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THE ROLE OF METALLURGICAL ANALYSIS IN GAS TURBINE MAINTENANCE

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Abstract

Metallurgical analysis of gas turbine blades to characterize component degradation can be used to assess the reparability of the blades, identify abnormal or detrimental engine operating conditions and define the potential for service interval extension. The following paper summarizes the role of metallurgical analysis in managing the operation and maintenance of turbine blades to reduce costs and improve reliability. The implications of various types of damage on operation and maintenance, including material degradation, coating degradation, hot corrosion, impact damage and damage within the internal passages will be discussed.

1 Introduction

Metallurgical evaluation of the post-service condition of turbine blades provides information needed to make informed maintenance decisions, maximize potential cost savings and manage risk. Original engine manufacturers (OEM) provide maintenance guidelines for service interval periods and component repair recommendations. However, the operating conditions between engine users and specific sites differ, resulting in a considerable variation the extent of part deterioration and post-service condition. Therefore, characterization of the blade set condition can be used to optimize maintenance decisions and provide insight towards the potential of service interval extension.

The operating conditions of a gas turbine are such that deterioration of turbine blades is inherent and blades therefore have a finite operating life. Under ideal base load conditions, degradation of hot section components is primarily a function of operating temperature. In such conditions, the component life is generally based upon (a) the depletion of the protective coatings or surface oxidation and (b) strength degradation and creep damage of the base alloy. Thermal degradation is exponentially correlated to temperature and minor changes in temperature can have large affects upon the rate of deterioration. In peaking applications, engine starts generate thermal-mechanical fatigue damage. In combination, these mechanisms are considered by OEM's to predict damage accumulation and establish criteria used to determine the component life and service interval length.

Non-ideal conditions such as corrosive environments, over-firing or impact damage can result in accelerated component deterioration. These modes of degradation may not be included within the OEM service interval length guidelines and, if they occur, may have implications relevant to the maintenance and repair of the blades. Identification of these issues can be used to generate corrective actions in order to minimize risk of component failure and maintaining the component reparability after each service interval. Conversely, many units are operated at part-load conditions under which damage will accumulate more slowly and so the OEM lifing criteria may be conservative.

As an alternative to predicting the damage expected after a service interval, destructive metallurgical analysis allows complete characterization of the actual post-service condition. Life Analysis refers to a metallurgical examination that characterizes the overall condition of a blade including the material state, coating degradation and damage within the internal passages. The data collected from the analysis can be interpreted to:

a. Assess reparability of the blade set. Minimize risk of otherwise undetectable damage.
b. Determine repair processes required to return set to serviceable condition.
c. Evaluate the performance and selection of the coatings (if applicable).
d. Provide indications of abnormal or detrimental engine operating conditions.
e. Assess for the potential of a service interval extension.

This paper will summarize the typical modes of deterioration found in metallurgical analysis of service exposed blades and present guidelines for using that information to make repair, maintenance and engine operating decisions (Table 1).

2 Metallurgical Analysis Procedure

The techniques used for life analysis, are well established in literature and practice. One blade, which is either representative of the set or exhibits independent, unrepairable damage (such as impact damage), is selected for destructive examination. The initial steps include review of the blade history, visual examination, non-destructive testing and gathering of relevant surface deposits.

The blade is typically sectioned to remove samples from the lower, mid and upper portions of the airfoil, the tip or shroud and any other features of interest. As the operating temperature of the root is below that at which material degradation occurs, a section of the root is examined to provide a pre-service material benchmark. The samples are prepared for microscopic examination by conventional metallographic polishing techniques.

The evaluation includes assessment of the base alloy microstructure, the coating/external surface condition and the internal surface condition. Modes of degradation can be identified through various forms of microscopy and micro-analysis techniques. Depending on the size/design of the component, mechanical testing of the base metal may also be performed.

3 Base Metal Deterioration

3.1 Alloy Aging and Creep Damage

Turbine blades are manufactured from precipitation-hardened nickel-based superalloys which develop their high strength at high temperatures from gamma prime, Ni_3Al

precipitates within the material. In the as-new condition, the size, density and morphology of the gamma prime precipitates are optimized for maximum strength (Figure 1a). However, during operation at elevated temperatures, the microstructure undergoes various changes. The strengthening gamma prime precipitates spheriodize, enlarge and join, resulting in a reduction in material strength (Figure 1b and c). Topologically close packed (TCP) phases, can also form resulting in a dramatic loss of ductility and reduction in creep strength (Figure 2a). Microstructural degradation takes place by diffusion mechanisms and the rate of degradation is therefore a function of both time and component temperature.

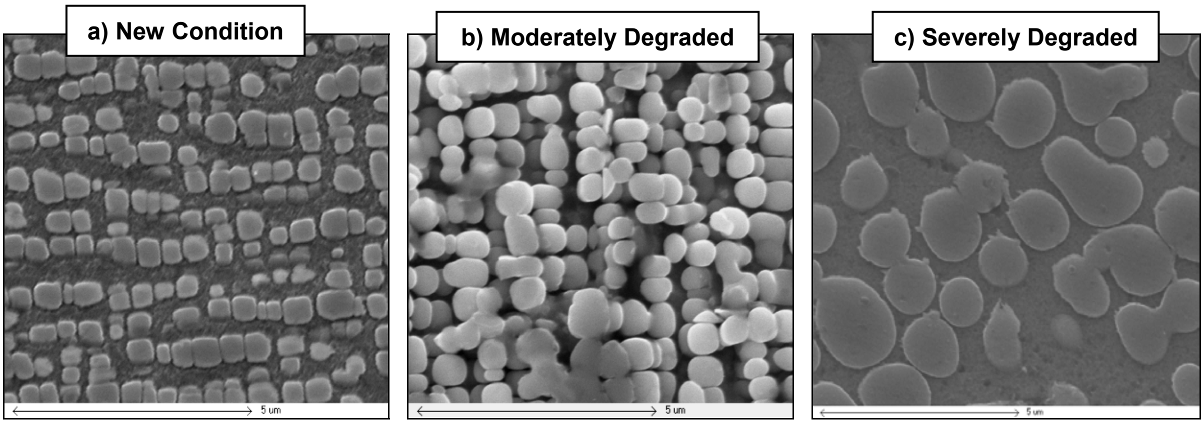

Figure 1: Scanning electron images displaying the gamma prime precipitates indicative of material condition of René 80 nickel-based superalloy in the (a) new, (b) moderately degraded and (c) severely degraded conditions. .

