Life Management of Hot Gas Path Turbine Components – Metallurgical Verification of Life Extension

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Life Extension of Gas Turbine Components

- The life of components in gas turbines are typically set by the gas turbine original equipment manufacturer (OEM).

- The design life of gas turbine blades and vanes is based on a number of pre-determined maintenance cycles in the form of hours, starts or an algorithm which combines the life consumption effects of starts, base load hours and other operational variations such as trips and fuel type.

- A significant amount of the through life maintenance cost on an industrial gas turbine is associated with the repair and replacement of hot section components. Therefore, there is a considerable economic incentive either to extend the total lives of these components or to increase the interval between inspections.
Life Management of Hot Gas Path Turbine Components

- Aerothermal and thermal analysis of the components
  - Gas temperatures
  - Heat transfer coefficients
  - Metal temperatures

- Finite Element Modelling of stress and strain experienced in service

- Destructive Examination
  - Condition of the substrate alloy and any coatings internal and/or external
  - Evidence of thermal and/or mechanical degradation
  - Damage to internal cooling passages
  - Mechanical testing to determine remanent life
Program Objective

• A blade life management project aimed at assessing the ability to extend the life of the turbine blades and vanes from 25,000 equivalent operating hours (eoh) to 33,000 eoh, was conducted by E.ON in collaboration with Laborelec.

• A number of analyses were carried out on several stages of blades and vanes. The objectives of these analyses were to identify damage already present within the components and possible damage mechanisms which may occur during the proposed extension. These included:
  • creep analysis,
  • determination of temperature and stress profiles
  • destructive metallographic examinations (undertaken by Laborelec).

• Destructive metallurgical examination of the blades and vanes was undertaken to verify that extending the operating life could be achieved without a significant compromise to their integrity.
Visual Examination of 2\textsuperscript{nd} Stage Blade

- Severe oxidation/corrosion of the squealer tip
- As a result, a layer ranging from 3-10 mm around the squealer tip was devoid of the TBC coating

- Crack Indications were observed running perpendicular to the platform edge towards the aerofoil fillet radius
- A small amount of cracking was associated with the oxidation on the platform edge.
Metallographic Examination

Metallographic samples were taken from the blade aerofoil and platform in order to determine and characterise:

- Compliance with chemical specification for materials and coatings,
- Evidence of thermal and/or mechanical degradation of the blade or vane microstructure,
- Evidence of any cracking from external surfaces or internal cooling passages,
- Performance of the coating during the extended service and its protection of the substrate alloy including a measure of external coating thickness and composition around the aerofoil,
- Any environmental attack to the substrate, with particular regard to any loss in load bearing section.
• The blade aerofoil and top platform surfaces were covered by a bi-layered coating system comprising an EB-PVD TBC overlaying a metallic MCrAlY bond coat.

• Over the majority of the aerofoil surfaces the MCrAlY coating typically showed a thin outer $\beta$-NiAl depleted zone, where the aluminium had diffused out to form the thin, adherent, thermally grown oxide (TGO).
• The internal cooling passages at all heights up the aerofoil were found to be covered with an internal aluminised coating of good condition.

• In addition, a Ni/Al rich deposit was found on the internal coating, mainly located behind the internal turbulator ribs. The origin of this deposit is not completely understood, however, the large quantity of Ni and Al suggests that the deposit originates from the powder used to deposit the internal coating.
**Image Analysis**

- Measures zones identified through degradation of MCrAlY Coatings around the aerofoil surfaces

**Suction Surface**

**Pressure Surface**

- MCrAlY coating was ~ 50 µm thinner at 10% aerofoil height
- A thicker depletion layer had developed at both the coating surface and coating/substrate interface over the trailing 50% of the aerofoil
- The greatest $\beta$ depletion and subsequent oxide scale thickness coincide with the area of reduced coating thickness together with the increased quantity of oxidised pores present at both the coating/substrate interface and towards the coating surface
β-NiAl Depletion

Depletion

Oxidised Pores

MCrAlY Coating

TBC

TGO

Substrate

β-NiAl Depletion

β-NiAl Depletion

Oxidised Pores
Blade Tip Damage

Substrate

MCrAlY Coating

IDZ

Substrate

Internal Oxidation and Nitridation
The sections taken across the platform and fillet radius revealed numerous through-coating-thickness thermal fatigue cracks, some of which had penetrated into the underlying substrate.

The majority of the cracks appeared to be associated with oxidised porosity at the bond coat surface.

A small proportion of the cracks had diverted at the coating/substrate interface resulting in propagation and subsequent oxidation along the interdiffusion zone.
Fillet Radius Indications

- Sectioning through the linear indications observed within the aerofoil fillet radius on the pressure surface, revealed straight, through coating thickness cracks.
- These cracks diverted and continued to propagate along the bond coat/substrate interface, oxidising both the coating and the substrate thus resulting in substantial delamination of the coating between the cracks.
The blade microstructure consisted of a bimodal distribution of $\gamma'$ ($\text{Ni}_3\text{Al}$) precipitates in a $\gamma$ matrix.

Throughout the majority of the aerofoil, the primary $\gamma'$ precipitates demonstrated a cuboidal morphology with only slight coarsening and rounding observed near to the leading and trailing edges.

The most extensive microstructural degradation was observed below the squealer tip surface, observed in the form of severe coarsening and coalescence of the $\gamma'$ precipitates.
Main Observation Points

- Minimal degradation of the coating and underlying substrate was observed over the majority of the aerofoil surface on the 2nd Stage Blade. Degradation of the component was largely confined to overheating of the tip section and cracking within the aerofoil fillet radius and platform.

