Design and Characterization of Additively Manufactured NGVs Operated in a Small Industrial Gas Turbine

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ABSTRACT

The use of additive manufacturing (AM), for example Selective Laser Melting (SLM), is poised to spark a revolution in the way high-temperature components for gas turbines are designed, but a number of grave uncertainties remain. These lie mainly with the materials sciences, but some questions with regard to manufacturing and operating SLM-parts as hot gas path components and the demands on the tolerances of the cooling features associated therewith remain as well.

In order to quantify the impact of these uncertainties, Nozzle Guide Vanes (NGVs) with a geometry that would normally be investment-cast were produced with SLM. A back-to-back comparison of vanes from the two manufacturing processes was performed.

The design of the SLM-vanes will be described and the SLM-manufacturing process of the NGVs will be touched upon, especially the use of MAR M-509, which is seldom used for SLM. In addition, characterization of the NGVs with 3D-scans of the outer geometry and the pin-fin matrix shall be discussed.

The NGVs were operated for approximately 70 hours at relevant load conditions in a highly-instrumented test engine on a test bed at the Oberhausen plant of MAN. The temperatures of the AM and investment-cast vanes were measured using Thermal History Paints (THPs); a comparison between these different kinds of parts will be drawn.

INTRODUCTION

Traditionally, cooling technologies led manufacturing, i.e. cooling techniques advanced at a much quicker pace than manufacturing methods did. With the meteoric rise of various additive manufacturing (AM) technologies like Selective Laser Melting (SLM) over the last decade, novel manufacturing technologies carry a significantly higher potential than improved cooling techniques, as Bunker [1] points out. Due to its layer-wise build-up of the parts, SLM enables cooling configurations that were hitherto either too expensive or downright impossible to manufacture. Furthermore, the material properties can be adapted locally by the same method. Last but not least, digital 3D geometries can be converted in physical components very rapidly.

Although the potential SLM carries can hardly be overstated and SLM has been used in the series design on low-temperature components [2] and their suitability for high-temperature components is being evaluated [3], a number of grave uncertainties remain. For high temperature components in particular these lie mainly with the materials sciences, e.g. when printing materials that contain γ'-phases [4], which are traditionally considered non-weldable. In addition, their susceptibility to cracking is highly dependent on the geometry and the processing parameters [5]. A large number of publications is dedicated to the characterization of the material properties of SLM. It is almost impossible to give an exhaustive overview, but some of the more relevant ones for the most commonly used material, IN718, are [6-9]. Some questions with regard to manufacturing and operating SLM-parts for the harsh environments encountered by hot gas path components and the associated demands on the tolerances of the cooling features remain as well.

There are far fewer papers in the public domain dedicated to innovative cooling technologies enabled by SLM. Some of these are concerned with “double-wall cooling”, e.g. [10, 11], as described in a number of patents [12-15]. This design creates, in effect, a void between an inner and an outer (hot gas path) wall, which means a combination of impingement, pin-fin and film-cooling can be applied. Both the calculation and the subsequent experimental validation of the layout commands considerable resources, but it does carry the potential for using far less coolant at far higher turbine inlet temperatures (TIT) than is currently the case.

Apart from these novel layouts, SLM also enables of intensifying the cooling of existing techniques. There seems to be some promise in the combination of impingement cooling with turbulators. This has been investigated in the past, e.g. [16-18], but SLM opens up completely new possibilities in this field as well because much more intricate forms can be achieved. These possible optimizations will not be discussed any further here; it should suffice to point to Takeishi et al. [19] who discuss experimental investigations of some possible shapes.