Due to the centrifugal loading and operating temperatures, the airfoil material also undergoes creep deformation. Creep is a diffusion-based mechanism correlated exponentially to temperature. Eventually, creep results in the formation of voids that link to cause creep cracking (Figure 2b). While the detection of creep voids is a reliable indicator of creep damage, in most alloys, voids only form after a large fraction of the creep life is exhausted and hence they may be absent even in significantly creep damaged material. Prior to the formation of such voids, it is difficult to identify damage due to creep. Creep damage may be evident by reduced creep rupture life measured by mechanical testing, however, the effect is confounded with the aging effects.

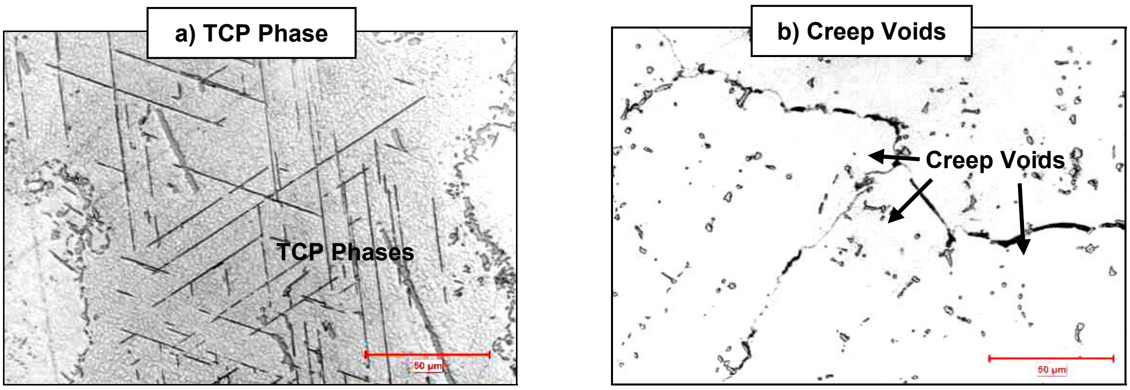

Figure 2: Optical micrographs displaying material degradation in the form of (a) TCP phase formation (dark gray, acicular phase) and (b) creep voids. As-polished condition

Both creep and microstructural damage can be repaired through appropriate heat treatments. Knowledge of the material condition can be used to ensure the appropriate thermal processing is implemented to restore the material properties needed for continued service at minimal risk. Base material that exhibits creep damage requires Hot Isostatic Pressing (HIP) at appropriate temperature and pressure to collapse creep voids which may have formed. Alloy degradation is corrected by heat treatments capable of fully restoring the microstructure and material strength.

As microstructural degradation occurs as a function of temperature, the condition of the base alloy provides a relative thermal map of the blade's operating temperatures. Once a typical thermal profile has been benchmarked for a given blade design, abnormal engine operation affecting the operating temperature of the blade can be detected. Examples include short term excessive overheating, long-term overheating and temperature profile shift.

The base alloy condition can also provide insight into the suitability of the service interval length. Gross microstructural damage or the presence of creep voiding, can indicate an inappropriate service interval at the conditions exposed. In the absence of an identifiable cause, it would be recommended to shorten the service interval in future. Conversely, if only moderate base alloy deterioration is present, service interval extension could be considered.

3.2 High Cycle Fatigue Cracking

Repetitive loading at moderate stresses can result in the formation of fatigue cracks and potentially failure. These cracks are generally attributed to vibrations, rubs or resonant frequency events. The stages of fatigue cracking include the accumulation of material damage, crack initiation, crack propagation and then ultimately final failure. At the common frequencies experienced by gas turbines, cycles are accumulated rapidly. Endurance limit cycles in the order of 10^7 can occur within hours or days. Therefore, parts are designed to avoid experiencing cyclic stress intensities or events that would result in fatigue crack formation.

While NDT methods can detect cracking, metallurgical analysis is used to determine the nature of crack initiation (Figure 3) and to determine the reparability of the remainder of the blade set. Efforts are made to determine if crack initiation was due to an isolated cause (ie. impact, material defect, etc.) or if the entire set was susceptible (ie. resonant frequency). Once identified as fatigue cracking, further investigation as to the engine condition responsible for the elevated loading may be warranted.

