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ADDITIVE MANUFACTURING GAS TURBINE HIGH PRESSURE NOZZLES: DESIGN AND VALIDATION

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ABSTRACT

Utilisation of nozzle sectors in gas turbines (GT), that are produced by additive manufacturing (AM) presents several advantages in terms of performances, decrease of production lead time, and environmental impact.

The standard manufacturing process for turbine nozzles is investment casting (IC). This process is based on the creation of equipment/tooling that requires, besides an important economic investment, a long development and qualification time. Moreover, any geometrical variation requires the tooling's modification, and therefore additional cost and time. These aspects make the investment casting process as robust as it is rigid and not very flexible in responding to the different needs of the market.

AM offers a greater versatility as it does not require specific equipment and tooling for the production of each component. In addition, any change of geometry can be implemented by updating the CAD model and the related printing and post-processing activities. Another advantage, especially for cooled nozzles, is represented by the freedom of designing more complex and efficient geometries and/or to optimize/tune the baseline geometry according to specific customer needs. Complexity of the nozzle design increases costs only marginally in AM and geometry design of the Hot Gas Path components in AM can be produced even for those not producible today by IC.

Baker Hughes (BH) has developed, and continues to improve and optimize, proprietary AM alloys for Hot Gas Path components. An example is given by NP110, a Nickel based super-alloy with excellent mechanical properties that makes it suitable for cooled high-pressure GT nozzles. The production process occurs completely internally BH; and it includes printing, postprocessing and machining operations. This "vertical capability" allows a better control and management of production times.

The NP110 alloy was selected for producing the first stage nozzle (S1N) of the NovaLT^{TM} family GT high pressure. The nozzles' design has been analysed following the same analytical verification process of casted nozzles: oxidation, crack initiation and propagation, high cycle fatigue (HCF) and creep have been assessed to satisfy the standard product maintenance schedule.

As well as the simulation, the whole nozzle industrialization process was optimized to ensure that the AM parts target all the requirements.

A significant sample of nozzles has been assembled on NovaLT^{TM}s' internal prototypes and validated through stress tests made by multiple transient missions. Finally, additional sectors have been assembled on a customer's NovaLT^{TM}12 for a long-time field validation and monitored by borescope inspections.

The paper describes the design and validation steps, including the disassembly and detailed inspections, which demonstrates comparable behaviours between the parts produced throughout IC and AM processes.

NOMENCLATURE

AM	Additive Manufacturing
DMLM	Direct Metal Laser Melting
FPI	Fluorescent penetrant inspection
GT	Gas Turbine
HCF	High Cycle Fatigue
HPT	High Pressure Turbine
IC	Investment Casting
LCF	Low Cycle Fatigue
S1N	First Stage Nozzle
TE	Trailing Edge

INTRODUCTION

NovaLT^{TM} family GT combines innovation with the best technology of our GT experience with more than 900 units installed and ~80 million fleet hours.

Designed to minimize environmental impact, the combustion system is capable of reducing CO_2 and NOx emissions down to 15 ppm. Furthermore, single-digit NOx emissions are available on request. A single annular combustor technology as the NovaLT^{TM}12 (and NovaLT^{TM}16) turbine is composed of 2 high-pressure stages and 2 low-pressure stages. The low-pressure turbine, in particular, is equipped with variable nozzle guide vanes, which eliminates bleeding and enables the highest efficiency at part load, reducing CO_2 footprint.

High pressure GT nozzles are traditionally produced via IC. As well known, one of the biggest limitations of this technology is represented by the tooling development costs, which are very expensive both from an economic and lead time perspective. In addition, IC of high-pressure GT nozzle, especially the cooled configurations allows a limited amount of possibility in terms of feasible geometries. To industrialize optimized shapes, new designs and, more generally, non-conventional solutions, require a lot of time and important investment.

On the other hand, AM allows more freedom of producing unconventional shapes, that could become useful when dealing with the production of novel components. Based on these benefits, AM Direct Metal Laser Melting (DMLM) technology was chosen as manufacturing strategy of NovaLT^{TM} GT family high pressure S1N.

