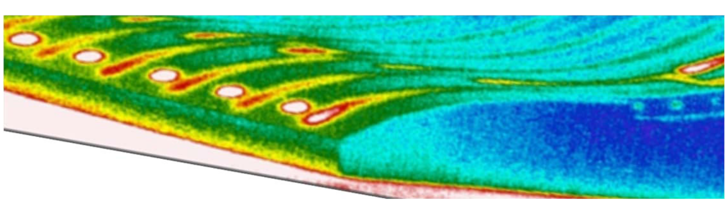

Figure 6: Thermal image of outer platform for AM vane 1 of SGT-800 from thermography test

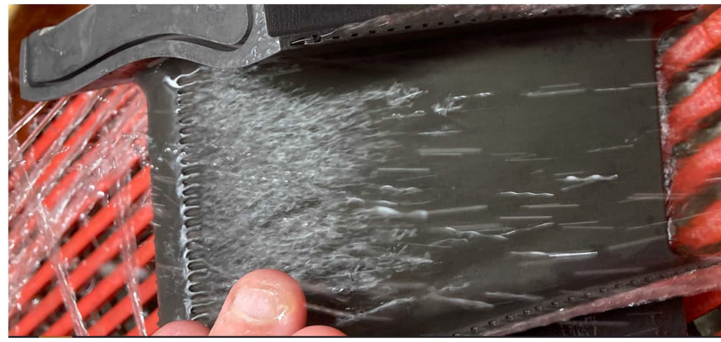

Figure 7: Water visualization of AM vane 1 of SGT-800

In addition, microstructure analysis and material test were also carried out to make sure the print process went well. One used method was to do cut-up investigation for these components and look at their microstructure. One can check if there are cracks in the parts, or look at the grain sizes in different build orientations. Typically, the AM material has smaller grain sizes comparing to its cast part, but the design process has already taken consideration of that. Figure 8 shows the examples of some cut-up results for AM vane 2. The other method is to do mechanical test for the test bars printed together with the part print. Typically, any defects during the print process can be captured when tensile test is conducted for these test bars.

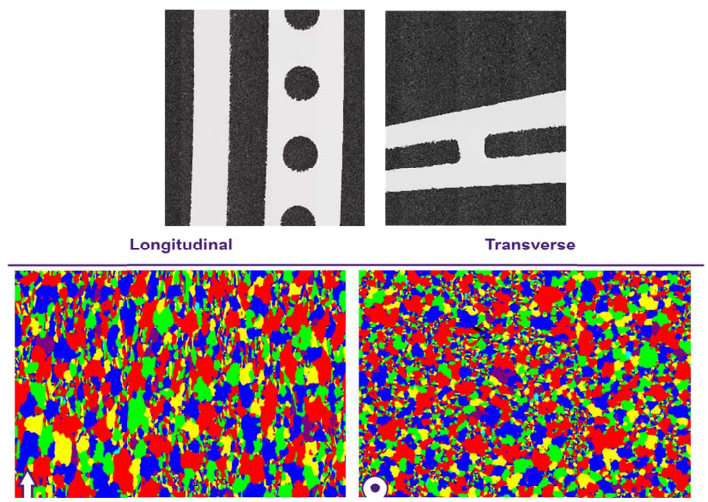

Figure 8: Cut-up investigation for AM vane 2 of SGT-800

4. THERMO-CRYSTAL VALIDATION UNDER ENGINE OPERATON CONDITION

A validation test was planned and carried out for these AM components. The goals of the test were to validate design methodology, identify improvement potential, compare AM designs with cast designs, and minimize the risk for engine implementation in customer engines.