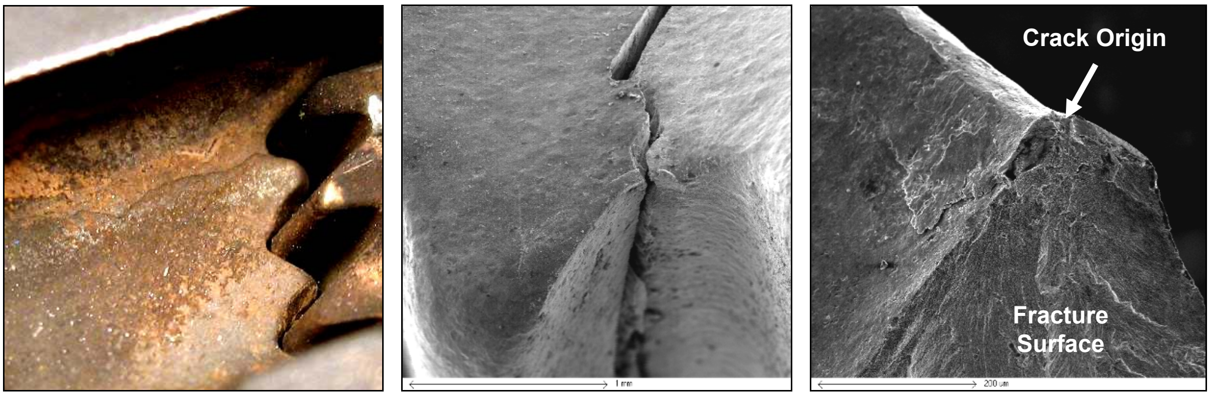

Figure 3: Photograph and SEM images displaying a high cycle fatigue crack initiating within the root.

Reparability is based upon the location and size/depth of the crack. Fatigue cracks generally initiate on the external surfaces and non-destructive techniques can be used to determine reparability blade-by-blade. Cracks at locations such as the root and the majority of the airfoil would be cause to retire the blade. In the case the entire blade set was susceptible to fatigue cracking, appropriate heat treatments should be applied to alleviate accumulated, cyclic base metal damage.

3.3 Thermal-Mechanical Fatigue Damage

Temperature gradients in blades result from both rapid changes in the operating temperatures and steady state differences in temperature resulting form cooling effects. These in turn can result in thermal-mechanical fatigue (TMF) damage from thermal stresses associated with the gradient. Repeated cycling can result in low-cycle fatigue crack initiation and propagation (an example of TMF is provided in Section 7.2, Figure 9). Therefore, thermal-mechanical damage often is the critical life limiting factor for engines with a high number of engine starts and trips. Damage is a function of part design, operating temperature, number of cycles, hours of operation between cycles and temperature change rate.

When thermal-mechanical cracking is present only on the external surfaces, non-destructive testing can be used to sort reparable blades from irreparable. Blades which are deemed reparable should be subjected to appropriate heat treatments in order to alleviate accumulated material damage. As there is no reliable, non-destructive method to detect internal cracking, if metallurgical analysis detects internal cracking within the airfoil, the remainder of the blade set should be retired.

4 External Coating Condition

4.1 Aluminide/MCrAlY Coating Deterioration in Clean Environments

Diffusion and overlay coatings provide oxidation protection for operating environments for which the base alloy material does not have acceptable resistance. Oxidation resistance of coatings is principally based on aluminium content. The high aluminium content existing as β-aluminide forms a protective aluminium oxide layer slowing down the oxidation damage process. This process is exhaustive and once the aluminium content is depleted below a critical level, the β-aluminide transforms to gamma prime. At this point, a mixed oxide is formed which does not provide the same protective nature.

Figure 4 displays examples of coatings after service with minimal, moderate and complete β-aluminide depletion. In simplification, the coating protective life is based upon the amount of β-aluminide remaining.

Coating breaches can occur due to either complete β-aluminide coating depletion or thermal-mechanical coating cracks (Figure 5). Generally, coating failure is deemed when the base alloy sustains oxidation damage that is either irreparable and/or increases the risk of failure to unacceptable levels.

Optical examination of the coating is able to determine the amount of remaining β-aluminide in a coating, examine for cracks as well as oxidation damage to the coating and underlying base alloy. Data obtained from characterizing the coating/subsurface condition can be used to (a) assess if the coating provided adequate protection during previous service, (b) if inadequate, determine a more suitable coating based upon the damage mechanisms and (c) assess if there is potential for service interval extension (incorporating other modes of damage).

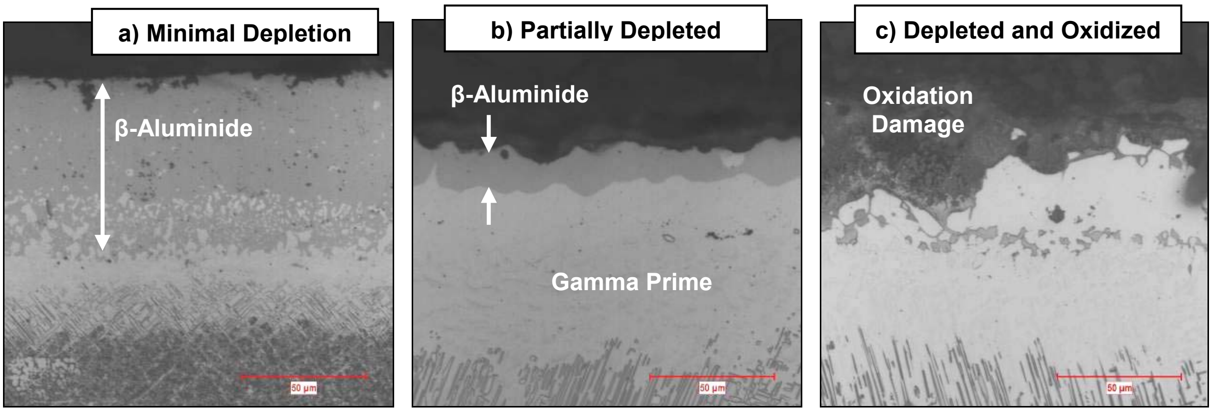

Figure 4: Optical micrographs displaying aluminide diffusion coatings after service exhibiting (a) minimal β-aluminide depletion, (b) partial depletion and (c) fully depleted and oxidation damaged.