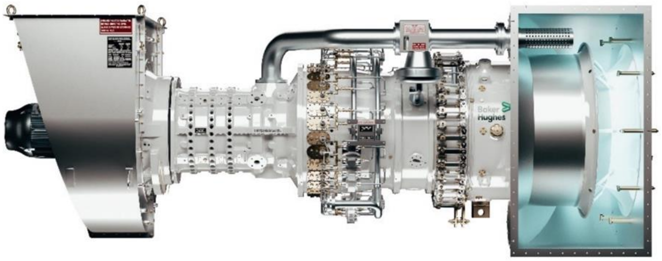

Figure 1 – NovaLT12

Alongside with the development and full mechanical characterization of novel alloys, such as NP110, the replacement of standard investment casted nozzle with additively manufactured parts required a deep and extensive analysis, simulation and experimental validation.

MATERIALS AND METHODS

As previously reported, the first step in the AM part introduction was represented by the full characterization of the novel alloy needed to produce such parts. Commercial metal powder alloys for DMLM were not found able to withstand the combination of load and temperature generated by the machine operation. Therefore, specific high-performance alloys were developed and fully characterized to allow the simulation of nozzle behaviour. The development started from the René108 (or CM247LC) high gamma prime superalloys family characterized by high strength at high temperatures as required for last generation industrial GT High Pressure Turbines (HPT) nozzles.

The alloy required modification to the chemistry due to the non-weldability related to the high gamma prime content in order to mitigate the generation of cracks. This in addition to a dedicated printing parameters optimization process. The result of this development well described in "Cecconi et al. (2023)", "Callisti et al. (2023)", is the NP110, a proprietary alloy patented by Baker Hughes (EP3426811B1). The NP110 was developed to this scope, a high-performance alloy for high pressure turbine components. The material was characterized both in as-machined condition and in as-built condition. The heat-treated and post-fabrication HIP treatments applied on the production process reduces considerably the residual stress [1] and the anisotropic proprieties [2]

Once all the material curves were released, the nozzle was simulated in all its operative conditions to verify that no critical condition will be created by the machine operation. The simulation process was performed in parallel with nozzle design optimization. This process allows to get the optimal geometry able, at the same, to withstand all the machine operative conditions.

To follow the experimental validation campaign, also the prototype testing was simulated. Specifically, a notched geometry was tested on a real machine to speed up to highlight any criticality in the most demanding area of the nozzle (which is, in the NovaLT^{TM} HPT S1N, the fillet on the trailing edge hub).

After the full simulation, several experimental tests on real engines were performed to both validate the simulations results and to demonstrate their accuracy.

DESIGN

Once the aerodynamic design was completed, it was required to estimate the heat transfer coefficient and metal temperatures of the component. This includes transient conditions for start-up, shut-down, emergency shut down etc... The analysis consists of several mechanical assessments to verify the feasibility of the component. The original investment casting geometry was partially modified to be compatible with additive process and to improve area that showed, in the casting version, some criticality. The life-time calculations are based on Finite Element Method modelling with in-house methods calculations to evaluate oxidation, LCF, HCF and Creep. The analysis was run applying characteristic as built and as machined in order to evaluate the life-time according with the status of the region. All these assessments had to be successfully completed with enough margin with respect to proprietary design requirements before to release the part.

Figure 2 - First Stage Nozzle NovaLT12

The nozzle was also analyzed in terms of crack propagation to verify the strength of the additive component in case of unexpected crack initiation. The first step in the crack propagation analysis included the definition of the most demanding locations in the component. In order to do that, the low cycle fatigue assessment was performed to select the areas that, even if largely withstanding with LCF requirements, would be the first of crack initiations.