Based on previous experience, the method of thermo-crystals was chosen for this test because of its high accuracy at high temperatures and its ability to map the whole component surface. The crystals have an accuracy of ±15°C at approximately 1000°C [12]. The crystals are silicon carbide crystals (SiC) that have been exposed to radiation (neutron scatter). The radiation has introduced defects that forces the crystal to a volumetric expansion. The crystals strive to return to their original state, and if exposed to high temperatures over period, the radiation-induced defects will be partly annihilated. This occurs if the process is stopped before the crystals have reverted to their original state. The diffraction angle between crystal layers can be recorded with an x-ray diffractometer. If either temperature or equivalent time are known, the other variable can be extracted from a calibration sheet. Due to small size of the crystals, i.e., a diameter of 0.2mm, more crystals can be used compared to thermo-couples. This provides an advantage that allows thermal gradients in a single component to be measured. This correct gradient is essential for main damage mechanisms like Thermo-Mechanical Fatigue (TMF), particularly for the front stage high temperature components that require cooling. A decision is thus made to use thermo-crystals to validate vane 1, HS1 and vane 2. It is consistent with the previous experience of thermo-crystal validation tests used during the development of the original 45MW version [12] and the upgrade version 50MW [3] previously.

The crystal test was performed during June 2021 in the SGT-800 test rig in the Siemens Energy test facility in Finspang, Sweden. The test went well and followed a pre-determined test profile. The sufficient test run on full load ensures the parts reach the stead-state condition, completely in line with the previous experience.

4.1 Crystal placement and test uncertainty

Crystals were placed on both AM components and the corresponding cast parts to illustrate a direct comparison. Three AM vane 1, four AM HS1 and three AM vane 2 were instrumented with thermo-crystals. The same number of corresponding cast components were also used, although less crystals were placed on these parts. In addition, a few parts of vane 1 and vane 2 were instrumented with ceramic pins with crystals on the top to measure the inlet gas temperature. This is critical to have accurate boundary conditions in the HT model calibration. A total number of 1342 crystals were used in the test. The distribution of these crystals in AM vane 1, AM HS1 and AM vane 2 is shown in Figures 9 – 11. The ceramic pins to measure the stagnation gas temperature were placed on the cast vanes.

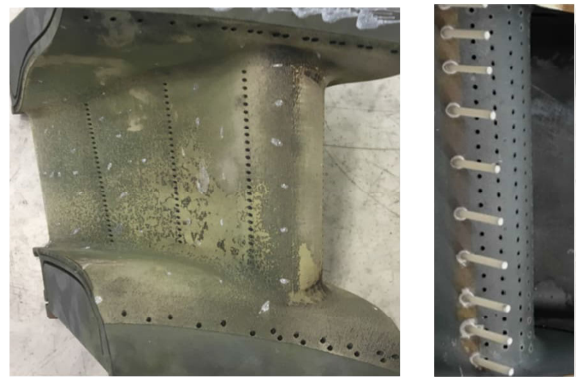

Figure 9: Thermo-crystal placement on AM vane 1 (ceramic pins on cast vane LE)

Figure 10: Thermo-crystal placement on AM HS1

Figure 11: Thermo-crystal placement on AM vane 2 (ceramic pins on cast vane LE)

While the crystal measurement has an accuracy of ±15°C, the instrumentation introduces additional uncertainties. In the installation, the crystals were placed in the bottom of cavity manufactured by EDM. Then ceramic cement was poured over the crystals to fill the holes. During this step there was a chance the crystals were displaced from their original placement. This displacement could have a high impact on the measured crystal temperature because of the high temperature gradient through the outer wall. To further understand the risks, several sensitivity studies were performed. It was found that the temperature variation between the minimum (bottom) and maximum (top) can vary by a certain amount, depending on the local boundary conditions. In the evaluation of the crystal results the most conservative case "crystal located in the bottom of the hole" was used. This corresponds to the coldest temperatures at the bottom of the crystal cavity and a correction to reach surface temperature is needed. This is used in the data analysis in the next section.