The current article is dedicated to the application of AM-parts to a small industrial gas turbine. The most important difference between this kind of engines and jet engines as well as large industrial gas turbines is the moderate TIT of the former. Whereas this may exceed 1600°C for the large frames [20], it rarely exceeds 1300°C for the smaller industrial gas turbines. Therefore, it is questionable whether the development of completely new cooling schemes for the hot gas component of these engines is viable from an economic point-of-view. Rather, one may endeavour to optimize existing geometries to reduce costs or incrementally increase the cooling effectiveness. This approach entails the manufacturing by SLM of components and geometries that would normally be investment-cast or are very close to such a shape, which poses some
challenges to the manufacturing process. One of the most important of these challenges that need to be overcome from a cooling perspective are the deviations from the nominal dimensions of the cooling features. Stimpson et al. [21] emphasize the increased surface roughness in AM parts, but it should be noted that this is, even though it may necessitate additional processing steps on the hot gas path walls and within cooling holes, not detrimental to the internal cooling effectiveness, but rather increases it. The same authors showed a significant increase in the pressure losses for micro-features. The impact of the higher surface roughness on real components remains an open question. Ferster et al. [22] point out that any overhanging features (e.g. turbulators) are bound to deviate from the nominal geometry due to constraints inherent to SLM.

The temperature on the NGVs was evaluated using Thermal History Paint (THP). The reader is referred to [23, 24] for a more in-depth discussion of this technology and to the “results”-section of this paper for a brief summary of the technology. These paints were previously used and validated in a combustor-environment by MAN [25, 26] and are compliant with the EU’s REACH-regulation [27].

CONCEPTION AND DESIGN OF THE NGV’S

The NGVs in question have a cooling design that is state-of-the-art for engines of this power output, with a combination of impingement- and film-cooling in the front section of the vane and a pin-fin matrix combined with a trailing edge slot in the aft section. The film-cooling holes are positioned around the leading edge, with an additional two rows of holes on the front part of the suction side and four rows of cooling holes on the pressure side of the aerofoil. These four rows are arranged in two clusters of two rows, one on the front and one on the aft section of the vane. Both clusters are fed from the same impingement cavity.

As stated in the introduction, when designing the NGVs for SLM, it was clear that the target of the project was not to create a cutting-edge NGV concept, but rather to test the thermal performance of such vanes and include minor optimizations at most. This decision was also based on the tight lead time for fitting the engine with these vanes.

Only a limited number of SLM-designs was integrated in the engine. One minor reason was mentioned in the previous paragraph. Much more importantly, the material of the investment-cast vanes is MAR-M-509. Both to have a proper comparison between the manufacturing techniques, because the NGVs will have to be printed from this same high-temperature alloy in future applications, as well as the difficulties associated with printing high γ-alloys mentioned before, the SLM-vanes had to be from MAR-M-509, which is not fully characterised for SLM. There is some uncertainty regarding the creep properties of the parts, especially because the grain size of the microstructure is around 100 times smaller than that of conventional cast parts. This potentially greatly reduced creep resistance made it not feasible to run the engine test with predominantly SLM vanes made with AM, which would have been necessary if a large range of designs were to be tested.

Therefore, only two sets of three vanes in the middle of a five-vane section (see the section on “testing” for more details) were substituted by SLM ones with modified cooling designs. Furthermore, two additional SLM vanes with exactly the same cooling configuration as the conventionally cast vanes were included as single vanes in the middle of a five-vane section at the hottest location directly downstream of a burner. The rationale behind the latter configuration was to have a back-to-back comparison of the two types of manufacturing to be able to understand any possible effect due to both the manufacturing technique (e.g. roughness, geometrical deviations) and material properties like thermal conductivity. In the “results” section, only the comparison between the investment-cast and AM vanes of the same build will be discussed.

Hence the set of NGVs consists of a mix of conventionally cast and SLM ones. To avoid any further uncertainties that might falsify the outcome of the comparison, e.g. differences in windage, it was decided the hot-gas washed outer geometry would be exactly the same for all vanes.

Due to the special characteristics of the AM process on the one hand and to take advantage of the benefits of the technology on the other hand, some internal features where modified for all SLM-vanes, e.g. the removal/smoothing of sharp edges and corners as far as possible to avoid thermal gradients during build-up of the parts. Sharp edges and corners would create stressed features ending in cracks later on in the process, even if stress relief heat treatments are taken into account.

For conventionally cast NGVs a small connection between the forward impingement and the rearward pin-fin cavities is required as a stifferner for the ceramic core that would otherwise break during the filling of the mold with pressurized wax. This connection was also removed.