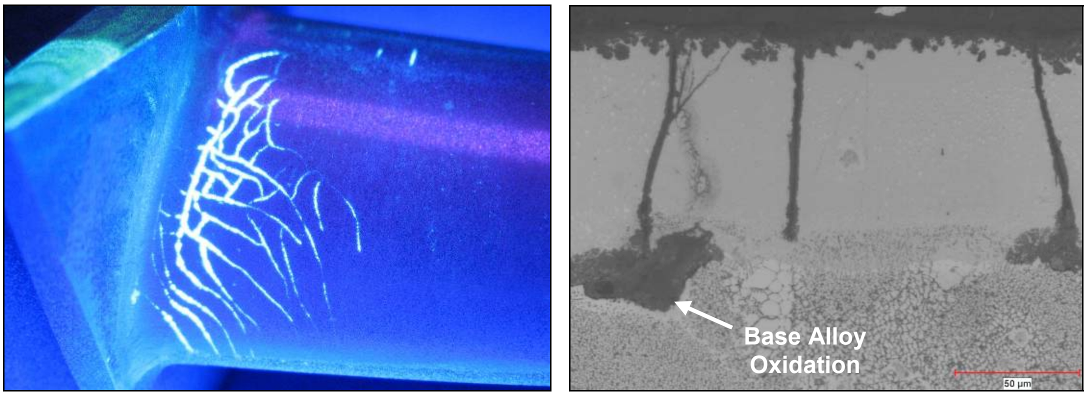

Figure 5: Photograph aided by fluorescent penetrant inspection techniques and an optical micrograph displaying coating cracks due to thermal cycling.

On sets that the coating had failed to prevent damage to the base metal, the coating type, service interval and operating conditions should be reviewed. In cases where the base alloy did not exhibit excessive alloy degradation, the coating may be defined as the primary life limiting mechanism. In such cases, a coating up-grade may be beneficial. Full depletion of the coating, combined with gross base alloy degradation, may suggest elevated operating temperatures or too long of a service interval at the operating conditions applied. If neither the coating nor any other form of degradation has approached their life limit, there may be the potential to increase the service intervals.

4.2 Thermal Barrier Coating Loss

Thermal Barrier Coatings (TBC) are applied to internally cooled blades to insulate the base metal from the hot gas environment. Due to their porous nature, TBCs are applied overtop of a diffusion or overlay coating called a "bond coat". This bond coat provides the oxidation protection for the blade's base metal.

TBC coating spallation is generally attributed to the formation of a brittle oxide layer between the TBC and the bond coat. Spallation occurs when this thermally grown oxide (TGO) reaches a critical thickness and thermal stresses causes the oxide layer to crack and spall. Figure 6 displays a TGO adjacent the spalled region of the airfoil.

Formation of this TGO is a function of the bond coat's oxidation resistance and operating temperature. Operating at higher temperatures increases the rate of TBC spallation initiation and continuation. Once TBC loss has initiated and locally no longer has the local insulation, neighbouring coating loss is accelerated.

TBC coating loss can also be initiated by impact damage. TBC coating loss by impact damage can be differentiated from TGO spallation by the sporadic nature of coating loss associated with impact damage.

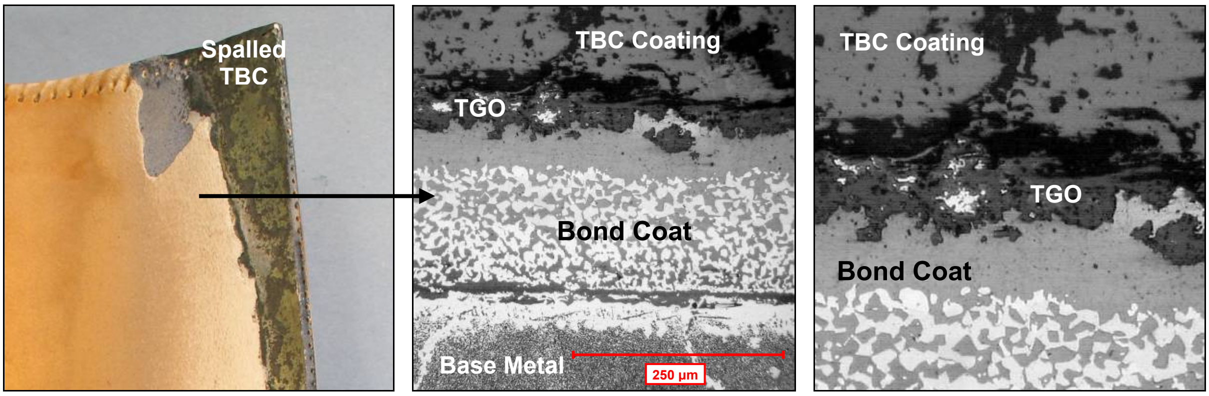

Figure 6: Photograph and micrographs displaying the TBC coating adjacent a spalled region. Spallation occurs due to the formation of a TGO layer and thermal stresses from engine starts/stops.

Examination can determine the cause of coating loss and the extent of damage caused by the loss. Generally, TBC loss results in increased bond coat/surface and base alloy degradation due to a local elevated operating temperature. Repairs to the blade set may have to be adjusted pending the extent of base alloy damage. It should be noted that TBC coating is considered consumable and the coating performance is only considered to have been inadequate for service if the damage sustained to the blades is irreparable.

4.3 Hot Corrosion

Hot corrosion is an accelerated attack of the coating and base metal that occurs due to the presence of contaminants in the hot gas environment. In particular, elements that can cause hot corrosion include sulphur combined with either sodium or potassium salts or, independently, vanadium and lead. Unlike in clean environments, the presence of these elements interferes with the formation of a protective oxide layer and accelerates the rate of attack.