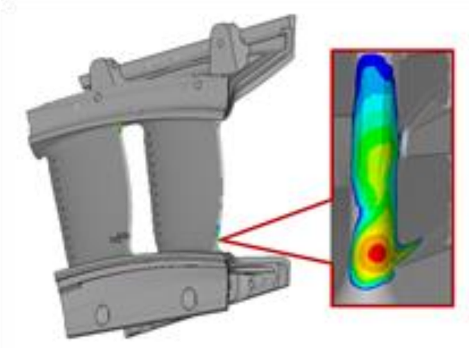

Figure 3 - HPT First stg Nozzle - LCF result

One of the most demanding locations found was in the hub of the airfoil which is a usual point of concern due to the characteristic component loading and geometry (in this case a simply supported nozzle). During the transient operation of the nozzle the thermal gradient across the inner and outer platform produces a bending of the platforms with consequently stress on the airfoils that works against this deformation. In particular the geometry variation on the connection between airfoils and platform create a stress concentration, with a potential location of crack initiation. Due to engine test constraints, such as the number of runs to be tested, it was decided to realize a dedicated feature on the critical part in order to accelerate the crack initiation and its propagation. The same feature was implemented on the real nozzle to test. The design of the feature was defined and released without any risk to affect the test success, so without any risk having any unplanned outage of the engine during the test campaign.

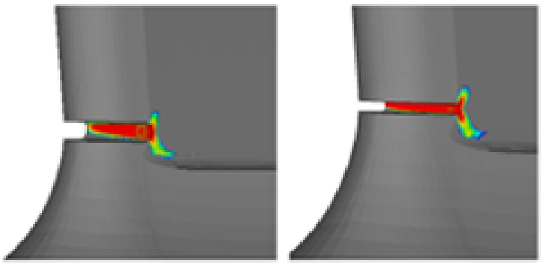

Figure 4 - TE sub model

The following step in the assessment was the use of an in-house tool to model the crack propagation. A sub-model was created with crack modelled.

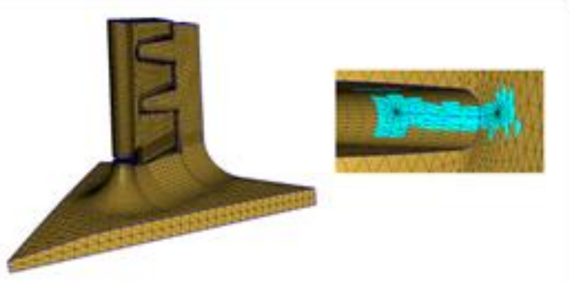

Figure 5 - TE Crack modeling

The transient mission LCF analysis was performed with the additive proprietary alloy material properties and compared with the material used for investment casting. The comparative results showed similar behaviour for traditional and additive material in terms of crack initiation and propagation. The assessment was performed with selection of crack geometry and input data to find optimal and reliable results. The geometry and position of the notch were then selected to maximize the probability of crack initiation and propagation, but at the same time minimizing the risk of engine failure during the test and to be kept under control by mean of borescope inspection during the test execution, validating the expected behaviour as described in next paragraph.

VALIDATION PLAN

The aim of this paragraph is to explain how the product validation strategy has been designed and how the activities have been carried out through the validation phase.

Product validation strategy is based on a risk mitigation approach. The aim of each step in the product validation process is to reduce the risks before moving on to the next one. The product validation has been carried out following the steps described in the following paragraphs.

Actually, the validation started in the early phase while developing and optimizing the NP110 alloy and printing parameters. In fact the first nozzles sectors were printed, components produced by AM and the same produced by investment casting, were heated in a furnace, rapidly cooled down by forced air convection and FPI inspected to detect the presence of cracks. This is a very tough kind of test, but useful to investigate the HCF performance with respect to the same component manufactured in investment casting while developing the alloy.

Prototype Test

After the full verification by simulation, the first step in the new AM nozzle validation phase was the part test in the Prototype Engine. The HPT S1N ring was rainbow arranged by casting and AM sectors instrumented. The scope of this test was to detect, under controlled conditions, unplanned or unexpected early failure mechanisms.

The engine test performed an overall of 56 cycles and 81 firing hours

After this first part of the test the engine was disassembled, and the nozzle analyzed without critical finding.

Figure 6 -S1N disassembled after first prototype test

The second phase of the product validation consisted in a more extensive testing campaign focused on the testing of the machine resistance against repeated loads (i.e. starts).

To carry out this evaluation, the engine was instrumented and used as test bench. On such engine, the HPT S1N ring was equipped with:

- Standard investment casted nozzles
- Notched investment casted nozzles
- AM Printed nozzles
- Notched AM printed nozzles

After the planned simulations , nozzles were visually inspected and did not show any damages neither on the trailing edge fillets (both hub and tip) nor on the notch.