Furthermore, the outer and inner flow distribution resp. impingement plates on the cold side of the inner diameter (ID) and outer diameter (OD) platforms were integrated in the NGV. The intent was to progress to more sophisticated 3D forms that follow the inner surface of the impingement cavity once the feasibility of the integration was proven. On conventionally cast NGVs these plates are made of sheet metal and welded. The assembly of the insert is related to this: it is welded to the OD-plate, and the plate to the NGV. In this way, the impingement plate has a cooling function and simultaneously keeps the insert in position.

It was also decided to manufacture a separate cooling insert and not to print it integrally to avoid the risk of high thermal gradients between the aerofoil and the insert. These would most probably would create cracks on the areas around the spacers, i.e. the pins on the inner wall of the aerofoil that ensure a constant gap with the cooling insert. This was motivated by the uncertainty whether or not these cracks could propagate into the main walls of the vane or insert.

The combination of these two decisions led to a minor problem. If the insert were to be assembled to the integrated plate, it would slide completely into the vane because the bottom of the tube is designed to allow thermal relative displacements. To solve this issue, an interface with a welding lip was conceived: the axial position of the tube is fixed by the integral outer plate, the orientation is still defined by the inner geometry of the aerofoil and the lip is for ease of the welding. For that reason a step in the integral plate and in the insert were included in the design. The steps were topped with a welding lip with the same thickness and length in both the insert and the impingement plate.

Furthermore the diameter of the impingement holes can be easily adapted. Although the surface quality of AM holes is not very good and substantial out-of-roundness can also occur, both is irrelevant for the impingement cooling holes which have a length-to-diameter ratio of less than unity.

It was furthermore decided to use the standard strip seals on all NGVs rather than try to include any modifications or achieve improvements in the AM vanes. Firstly, the design intent of the strip seals will not be met if one of the ends is stiff. The seal will not be efficient in case there is no contact on the both edges of the strip seal. Secondly, in case there is substantial contact in circumferential direction the loads on the thin strip seal will probably damage the, now less flexible, seal in an unpredictable fashion. Thirdly, the configuration will not be compatible with the conventionally cast NGVs or will require different part numbers for each of the AM parts, adding complexity to the manufacturing and part tracking workflows where it is not needed.

The film-cooling holes were included in the SLM, but an additional EDM-operation was performed during final machining for all holes to guarantee a nominal cross-sectional area and a surface roughness that is the same as that of the holes in the conventionally cast vanes. This approach was vindicated post-factum by e.g. [28].

For the six vanes with a modified cooling scheme, further
modifications were made: The standard cooling insert is made of two different sheet metal parts that are welded together. Subsequently, the impingement cooling orifices are drilled by laser or Electric Discharge Machining (EDM). The conventional manufacturing process limits the cooling options, whereas AM technology allows complex geometries and the flexibility to manufacture multiple cooling configurations in real time. Having this in mind, the AM insert was designed with a splitting vertical wall, allowing the creation of a leading edge cavity that is fed from the inner diameter and closed at the outer diameter. The rear impingement cavity that is thus created is fed from the outer and closed at the inner diameter. Because of the size of the components, this design would be not feasible by conventional processes to a competitive cost (the AM vanes that are compared with the cast ones do not feature this design).

MANUFACTURING, CHARACTERIZATION AND TESTING

The SLM-manufacturing process of the NGVs including the inserts will be described in this section. The different technologies used in the characterization, as well as some details about the conditions under which the vanes were tested will also be presented here.

Manufacturing

In this study, an EOS M270 machine at the Fraunhofer ILT (Aachen, Germany) was used to manufacture the NGVs and the inserts. The vanes were made from the Cobalt-base alloy MAR-M-509 procured from Praxair, the inserts from the Nickel-base alloy Inconel 718 supplied by Oerlikon. Both powders were gas-atomized and had a particle size of 15 – 40 μm. The chemical composition of the powders was in the range of conventional MAR-M-509 resp. IN718.

The EOS M270 machine had a maximum laser power of $P_{L,max} = 200$ W and a laser spot diameter of approx. $d_s = 80$ μm. For the manufacturing of the components, process parameters with a layer thickness of $D_s = 30$ μm were used. These process parameters were developed by the Fraunhofer ILT in previous studies. After printing, a stress-relieving heat treatment was performed. Following this, the components were separated from the base plate by EDM. As the last manufacturing step, the specimens were milled and ground.