Two broad classes of hot corrosion have been recognized, divided by the temperature ranges at which they occur. Type I hot corrosion occurs above 871°C while Type II occurs between 649 to 871°C. Although the mechanisms differ, the causes, implications and preventative measures are similar.

Metallurgical analysis can identify the type of corrosion and elements present causing the hot corrosion. Ideally, the prevention of hot corrosion is by the elimination of corrosion agents at the source. Corrosive elements can originate through either fuel or air intake. Sea water humidity is a constant source of these salts and hot corrosion by these salts can indicate filtration inadequacies.

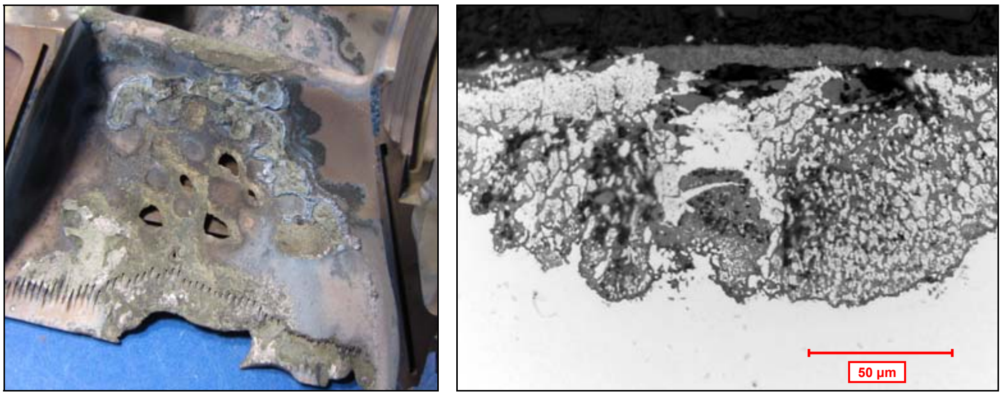

Figure 7: Photograph and micrograph displaying an example of hot corrosion.

A less ideal option but at times more feasible, is applying coatings that provide corrosion protection. Overlay coatings consisting of the protective elements chromium and/or cobalt can provide some measure of protection to the base alloy. Platinum aluminide coatings also exhibit corrosion protection. Determination of the type of hot corrosion, elements causing corrosion and the extent of corrosion should be taken into account when selecting coatings for corrosion protection.

4.4 Impact Damage

Impact damage is the result of object(s) impacting blade(s) at high speeds. Sustained damage can range from insignificant to coating damage to catastrophic failure. Evidence of impact damage indicates concerns up-stream of the turbine blades. Impact damage can be a symptom of upstream component(s) failure or filtration inadequacies. It can also point towards poor maintenance practices such as leaving equipment/objects within the gas path during shutdowns.

Metallurgical analysis can assess the extent of damage, both surface and subsurface if the coating has been compromised. Information can be used to determine the reparability of the blade set. Due to the sporadic nature of impact damage, inspection methods can be developed to salvage blades from those irreparable.

4.5 Airfoil Deposits

Deposit build-ups on airfoils can reduce efficiency or provide an indication of an up-stream issue. Indirect damage to the airfoil can be sustained from cooling holes becoming blocked. The origins of deposits can range from ingested material, parts rubbing or up-stream failures (melted and adhered metal).

Determining the composition of deposits building up on turbine blades can provide insight as to the material origins. Similar to impact damage, deposits can indicate issues with filtration, upstream component failures or objects left within the gas path during maintenance. Adhered airfoil deposits generally do not directly affect the reparability of a blade set.

5 Internal Surface Condition

Due to the inaccessibility and nature of damage incurred within the internal cooling passages, internal damage to the base alloy cannot be repaired. The decision to continue servicing the parts should include an evaluation of whether the existing internal damage can be tolerated. As non-destructive testing cannot detect the majority of internal damage modes, to determine whether a set of internally cooled blades can be safely returned to service requires a metallurgical life analysis.

5.1 Uncoated Internal Surfaces

Blades that are not internally coated can exhibit multiple forms of damage. Uncoated surfaces can experience alloy depletion at the surface. Base alloy elements such as aluminium and titanium can diffuse to the surface leaving behind a surface layer void of gamma prime (Figure 8a). Excessive thickness of this depleted area results in both reduced fatigue strength and a decrease in effective wall thickness when considering mechanical loading of the component. Note that the depleted material is indistinguishable by ultrasonic wall measurements. Metallurgical analysis is the only method to determine the remaining, effective wall thickness capable of sustaining service loading.

Other forms of oxidation damage which uncoated, internal surfaces are susceptible to are intergranular oxidation (IGO) and stress assisted grain boundary oxidation (SAGBO). An example of IGO is presented in Figure 8b. Oxidation occurs along the base alloy grain boundaries resulting in oxide spikes into the material. These oxide spikes are brittle and can lead to concerns of thermal-mechanical cracking.

Internal surfaces can sustain some damage and remain fit for continued service. Some blade designs have defined specifications as to assessing remaining life. Examination and monitoring of the internal damage is recommended until the damage is beyond tolerable limits.