4.2 Temperature prediction against the measurement

The comparison of the measured temperatures by crystals and the predicted values by the in-house design tool (flow and metal temperature calculation) is presented in Figure 12 for AM vane 1. In the figure, the crystal readings and the predicted values are presented by the solid line and the dots, respectively. The uncertainty introduced by the crystal position is represented by the shadowed area. If the predicted value lies in the shadow area, the prediction should be considered sufficiently good. The results for AM vane 1 are presented in four different regions: inner platform, airfoil pressure side, airfoil suction side and outer platform. The following observations can be made:

(1) The predicted values are similar to the measured values. This demonstrates the methodology used by the in-house design tool works well.
(2) Overall, the predicted values are higher than the measured values, though not significantly. To be more on the safe side, the industry typically wants to be more conservative in the prediction, which will increase the reliability of the component in terms of life time. This also provides some opportunities for further improvement in cooling air saving.
(3) The prediction is rather consistent in terms of the deviation between predicted and measured values. This consistency makes the model adjustment slightly easier. Typically, the HT model will be adjusted based on the measurement data for further life time prediction. Ultimately, some adjustment strategy will be applied to other components and products as well.

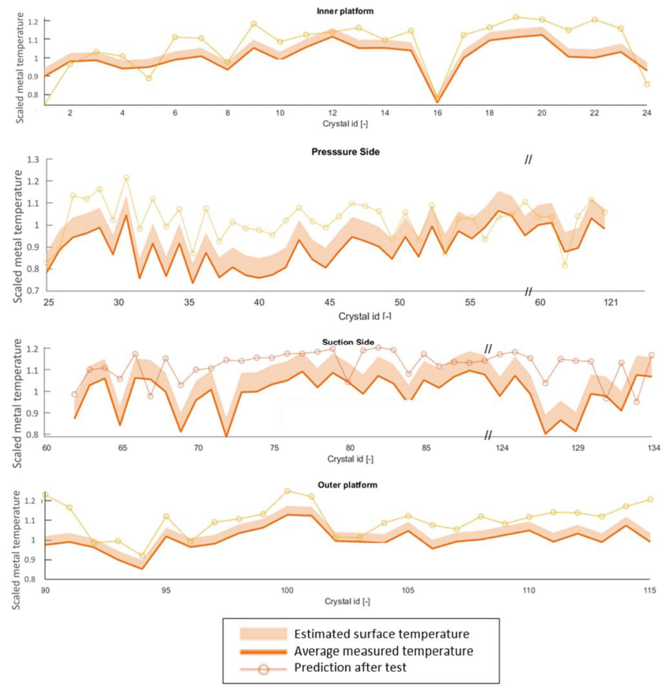

Figure 12: Crystal measured metal temperature against the predicted values for AM vane 1

In order to adjust the model to match the crystal test data, a few improvements were carried out. One of the first corrections that was applied is the adjustments of diameter and area to meet the cold flow test. Because of the size of the channels relative to the roughness, shrinkage and roughness could reduce the flow through area by a certain amount, depending on the laser incident angle and printer settings. The internal HTC was updated by using the results with help from an IR camera test [13]. Finally, the external boundary condition such as gas temperature and external HTC were adjusted in the crystal evaluation by using the results from multistage three-dimensional CFD calculation. After the above adjustment, plus a few local specific adjustments, the calculated temperatures are shown in Figure 13 where most of the predicted values are in line with the measurement. Some local points still deviate from the measurement, but it is common practice that it is very difficult or maybe impossible to match all the measurement points. The most important thing is that the overall distribution is physically reasonable, and maximum temperature is lower than the allowable temperatures. This calibrated HT model certainly meets all these requirements. Therefore, one of the crystal validation purposes for the AM designs was fulfilled, e.g., validate the design methodology. This paves the way to introduce these AM components into the customer engine operation in the future.