After printing, some cracks were identified at the OD leading edge vane hook for nearly all specimens of the NGV. One of the larger cracks is shown in Figure 2. The geometry in this area is determined by castability concerns and is characterized by a mass concentration and sharp edges. These features are, though, by no mean optimal for SLM and would normally be changed. In this case, they had to be retained because the printed and cast vanes should fit into the same vane carrier. The cracks were welded before final machining. Even though this would under no circumstance be permissible for a series engine, it was deemed to be so in this case due to the limited operating time of the test engine.

The insert is an exceedingly thin part, with a wall thickness of only approximately 0.4mm. Therefore the SLM-manufactured inserts posed more challenges than initially expected: in the first trials their geometrical deviation to the nominal values was 10 times higher than the maximum geometric deviation of the vanes. Both the pressure and suction side walls of the insert were negative out of tolerance, i.e. the curvature was less than required. As a result it was not possible to assemble the inserts and the NGV.

It should be noted that the following Figures of the AM-inserts do not show the distribution of the impingement cooling arrays that were printed as an integral part of the components.

The NGVs were manufactured as shown in Figure 1. This direction is chosen to attain as little a deviation between the nominal and actual contours of the aerofoil as possible as well as to minimize the overhanging surfaces of the endwalls. This orientation does produce a significant angle between the build-direction and the pin-fin matrix at the trailing edge of the NGV. Even though the consequences may not be as grave as for rib turbulators in serpentine channels, the resulting pin-fin geometries do have to be measured.
The GOM-measurement at the Fraunhofer ILT of an insert that was manufactured with MAR-M-509 is shown in Figure 3. Both on the suction and on the pressure side a minimum respectively maximum was found in the upper aft section of the insert. For the SS a deviation of approx. 0.09 mm was identified, for the PS this was approx. 1.7 mm.

A general explanation for the distortion of such a geometry with a thin wall thickness is depicted in a simplified manner in Figure 4. Two points (A and B) are connected by a curve. This represents the geometry during the melting process. When the material cools down, it solidifies and shrinks. Due to shrinkage the material moves in the direction of a straight line, which forms the smallest distance between the points A and B.

To reduce the geometrical deviation several approaches were examined. First, an adaption of the part orientation was investigated. Second, a change of material from MAR-M-509 to IN718 was considered. Thirdly, preheating the insert up to 500°C during the SLM manufacturing should reduce the distortions. Last, an increase in the part stiffness through design adaption, for example in the shape of a lattice structure, might ameliorate the situation.

In Figure 5 two different build-up orientations are compared. On the left-hand side the part is aligned, i.e. the bottom surface of the insert is parallel to the base plate. On the right-hand side the build-up direction is parallel to the leading resp. to the trailing edge. Orientation B has two local maxima on the pressure side: one at the top and one at the bottom. The upper one has, with +1.17 mm, a higher geometrical deviation than the bottom one. The overall distortion was reduced in orientation B compared to orientation A.

In the experience of the Fraunhofer ILT, residual stress induced distortion of IN718 is significantly lower than that of MAR-M-509. Therefore changing the material from MAR-M-509 to IN718 was tested. The results are shown in Figure 6. The location of the deviation maximum is similar for both materials. On the left-hand side the insert made from MAR-M-509 and on the right-hand side the insert made from IN718 is shown. When using IN718 the maximum deviation on the pressure side is +1.45 mm, which is less than that for MAR-M-509. This confirms that the distortion induced by residual stress for IN718 is lower than for MAR-M509. As a result of this analysis, IN718 was used in the following tests as the material for the insert, because the choice of material of this component was irrelevant for the operation of the NGV.

Figure 7 contrasts the manufacturing of the insert without (left-hand side) and with preheating (right-hand side). Using a laboratory system, the base plate was preheated to a maximum preheating temperature of 500°C. By using preheating, the maximum geometrical deviation on the pressure side was reduced from 1.45 mm to 1.17 mm. It seemed likely that a further increase of the preheating temperature would lead to an even smaller geometrical deviation. However, this could not be verified, since an SLM system with higher preheating temperatures was not available for these tests.