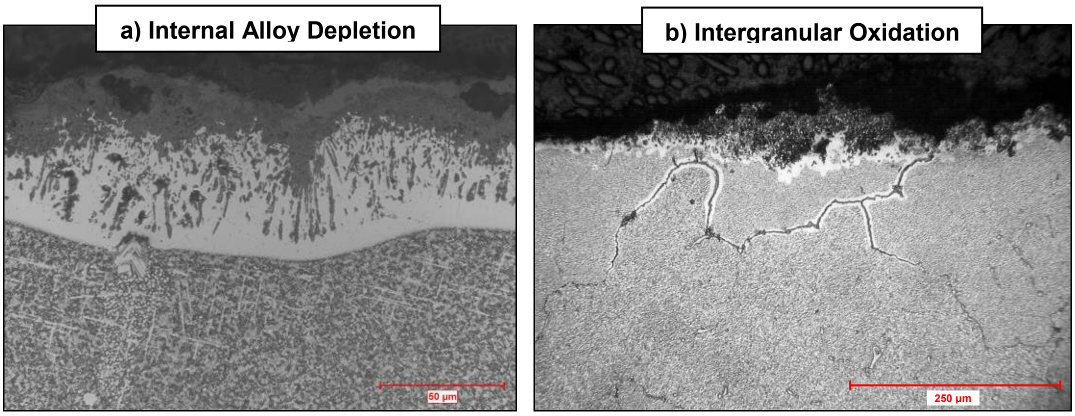

Figure 8: Optical micrographs displaying the internal surfaces exhibiting (a) alloy and oxidation damage and (b) intergranular oxidation (IGO).

5.2 Internally Coated Surfaces

Some blades are manufactured with internal diffusion coatings to protect the internal surfaces from oxidation damage. Internal coatings behave similar to the external coatings and degradation occurs due to the depletion of its aluminium content.

The only method to characterize the extent of internal coating degradation is by destructive microscopy. Assessment of whether the internal coating should be replaced prior to continued service can be made. It should be noted that due to the high temperatures of some heat treatments used to repair the base alloy that removal of the internal coating may be necessary regardless of its condition.

5.3 Hot Corrosion on Internal Surfaces

Hot corrosion within the internal cooling passages occurs by the same mechanisms as on the external surfaces. Due to the internal temperatures, hot corrosion generally occurs by Type II hot corrosion. The concern of hot corrosion is damage to the internal coatings and base alloy.

The suitability of a blade set with internal hot corrosion for repair and continued service would be based upon the extent of hot corrosion. Only superficial internal hot corrosion damage would be tolerable. Any significant depth of internal hot corrosion damage would be cause for retirement.

Coatings that can be applied internally offer little corrosion resistance and therefore, prevention of internal hot corrosion requires the elimination of the corrosion agent source. As the air used to cool the blades is taken from the compressor, the corrosion agents causing the hot corrosion on the internal passages are generally from the air intake. Hot corrosion on internal surfaces may indicate inadequate filtration for the engine operating environment.

5.4 Internal Deposits

Internal deposits can cause the blockage of cooling holes, disrupt cooling and accelerate local thermal degradation. As the deposit material was transferred through the cooling air, the source of the material is up-stream the compressor cooling air discharge. Analysis of the deposits can determine the nature of the material and provide insight as to its origins. One common source is material ingested through the air in-take and substantial deposits may indicate filtration inadequacies for the engine operating environment.

6 Use of Metallurgical Assessment Findings

6.1 Repair Decisions and Development

The information obtained through metallurgical examination can be used to (a) identify the reparability of the remaining blade set, (b) identify repair procedures necessary for continued service, (c) determine if a change in the coating type would be beneficial and (d) determine the cause of indications or conditions noted during inspections. Metallurgical evaluation is by far the most thorough way of characterizing the sustained damage and therefore, can be used to develop repair processes customized to the part and ensure the appropriate restorations are completed.

6.2 Risk Management

Risk is managed by making decisions to repair blades, how to repair the blades and ultimately, to re-service blades based on a detailed understanding of the part condition. A metallurgical assessment can provide a thorough characterization of the damage sustained, many modes of which are undetectable by non-destructive inspection techniques. This minimizes the risk of damage undetectable by other methods that may have implications upon the continued serviceability of the components.

6.3 Engine Operating Indicators

The feedback that metallurgical analysis provides to an engine manager varies over the life cycle of an engine program. Analysis of the first set of service run components is used to evaluate levels of base material degradation, coating deterioration and assess for potential design deficiencies. This initial stage of investigation may be performed upon the engine fleet leader, new models or after component up-grades/modifications which may alter the operating conditions.

Once a suitable data population has been obtained to adequately benchmark the typical blade deterioration rate for a fleet of engines, examination of subsequent blades can identify differences in engine operation. This can be used to detect abnormal operating conditions such as short term over-firing, long term over-firing or a shift in the thermal profile within the engine. Regular monitoring of the fleet leading components will help to manage the life limiting mechanism of those components.

Continued metallurgical analysis of gas turbine components can identify conditions that may need to be addressed by the engine manager. For example, re-occurring incidences of high cycle fatigue cracks on blades sets may warrant the review of operating records/practices to ensure that the engines are not being operated in speed zones known to result in detrimental resonant frequencies. The presence of continuous hot corrosion cases is another example which the engine manager should attend upon. Determination as to whether the corrosion agents responsible for the damage and the location of corrosion (internally and/or externally) will provide guidance to the engine manager to further investigate plant filtration or gas quality.

If minimal to moderate degradation was sustained, there may be potential for a service interval extension. Further work and assessment of other critical parts would be necessary to positively identify an interval extension. Engine models can be developed based on this assessment so that extended intervals could be reliably managed based on operating conditions. Needless to say significant maintenance cost savings could be realized if the service intervals could be extended.

7.0 Case Studies

7.1 Case Study #1

A combined cycle facility running four GE MS7001 EA engines had been uprated from a 2020°F to a 2055°F firing temperature. The engines experienced extremely rapid part deterioration and the facility decided to return to a 2020°F firing temperature. Upon returning to what was thought to be the same 2020°F firing temperature that was used before the uprating the components still experienced relatively rapid deterioration.