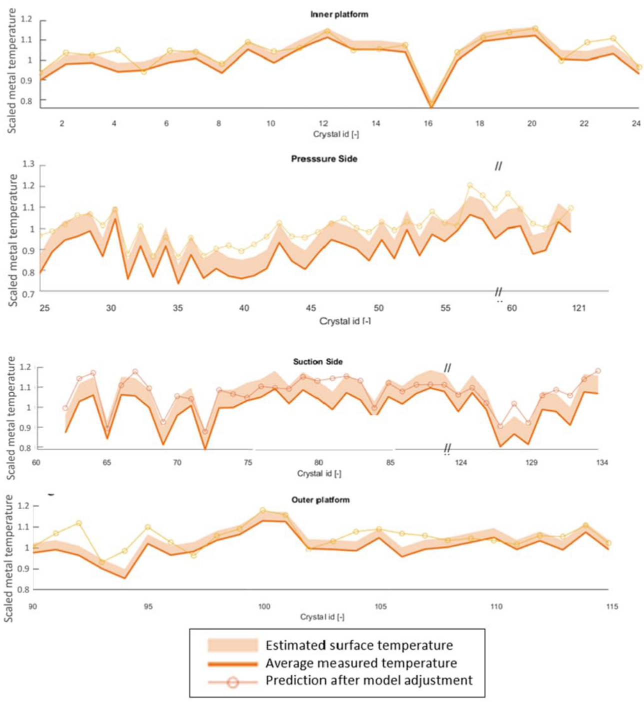

Figure 13: Metal temperature predicted by adjusted model against the crystal measurement for AM vane 1

4.3 Comparison between AM and cast parts

In addition to the validation of the design methodology by looking at the predicted and measured metal temperatures, it is interesting to compare the performance between AM parts and cast counterparts. For vane 1, the metal temperature distributions are shown with the same scale in Figure 14 and Figure 15 for AM part and cast part, respectively. While the AM vane 1 has more than 20% less cooling air consumption than its cast counterpart, the AM vane 1 still achieved a lower average metal temperature. The average temperature reduction is 56 ºC. The maximum temperature is also reduced by roughly the same amount. In addition, one can see that the metal temperature distribution of the AM vane 1 is much more even compared to the cast vane 1, thanks to the flexibility in placing cooling channels locally. With the combined effect of lower average temperature and more even distribution, the AM vane 1 will achieve a longer life than the cast vane 1.

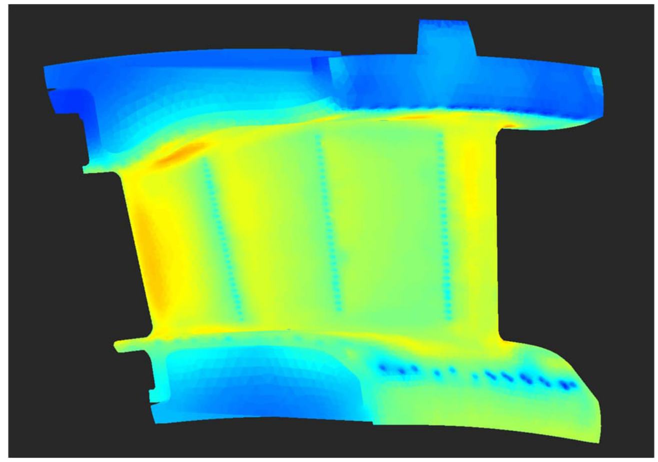

Figure 14: 3D metal temperature distribution predicted by calibrated model for AM vane 1 of SGT-800

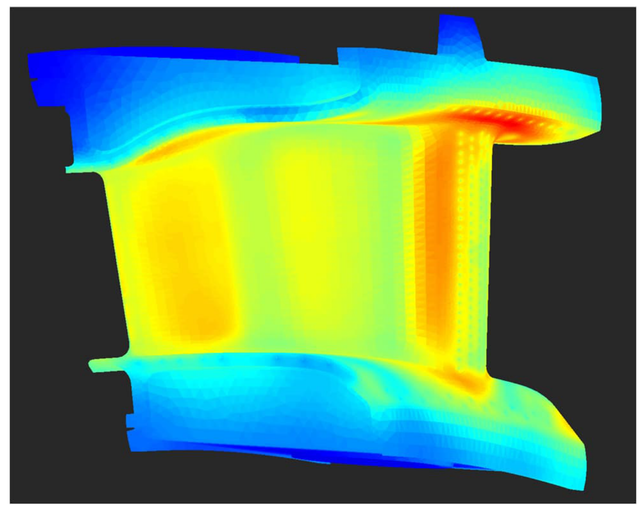

Figure 15: 3D metal temperature distribution predicted by calibrated model for cast vane 1 of SGT-800

Another way to compare the AM design and the cast design is to plot the crystal measurement results directly in the same figure. Such comparison is presented in Figs. 16-18 for the crystal readings of AM parts and cast parts for vane 1, HS1 and vane 2. For vanes 1 and 2, the plot is done at the middle section of airfoil while for HS1, the positions are a bit random. However, the same crystal number always means the same position for the AM and cast parts. It is clear that all three AM parts have achieved lower average metal temperature. For the AM HS1, the average metal temperature was dropped by approximately 80 ºC. For the AM vane 2, the average metal temperature was dropped by approximately 70 ºC. With this result, all three AM parts have achieved the original design goals.