![Figure 7: Distortion of the Insert Using Preheating](image)

The results presented so far did not achieve the required geometrical accuracy. It was then decided to scale the 3D geometry to reduce the size of the insert by the average deviation of 0.15 mm. Because the wall thickness of the insert is only 0.40 mm, which means it has flexibility, it is assumed that the pressure difference over the insert will deform it to fit in the NGV cavity as long as the local bulging of the component during the cooling-down phase of manufacturing is suppressed. Therefore, a redesign was carried out to increase the component stiffness. One possibility to increase this is the integration of a lattice structure within the insert which would have to be removed after manufacturing. The results of this approach are shown in Figure 8. This proved to be the most promising approach and lead to a geometric deviation within the specified tolerances of ±0.1 mm over the entire part. A local maximum as in the previous experiments could not be identified.

![Figure 8: Increase of Stiffness due to the Integration of a Lattice Structure within the Insert](image)

**Characterization**

It is only possible to make qualified statements on the cooling of different vanes if it is ascertained that they all receive an equal amount of coolant. Therefore, the throughflow of all vanes was measured on a flow bench at a supplier that is normally used for the qualification of series vanes. The flowbench is qualified using both a Gauge R&R and reference measurements at a high-accuracy
throughflow test rig at a German university. The flow benches yield “reduced mass flows”, i.e. the feed pressure and temperature are factored into the mass flow, making the results from the flow bench better transferable to engine conditions.

The pin-fin matrix of the SLM-vanes was measured with both CT-scans prior to the test and 3D optical measurements after the test. The latter could not be performed prior to the test, as it involved cutting up some of the SLM-vanes. The outer geometry of the NGVs was characterized with 3D optical measurements before and after operation.

The CT-scans were performed using a DL 2D-CT Mini-Focus scanner with a power of 450kV and a distance between the scanning planes of 0.5mm. The accuracy was estimated to be approximately 0.1mm, which amounts to 10% of the nominal pin diameter. This low value was caused by the thick metal walls of the NGV, which made more accurate measurements with CT (normally an accuracy of <50µm can be achieved) impossible. Because of this, it was decided to cut-up an NGV after operation and perform an optical measurement on an ATOS scanner as well.

The optical measurement at MAN’s Oberhausen site of both the pin-fin matrix and the hot gas path geometry was performed using a GOM ATOS Triple Scan 8M (GOM GmbH, Brunswick, Germany) with a measurement accuracy of 3 – 30µm. The hot gas path geometry was measured before and after operation to detect any possible deformations due to thermal and mechanical loads on the NGV. Furthermore, both the SLM and the cast NGVs were compared to the nominal CAD data of the vane to quantify any deviations and compare those among each other. The “Best Fit” approach was used for all comparisons. This is based on the statistical least squares method and ensures that the differences between the target (CAD) and attained values are smallest in all measured points.

The comparison between the attained outer geometry and the CAD geometry was performed for all AM-vanes. One representative comparison is shown in the “results” section. The pin-fin matrix was only compared for two of the vanes. Since the comparison of the outer geometry showed very little spread among the vanes, it was assumed this would be the case for the inner geometry as well. The results validated this assumption.

The temperatures on the hot gas path walls of the AM and investment-cast NGVs were measured using THPs. The measurement technique is based on thermally-activated permanent changes to luminescence materials. The paints comprise of an oxide ceramic material and a water-based binder. The oxide ceramic is doped with lanthanide ions to make the material luminescent. While the paint layer has different thermal properties to the substrate metal, for the specified coating thickness of 30µm, the effect is normally limited to less than 5°C. The layer thickness is controlled during application to reduce the influence on the measured temperature.

Before the vanes were mounted into the engine, they were sprayed with THP according to the supplier’s directions at MAN’s premises by the same operator using the same equipment on the same day. Subsequently, all components were cured in the same furnace at a temperature of 200°C for two hours.