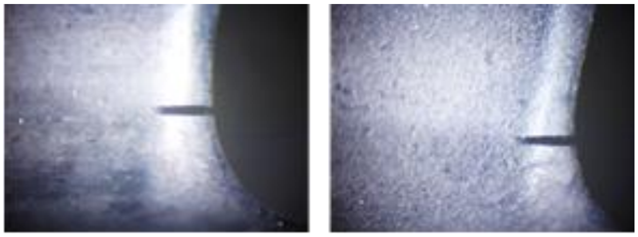

Figure 7 - Comparison between notch area of additively manufactured nozzle (on the left) and investment casted (on the right) after prototype test

In addition, the comparison between additively manufactured nozzle and investment casted ones did not show any difference. Liquid penetrant inspection was performed as well. By this analysis, no indications of defects were found.

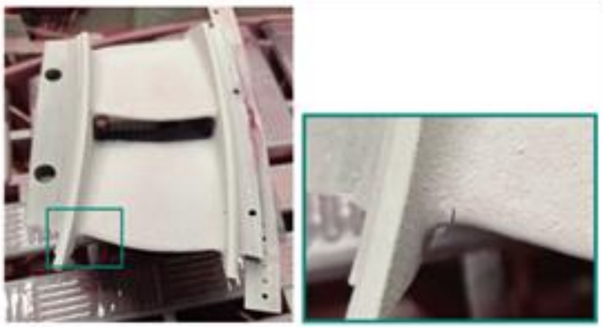

Figure 8 - Additively manufactured nozzle liquid penetrant inspection and detailed view on the notch

The notched area did not show any indication a well. Finally, to conclude the non-destructive analysis of the parts, computer tomography was used to further inspect the parts. Specifically, the notch area was the region of main interest (basing also on the results of the previous test).

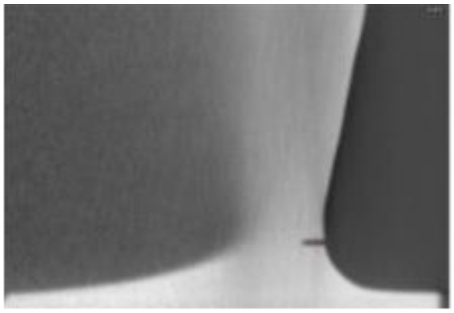

Figure 9 - Additively manufactured nozzle notch Computer Tomography

Even in this case, no indication was found. Concluding, results demonstrated that neither investment casting nor additive manufacturing parts integrity were affected by the prototype testing.

Endurance Test

After the prototype, the validation continued on a commercial unit (with the agreement of the customer).

5 AM S1N sectors out of 22 were assembled on the commercial unit. The engine, so far, has already run for more than 20000 hours without showing any issue the AM Nozzles. Every 8000 hours a borescope inspection was carried out for monitoring the parts. At 20000 hours the parts were disassembled for a deeper check. The AM nozzles observed did not show any difference from the casting version. The parts, AM and casting, shows a similar state of degradation due to the normal wearing.

The parts have been reassembled and engine restarted its running. The endurance test is still ongoing to target the 35000 hours of the first major maintenance.

Figure 10 A S1N Boroscope inspection

CONCLUSION

This article showcase how the design, production and validation of the new additive nozzle in NP110 for the NovaLT® family was structured. Starting from the development of a new AM superalloy, the full mechanical properties characterization and the life assessment including all the load cases was simulated. Alongside with the simulation, the part design was optimized to further withstand operative conditions. Together with standard geometry simulation, a notched version was simulated and tested too.

All the simulations were followed by experimental validation on real engines, which confirmed that the additively manufactured nozzles behave in the same manner with respect to the investment casted version.

It was a multi-years and multi-disciplines program that led to prove that AM is a suitable technology to produce GT nozzles sector, even if, requires the development of specific knowledge and consolidated experience.

The AM technology also allows the customization of the nozzles, in fact, adjustment to the design can be introduced in a simpler way without the necessity to modify, or rebuilt, the molds or other expensive tooling, saving time and decreasing cost of customization while maximizing the performance according to specific machine/site operating conditions.

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