Figure 16: Crystal readings for AM and cast vane 1 of SGT-800 at airfoil middle section

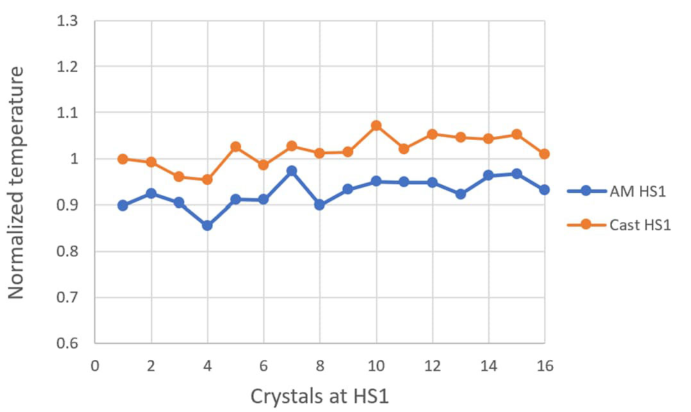

Figure 17: Crystal readings for AM and cast HS1 1 of SGT-800

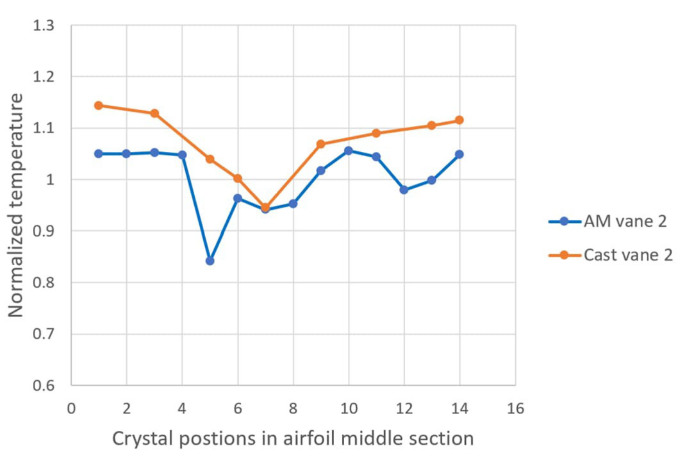

Figure 18: Crystal readings for AM and cast vane 2 of SGT-800 at airfoil middle section

5. FUTURE PERSPECTIVE

The validation test at the engine operation condition has demonstrated AM vane 1, HS1 and vane 2 have better performance than their cast counterparts. Using the same procedure in previous upgrades, an evolutionary and stepwise approach will be utilized to ensure the reliability of the AM components, thus the high reliability of the product can be maintained. Siemens Energy envisions the following plan for introducing the AM technology into the hot gas path turbine components in SGT-800: the AM vane 1, HS1 and vane 2 will start long term validation in a customer engine. The goal is to generate sufficiently long time of operation experience for these AM components. Going forward further redesigns and optimization can unlock the full potential of AM, e.g., optimized aerodynamic shape and additional cooling air saving. With this, the gas turbine efficiency will be brought to a whole new level.