Testing

The NGVs were operated for approximately 70 hours at high part-load and full-load conditions in a highly-instrumented MGT6000 test engine [29, 30] on MAN’s test bed at its Oberhausen plant in the autumn of 2017. The MGT6000 engines are offered in both a single- and twin-shaft design; the former was used in this particular test. The test bed is used for both prototype and commercial testing and although a water brake is used instead of a generator, all required load conditions and transients can be achieved. As this was a prototype test, several hundred temperature and pressure measurements were recorded. Some of the former were used as a reference for the THPs and, in some cases, were used to support the calibration of the THPs. The highest TIT-level was somewhat above the normal full-load level. This was held for about one hour and was only chosen in order to have a well-defined condition for the THPs and further comparisons with CFD-calculations.

The MGT6000 has six Advanced Can Combustors and thirty NGVs. Due to the swirl in the combustion chamber and the temperature profile generated by the cans, the three vanes directly downstream of the swirler have an above-average temperature, whereas the two at the circumferential extremes of each combustion chamber have a temperature that is lower than average. For the further discussion only the vanes in the hot centre positions of the combustion chambers are relevant. Two sets of three vanes in these centre-positions were replaced with SLM-vanes with a modified cooling design but a coolant consumption that is nominally identical to cast vanes, i.e. no impact on engine performance is expected and any improvement in surface temperature can be solely attributed to the enhanced cooling scheme. Furthermore, the middle vanes behind two of the four remaining combustion chambers were replaced with SLM vanes with the same design as investment-cast ones. Only these will be compared with cast vanes in this publication.

A fair evaluation of the temperatures of the cast vs. the AM-vanes requires a detailed knowledge of the average TIT as well as the Radial Temperature Distribution and the Overall Temperature Distribution Factors of all individual combustion chambers. In reality, none of these is known with absolute certainty. Any instrumentation that would yield a reliable TIT- or temperature distribution measurement (e.g. kiel-probes) for the individual combustion chamber would alter the temperature distribution around and within the vanes. Therefore, the average TIT can only be determined indirectly from temperature sensors within the combustion chamber and an estimated uncertainty of the TIT of the individual combustion chambers. Any differences below this uncertainty cannot be attributed to different manufacturing or cooling techniques. Both the radial and overall temperature distribution factors are extracted from combustion chamber simulations and previous TIT-measurements on a representative combustion chamber [28].

RESULTS

In this section the results from the throughflow measurements along with the comparison of the vane geometry with CAD data before and after testing will be discussed. The surface temperatures of the SLM and cast vanes will also be presented.

Throughflow

The throughflow measurement of the AM vanes after final machining yielded values for the airflow that only deviated approximately 0.5%-points from the nominal value of the reduced mass flow. This was well within the tolerances for acceptance to series engines as well as the specified measurement uncertainty of the flow bench. The throughflow of the cast vanes showed a slightly higher discrepancy from the nominal value. Still, as this was within the predefined bounds as well, the differences in the resulting metal temperature that may be caused by this difference in throughflow are limited to a few Kelvin and within the measurement accuracy of the THPs.

Geometry Comparison

As mentioned, both CT- and ATOS-scans of the cooling features within the vane were made. The former would be preferable, as it is non-destructive, but the accuracy of these measurements needed to be confirmed.

As can be seen from Figure 9 top left, which shows a CT-based cut through the pin-fins of an SLM-vane at their mid-length, the pin-fin shapes are by no means perfectly round. Also, although the shapes appear to be roughly similar, they are not identical and cannot be simplified in a generally applicable manner for CFD simulations. Figure 9 top right shows that the CT indicates the pin-fins are shifted towards the ID and the front of the vane, with the
orange contours being the nominal dimensions, the grey contours the actual ones. The same tendency can be seen for the spacers within the front impingement cavity of the vane (Figure 9, bottom). In addition the CT indicated that the spacers were in general slightly smaller than specified, with the consequence that the gap between the aerofoil and the insert would be narrower than the design intent. The net effect of this, combined with the changes from a cold to a hot geometry, are very difficult to quantify.