This facility had been conducting life analysis on turbine blades as a standard practice for over a decade. The standard deterioration rate at the original 2020°F firing temperature had been well benchmarked. Examination of components operating at the 2055°F firing temperature found a substantial increase in both the base alloy and coating deterioration and it was concluded that the parts were unlikely to survive a full 24,000 hour service interval. However, examination of the components after attempts to return to a 2020°F firing temperatures still found a relatively fast base alloy degradation rate compared to the benchmarked components. Life analysis evaluation concluded the buckets were operating at higher temperatures than the original 2020°F temperature and, therefore, the firing temperature had not been successfully returned to the pre-uprating condition.

In response to the life analysis results, modelling was conducted which found that the exhaust temperature control curve had underestimated the firing temperatures since the uprating. Improper control curve constants had underestimated both the 2055°F firing temperature as well as the attempts to return to the 2020°F firing temperature. The OEM ultimately had to apply corrections to the control curves as a result of the investigation. The engine operator had concrete evidence of the incorrect firing temperature as a result of the metallurgical analysis program that he had subscribed to over the life of his components.

7.2 Case Study #2

A set of Rolls-Royce RB211 24G HP turbine blades was submitted for repair. The blade had a total of 49,000 hours since new and 28,000 hours since last repair. During operation, the engine had experienced a thermal spread condition and, to avoid trips, several thermocouples had been disengaged. Inspection found several blades to exhibit thermal-mechanical fatigue cracks on the lower airfoil. To determine the extent of damage, two blades were selected for metallurgical analysis.

Optical examination of the damaged region confirmed the damage was typical of thermal-mechanical fatigue. Both blades exhibited cracks initiating on the external and internal surfaces as illustrated in Figure 9b.

The overall base metal degradation was considered more advanced than typical for blades of similar service hours. The region of TMF damage exhibited significant base alloy degradation indicating this area had a relatively high operating temperature. This elevated operating temperature would have (a) resulted in large thermal changes during engine starts/stop and (b) have reduced the material strength. Both factors would have contributed to thermal cracking.

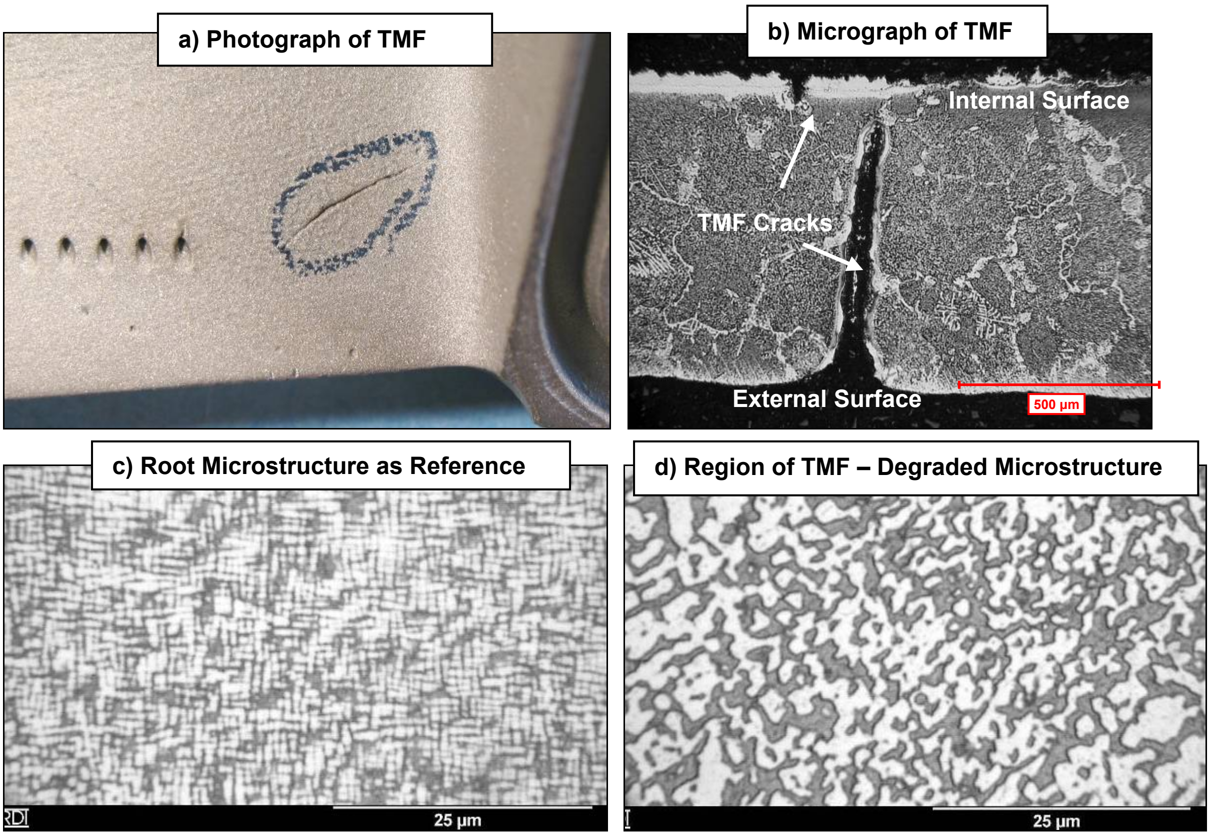

Figure 9: Optical micrographs displaying the TMF cracking and microstructural degradation relative to the root structure of RB211 24G HP Blade.

Without destructive testing and the detection of the internal TMF cracking, a repair shop could run the risk of basing reparability based upon external features alone. In this example, only a portion of the blades exhibited external cracking. However, because internal TMF cracking was detected, the entirety of the blade set was recommended for retirement. Also, the engine operator was made aware that the advanced degree of base metal degradation indicated the engine had been over-firing which had increased the blades susceptibility to TMF.