6. CONCLUSION

To apply the AM technology into SGT-800 with high firing temperature, three cast components in the turbine hot gas path section are redesigned by using the AM technology, i.e., vane 1, HS1 and vane 2. Through DfAM, both cooling air saving and metal temperature reduction were achieved during the design phase. To validate the design, a crystal test at the full load engine operation condition was carried out. The test results confirmed the validity of the design methodology and tool as all AM cooling performance of these three parts is in-line with pre-test temperature predictions. Some deviations between the predicted values and measured ones can be improved by better predictions for the internal and external boundary conditions. This test confirmed the AM vane 1 achieved more than 20% cooling air saving, and average metal temperature reduction by 56 ºC. For AM HS1 and AM vane 2, the cooling air saving is not significant, but the average metal temperature was reduced by approximately 70-80 ºC. In addition, the test also confirmed that all AM parts have more even temperature distributions than their cast counterparts, thanks to the flexibility in internal cooling channel placement. With the combination of reduced part temperature and reduced thermal gradient, the AM parts are expected to have longer life time than their cast counterparts. This successful test has created the foundation for the serialization of the AM hot gas path turbine components in SGT-800. A stepwise approach of serialization was discussed in the future perspective section. It is envisioned that fully optimized AM vane 1, HS1 and vane 2 will be ultimately introduced to SGT-800 to bring gas turbine efficiency to another level in the future.

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PERMISSION FOR USE STATEMENT

REFERENCES

[1] W. Fu, C. Haberland, E. V. Klapdor, D. Rule and S. Piegert, Streamline frameworks for advancing metal based additive manufacturing technologies, J. the Global Power and Propulsion Society, Vol. 2, pp.317-328, 2018.

[2] O. Andersson, A. Graichen, H. Brodin and V. Navrotsky, Developing additive manufacturing technology for burner repair, J. Eng. Gas Turbine Power, 139 (3), March 2017.

[3] T. Wimmer, T. Ruehmer, Y. Mick, L. Wang and B. Weigand, Experimental and numerical investigation on an additively manufactured gas turbine ring segment with an in-wall cooling scheme, GT2019-90227, *ASME Turbo Expo*, Phoenix, USA, 2019.

[4] K. Sheehan, Additively manufactured turbine vane 1 V64.3 with in-wall cooling design, AM Industry Summit, Long Beach, CA, USA, June 21-22, 2022.

[5] I. Fedorov, D. Barhanko, M. Hallberg and M. Lindbaeck, Hot turbine guide vane performance improvement with metal additive manufacturing at Siemens Energy, GT2021-59523, *ASME Turbo Expo*, Virtual, 2021.

[6] B. Gudmundsson, U. Nilsson, U. Linder, S. Shukin, I. Afanasiev and V. Kostege, Experience from the joint development of the GTX 100 turbine blading, ASME, 98-GT-201.

[7] S. Shukin, M. Annerfeldt and M. Bjorkman, Siemens SGT-800 industrial gas turbine enhanced to 47 MW: design modifications and operation experience, GT2008-50087, June 9-13, 2008, Berlin, Germany.

[8] L. Wang, M. Bahador, S. Bruneflod, M. Annerfeldt, M. Björkman and I. Hultmark, Siemens SGT-800 Industrial gas turbine enhanced to to 50 MW: turbine design modifications, validation and operation experience, GT2013-95462, ASME Turbo Expo 2013.

[9] M. D. Firat, Experimental investigation of cooling performance of additively manufactured channels, master thesis, Linkoping University, Sweden, 2021.

[10] A. Wildgoose, K. Thole, P. Sanders and L. Wang, Impact of additive manufacturing on internal cooling channels with varying diameters and build directions, GT2020-15049, *ASME Turbo Expo*, London, England, 2020.

[11] A. Wildgoose, K. Thole, E. Tuneskog and L. Wang, Roughness related to cooling performance of channels made through additive manufacturing, GT2023-101151, *ASME Turbo Expo*, Boston, MA, USA, 2023.

[12] M. Annerfeldt, S. Shukin, M. Bjorkman, A. Karlsson, A. Jonsson and E. Svistounova, GTX100 turbine section measurement using a temperature sensitive crystal technique, A comparison with 3D thermal and aerodynamic analysis, PowerGen Europe, Barcelona, Spain, 2004

[13] M. Kinell, E. Utriainen and P. Jaksch, An alternative experimental method for establishing detailed internal heat transfer coefficient distributions of complex cooling geometry using IR thermography, GT2014-25616, Dusseldorf, Germany, June 16-20, 2014.