After operation, vanes were cut along the chamfer line and subsequently measured using the ATOS scanner described above. These scans gave a more quantitative comparison between the CAD and the actual dimensions than the CT-scans did. Figure 10 (top) shows the same tendency as Figure 9 (top right) on the SS. On the PS, which is not shown here, however, the pin-fins tended to the OD and front, a feature not shown in the CT-scans. The overall shift in the position of the pin-fins amounted to up to 0.2mm; their overall size corresponded by and large to the nominal value. The spacers showed the same shift in both the CT- and ATOS-scan, cf. Figure 10, bottom, for the latter results. The magnitude of the shift was almost exactly the same as the shift indicated by the ATOS-scan in the position of the pin-fins.

The differences between the dimensions from the CT-scans (not shown here) and the ATOS-scan are mostly within the measurement accuracy of the ATOS-scan, but at some positions differences of several tenths of a millimeter can be found. Although nothing definite can be said about this, it seems likely this can be attributed to the difficulty in quantifying the uncertainties in the CT-values due to issues with the wall thickness mentioned above, i.e. the ATOS-values were considered to be more reliable. The comparison showed that the characterization of the internal features with CT, which is routinely done in the framework of component qualification and quality assurance, is sufficient.

Neither the displacements on the pin-fin matrix nor those on the spacers would a priori be detrimental to the cooling effectiveness and, as could be seen from the throughflow measurement, they were inconsequential for the cooling mass flow.
those around the hooks were inconsequential anyway and, within the indicated bounds, did not influence assembly or tightness. For the SLM-vanes, the outer platform on the pressure side bended considerably more inwards than was the case with the cast vanes. This was evaluated and, although the values are slightly outside of the specified tolerances, the NGVs were accepted. The reasons were that the deviations were in a range that should neither affect the overall engine performance as the narrower flow channel was far away from the throttle area of the vanes, nor have any influence on the cooling phenomena pertinent to this study. All in all, the AM vanes were closer to the nominal values on both the aerofoil and the ID platform than the cast vanes.

The differences in the geometries before and after operation were within the measurements accuracy of the ATO-S-scans.

Surface Temperature

As previously mentioned, the engine operation was approximately 70 hours at high part-load or full-load conditions. This was the longest industrial application of the THP to date. Most components painted with THP in this test showed no spallation. A vane with THP post-test is shown in Figure 13 (top). Some damage to the paint can be seen, especially in the aerodynamically highly loaded leading and trailing edge regions. The higher degree of damage to the THP on the vanes is likely related to the more aggressive operating environment of these components relative to those at later stages or outside the hot gas path. The bottom picture of Figure 13 shows the corresponding lifetime decay measurements on the aerofoil of the vane. Obviously, the damage to the paint did not preclude taking measurements, but the damaged areas’ thickness of the paint would potentially have an influence on the strength of the signal as well as the measured temperatures. It should be noted here that high values of lifetime decay (in red) signify lower temperatures than low values in lifetime decay (in blue).

After the test, the results from the THP measurements indicated that the overall strength of the lifetime decay signal that is the basis for the measurements [23, 24] was lower for the SLM than for the cast vanes. It is not known what caused this phenomenon. It would seem obvious that, since the crystalline structure of the MAR-M-509 differs depending on the manufacturing method, the diffusion processes and hence the interaction between the THP and the substrate material might differ as well. Therefore, one of the AM-vanes was cut-up and investigated under an electron microscope. Figure 14 shows a micrograph of the metallic substrate of this vane (bottom layer) as well as the paint (middle layer) and the acrylic binder (top layer) used to encapsulate the slices of the vane for the microscopic investigation. The porosity of the THP may be partly related to the preparation of the sample. However, it is a clearly distinct layer from the substrate, indicating that there was no obvious deterioration of the THP due to the adverse effects of diffusion or other interactions.

It is also good to notice that, although there are some small pores in the printed metallic substrate, the overall quality of the material seems to be excellent.

![Figure 12: Comparison of an AM-NGV and the Nominal CAD-Measures](image)

![Figure 13: AM-NGV with THP (top) and Measured Lifetime Decay Values (bottom) after Approx. 70 Hours of Engine Operation](image)

![Figure 14: Micrograph of THP on an AM-Vane](image)

Figures 15 and 16 show the results of the temperature measurements on both a cast vane (left) and a printed one (right) with an identical position relative to a burner. Shown in Figure 15 are the temperatures on the PS on the top and SS on the bottom. Although several hundred measurements were taken, all measurements for which the uncertainty was too high were left out, therefore the number of points shown on the PS of the printed vane as well as the SS of the cast vane is greatly reduced. A comparison is possible nonetheless.