- The reduction of coating thickness, together with the presence of porosity at the both the coating surface and the coating/substrate interface on the aerofoil surface of the 2nd Stage Blade, resulted in a more rapid degradation of the coating.

- Although the NiCoCrAlY coating was close to exhaustion of aluminium at the mid chord of the aerofoil and on the platform, it had clearly performed its required function of protecting the underlying substrate from oxidation and nitridation for ~ 33,000 eoh.

- Thermal fatigue cracking was present along the platform and in the fillet radius. This was similar to that observed on the blades following 25,000 eoh. However, modelling identified the possibility of significant crack growth within the aerofoil fillet region on and therefore a recommended starts limit was imposed.
Visual Examination of 1st Stage Vane

- Some loss of the TBC coating, with associated oxidation damage, was evident along the trailing edge.
- Oxidation of the platform edges was observed on both the pressure and suction surface sides. This was most prominent on the inner (smaller) platform with associated cracking.
- FOD present on the suction surface trailing edge resulting in cracking and local spallation of the TBC coating.
Metallographic samples were taken from the blade aerofoil and platform in order to determine and characterise:

- Compliance with chemical specification for materials and coatings,
- Evidence of thermal and/or mechanical degradation of the blade or vane microstructure,
- Evidence of any cracking from external surfaces or internal cooling passages,
- Performance of the coating during the extended service and its protection of the substrate alloy including a measure of external coating thickness and composition around the aerofoil,
- Any environmental attack to the substrate, with particular regard to any loss in load bearing section.
• A thin adherent oxide was present on the coating surface followed by minimal amount of $\beta$-NiAl phase depletion.
• The remaining coating in the area adjacent to the trailing edge, showed a greater degree of in-service degradation in terms of significant $\beta$-NiAl depletion.
The coating applied to the platform surfaces showed a significant amount of porosity in the bond coat, in particular at the aerofoil fillet radius.

Oxidised porosity and pitting present in the top third of the bond coat had resulted in the local depletion of $\beta$-NiAl phase.
• Numerous thermal fatigue cracks were observed along the platform surface.
• The majority of the cracks appeared to have initiated from the base of the oxidised pores towards the bond coat surface.
• A number of the cracks penetrated into the underlying substrate, the longest of which intersected an underlying cooling hole.
Substrate Microstructure

- The microstructure consisted of carbides distributed in a Co/Cr-rich $\gamma$ matrix. The primary Ta-rich MC carbides of a ‘Chinese script’ morphology were present throughout the substrate, predominantly in interdentritic regions.

- The microstructure showed negligible degradation over the majority of the aerofoil, with slight coarsening of the carbides towards the trailing edge.
The most extensive degradation of the substrate was observed at the trailing edge at 10% and 50% height where the TBC and underlying coating had been lost during service.

This resulted in the formation of AlN needles, rounded and coarsened $M_{23}C_6$ carbides and a Cr/W rich phase most likely sigma phase.
A significant amount of casting porosity was observed within the substrate, the majority of which was located towards the cooling passages and within the turbulator ribs.

In some cases the porosity was interconnected and open to the surface of the cooling passage. This had resulted in the internal oxidation of the substrate, primarily the carbides.
• Significant crack-like defects were observed propagating from the external surface through the coating into the underlying substrate alloy, the largest of which was almost through wall.

• The majority of the cracking seemed to follow an interdendritic path along the primary carbide network and was, therefore, highly-branched.

• The cracks varied in appearance, some were tight, whereas others exhibited large separation of the faces, resulting in open voids.
Main Observation Points

• Given the extended period of operation, the coating generally showed minimal degradation in terms of $\beta$-NiAl phase depletion and thickness loss, indicating that the remanent coating still contained a substantial reservoir of aluminium for further oxidation protection.

• The general microstructural condition of the vane alloy was typical of that expected for service exposed material, with no evidence of any significant overheating or microstructural degradation over the majority of the aerofoil sections examined.

• The main area of the vane showing any significant degradation was at the trailing edge, where loss of coating and overheating had occurred. The damage comprised of consumption and loss of the MCrAlY coating at the trailing edge, resulting in severe degradation of the underlying substrate.
Main Observation Points

- Observation of small areas of embedded casting porosity is common in cast gas turbine components. However, the amount observed throughout the 1st Stage Vane was deemed higher than usual and comparable to that initially reported by Laborelec.

- Perhaps of greater concern was the unusual observation of significant cracking linking up possible porosity. Due to the materials susceptibility to cracking along the interdendritic carbides together with the loss of ductility of cobalt based alloys after long term exposure, difficulties may be encountered with refurbishment.

- The vane exhibited damage around some of the platform and aerofoil cooling holes. This consisted of cracking from both the external coated surface and the cooling holes intersecting, but looks unlikely to have a serious effect on integrity.
Summary

• On the basis of the evidence gained from the blade and vane examinations, it can be concluded that the life extension from 25,000 eoh to 33,000 eoh has been successful and has not significantly compromised the integrity of the components. However, due to the possibility of significant crack growth within the aerofoil fillet region on the pressure surface of the 2\textsuperscript{nd} Stage Blades during service, a recommended starts limit was imposed.

• Minimal degradation of the coating and underlying substrate was observed over the majority of the aerofoil surface on both components. Degradation of the component was largely confined to overheating of the tip section and cracking within the aerofoil fillet radius and platform on the 2\textsuperscript{nd} stage blade and overheating of the trailing edge and cracking on the platform on the 1\textsuperscript{st} stage vane, all of which were observed to a similar degree following 25,000 eoh.

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