8.0 Summary

Due to the variation in engine operating conditions, the post-service condition of turbine blades can vary significantly. Metallurgical analysis of the blades can provide information necessary to make informed maintenance decisions. Metallurgical characterization of the blade set condition can provide data to base (a) repair decisions upon, (b) manage risk and (c) assess for detrimental engine operating conditions. Therefore, metallurgical analysis of turbine components should be incorporated within maintenance programs.

Table 1: Summary of Degradation, Consequences and Maintenance Considerations

Location	Degradation Mode	Causes and Consequences	Maintenance / Repair Considerations
Base Alloy	**Base Alloy Aging**	•Material degradation due to high temperature operation. •Reduction in material strength and impact properties. •Temperature dependent.	•Life limiting mechanism for base load applications. •Undetectable by NDT methods. •Reparable with proper heat treatment. •To (a) minimize repair costs and (b) minimize risk of insufficient heat treatment, heat treatment should be based on analysis findings. •Abnormal heat patterns can indicate engine operating irregularities. •Limited aging may indicate potential for service interval extension.
	Creep Damage	•Combination of high temperature and stress causes material to creep. •Advanced stages of creep damage results in void formation. •Creep damage can lead to deformation, cracking and failure. •Occurs simultaneously with alloy aging. •Temperature and stress dependent.	
	High Cycle Fatigue	•Repetitive/cyclic loading can result in fatigue cracking. •Can lead to catastrophic failure.	•Analysis to determine the cause of crack initiation. •Blade set reparability based upon location and size of crack(s). •Detectable by NDT methods. •Heat treatment can alleviate cyclic damage accumulation (if not cracked). •Prevention requires elimination of cyclic loading or part modification.
	Thermal-Mechanical Fatigue Damage (TMF)	•Accumulation of cyclic stresses from temperature changes can result in low-cycle fatigue cracking. •Associated with number of engine starts/stops/trips. •Life limiting mechanism for peaking or high start applications. •Can result in cracking and failure.	•Life limiting mechanism for peaking and high-start engine applications. •TMF cracking can occur internally and externally. •Heat treatment can alleviate cyclic damage accumulation (if not cracked). •Location and size of TMF cracks can determine set reparability. •TMF on external surfaces only – with use NDT to assess reparability on a blade-by-blade basis. •TMF on internal - retire blade set.
External Coating / Surface Condition	**Coating Depletion**	•Depletion of protective elements in coating. •Temperature and start/stop dependent. •Complete depletion can result in coating failure/breaching and damage to base alloy.	•Life limiting mechanism for base load applications. •Coating can be re-applied for continued service. •Analysis to assess coating performance and selection. •If irreparable damage sustained to base alloy, consider upgrading coating. •Limited depletion may indicate potential for service interval extension.
	Coating Cracks	•Usually due to engine starts/trips or impact damage. •Localized oxidation damage to underlying base alloy.	•Requires removal and re-application of coating. •If irreparable damage sustained to base alloy, consider changing coating.

Table 1 (Continued)

External Coating / Surface Condition (Continued)	**TBC Coating Loss**	•Coating loss due to thermally grown oxide beneath TBC or impact. •Oxide growth temperature dependent. •Coating loss results in elevated base metal operating temperature and accelerated base metal damage.	•Coating loss may result in increased base metal damage requiring adjusted repairs. •TBC is a consumable coating and only deemed inadequate if irreparable damage to the blade is sustained.
	Hot Corrosion	•Accelerated damage to coatings and base alloy. •Can result in irreparable damage or part failure. •Requires the presence of corrosion agents (Na, K with S. or V, Pb independently).	•Metallurgical assessment to determine corrosion type, corrosive agents and reparability. •Significant corrosion may be cause to retire blade set. •Elimination of corrosive agents' source(s) ideal solution. •Consider applying coating with appropriate corrosion resistance.
	Impact Damage	•Damage can range from superficial to coating damage to catastrophic failure.	•Material/objects from up-stream. •Sources can be intake through filtration, up-stream failure or material left in engine during maintenance. •Prevention based upon elimination of source.
	Deposits	•Potential for cooling hole blockage.	
Internal Surfaces	**Coating Depletion**	•Consumption of protective properties of coating. •Temperature and start/stop dependent. •Can result in coating failure/breaching and damage to base alloy.	•Coating can be re-applied during repairs. •May need to be removed depending on repair heat treatment process for base alloy.
	Internal Surface Alloy Depletion (Un-Coated)	•Depletion of strengthening elements at surface, weakening surface layer. •Temperature dependent. •Resulting in (a) lower surface fatigue resistance and (b) reduction in effective wall thickness.	•Sustained damage irreparable. •Decision to continue servicing based upon tolerating existing damage. •If depth of damage unacceptable, retire blade set. •If acceptable, monitor condition between service intervals. •Undetectable by NDT methods.
	Intergranular Oxidation (IGO) (Un-Coated)	•Oxidation damage along material grain boundaries. •Potential for IGO damage causing brittle oxides for form along grain boundaries.	
	Hot Corrosion	•Accelerated damage to coatings and base alloy. •Can result in irreparable damage or part failure. •Requires the presence of corrosion agents (Na, K with S. or V, Pb independently).	•Metallurgical assessment to determine corrosion type, corrosive agents and reparability. •Significant corrosion may be cause to retire blade set. •Corrosive agents from up-stream compressor before the cooling air off-take. •Elimination of source ideal solution.
	Internal Deposits	•Foreign material within cooling passages, potential for cooling hole blockage.	•Metallurgical assessment to determine nature of deposit. •Deposits from up-stream compressor before the cooling air off-take, usually air-intake. Can indicate filtration concerns. •Elimination of source ideal solution.