The comparison of the PS shows that, within the bounds set by the measurement uncertainty and the uncertainty of the TIT, no difference between the vanes can be distinguished. The temperature distribution on the SS of the vanes is not as similar. Although the temperatures in some positions are also within the bounds mentioned previously, large areas can be distinguished where this does not seem to apply. Therefore, the possibility this can be attributed to a fundamentally different temperature distribution on the SS was investigated.

In this context it should be pointed out that the first row of measurements on the ID of the printed vane in Figure 16 should be ignored; purge flow is injected into the hot gas path at this position and the shown measurements on the cast vane are at a slightly different position. It should be noted that this also holds true for the...
difference between the vanes in the upper part of Figure 15. As the injection is perpendicular to the flow, purge flow mixes out quickly [32] and the first line of shown measurements can therefore not be compared.

As the neither the ID nor the OD has no active cooling and the wall thickness is equal for both vanes (the differences shown in Figures 11 and 12 are irrelevant in this respect), the means of manufacturing does not play a role here. Figure 16 shows that the temperatures on the OD are actually very similar. Differences can be explained by slight variations in the amount of purge flow injected into the hot gas path. An explanation for the different temperatures on the SS of the aerofoil can thus not be provided.

In future, the Thermal History Coating technology [24] could be used to improve the durability of the sensor layer for this type of extended prototype testing and components.

**Figure 15: Temperature Distribution on the PS and SS of a Cast and an AM-Vane**

**Figure 16: Temperature Distribution on the Outer Platform of a Cast and an AM-Vane**

**SUMMARY AND CONCLUSION**

The potential to develop novel cooling geometries normally is the most important aspect in a discussion on Additive Manufacturing. These novel geometries do carry some potential for small industrial gas turbines, but the costs for their development are substantial. Therefore, in this case the path forward may be evolutionary rather than revolutionary. In this context, it seems opportune to investigate the differences between a set of conventionally-cast NGVs and NGVs manufactured using AM that have an identical hot gas path geometry.

The design took some aspects particular to AM into account, e.g. the removal respectively smoothing of sharp edges and corners to avoid cracks wherever possible, the integration of the outer and inner inserts with the NGV, the removal of the internal passage connecting the front and rear cooling cavities as well as the addition of a welding lip on the upper cooling plate and insert to improve the welding.

Most of the AM-vanes deviated in some aspects of their cooling design from the cast ones, but a set that was completely identical to the conventionally-cast vanes was printed as well. The majority of the comparisons presented here focused on this last set of vanes and their cast counterparts.

Throughflow tests showed an almost nominal reduced mass flow of the SLM-vanes that was better than the median deviation of the cast ones.

The characterization of the outer contour using a 3D-scan showed that the differences between the SLM- and cast vanes as well as those between the nominal and actual dimensions were mostly within the tolerances and therefore for the most part negligible.

The build direction had some implications for the internal cooling features. These were therefore subsequently characterized in addition to the geometry of the hot gas flow path. The results indicated a clear trend in the positioning of the features, but the differences between pre-test non-destructive CT-scans and post-test ATOS-scans of cut-up vanes were so small, one can rely on the former method for qualification of SLM-vanes this size.

Manufacturing had to take account of some pronounced deviations between the nominal and actual dimensions of the insert, which is an exceedingly thin-walled component. Ultimately, the insert was printed in IN718 to minimize these, after a number of other options did not yield the desired outcome. Even so, the insert had to be modified geometrically to fit into the NGV.

The temperature measurements after engine operation showed an overall very good agreement of the temperature distribution on both kinds of NGVs, with some notable and as yet unexplained deviations on the SS of the aerofoil.

Therefore, SLM-vanes could substitute cast ones in small industrial gas turbines when more accurate material data become available and if the costs of AM decrease.

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