20TH SYMPOSIUM OF THE INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE
BANFF, ALBERTA, CANADA
OCTOBER 2013

IAGT™

13-IAGT-XXX (*REFERENCE PROGRAM*)

AIRFOIL THICKNESS AS A LIFE LIMITING FACTOR OF GAS TURBINE BLADES

Kevin Wiens, P.Eng.*†

Liburdi Turbine Services Inc.(†kwiens@liburdi.com)
400 Highway 6 North, Dundas, ON. www.liburdi.com

Keywords: *gas turbine, wall thickness, life extension, coating, chemical stripping, gas turbine blades, inspection.*

Abstract

Historically, gas turbine blades have been retired from service primarily due to creep life limitations. With the introduction of full solution rejuvenation to repairs, creep is no longer limiting turbine blade life. With the extension of life beyond the original limits, wall thickness has emerged as a significant cause of blade retirement.

Reductions in airfoil thickness result in reduced load bearing capacity of rotating components and can increase the stresses that develop under transient thermal conditions for both rotating and stationary parts. These damage modes are considered in establishing safe wall thickness limits in different locations for each component. Understanding the causes of low wall thickness is critical in maximizing the usage of turbine blades while avoiding unplanned engine shut-downs. Through case studies it can be shown that maximizing service life requires proper control of the original manufacturing process, monitoring of wall thickness by nondestructive methods and careful removal and re-application of protective coatings at appropriate service intervals.

1 Introduction

The use of gas turbine components was originally limited by the thermally-induced degradation of the base materials. The life limits applied by the original equipment manufacturers (OEM's) were largely based on creep in the case of the rotating components. Retirement of gas turbine blades typically occurred after two service intervals; typically 50,000 – 75,000 hours of service.

With the introduction of rejuvenation processing during repair, the use of gas turbine components is no longer limited by creep [1, 2]. Life extension well beyond the OEM limits has been achieved for most turbine blade types. The only cases where rejuvenation are not applicable are cases where other degradation modes, such as oxidation or thermal mechanical fatigue, are the life limiting factors.

However, turbine blade life cannot be extended indefinitely, even in cases where creep is the primary degradation mode. For these components, airfoil thickness has emerged as the most common retirement cause.

Figure 1 shows the causes for retirement for four types of aero-derivative first stage turbine blades, all of which received rejuvenation heat treatments during prior repairs. The data was collected from 90 sets of turbine blades (7260 individual blades). While the prevalence of the retirement causes varied for each type of blade, airfoil thickness was found to be the most dominant cause[1] overall.

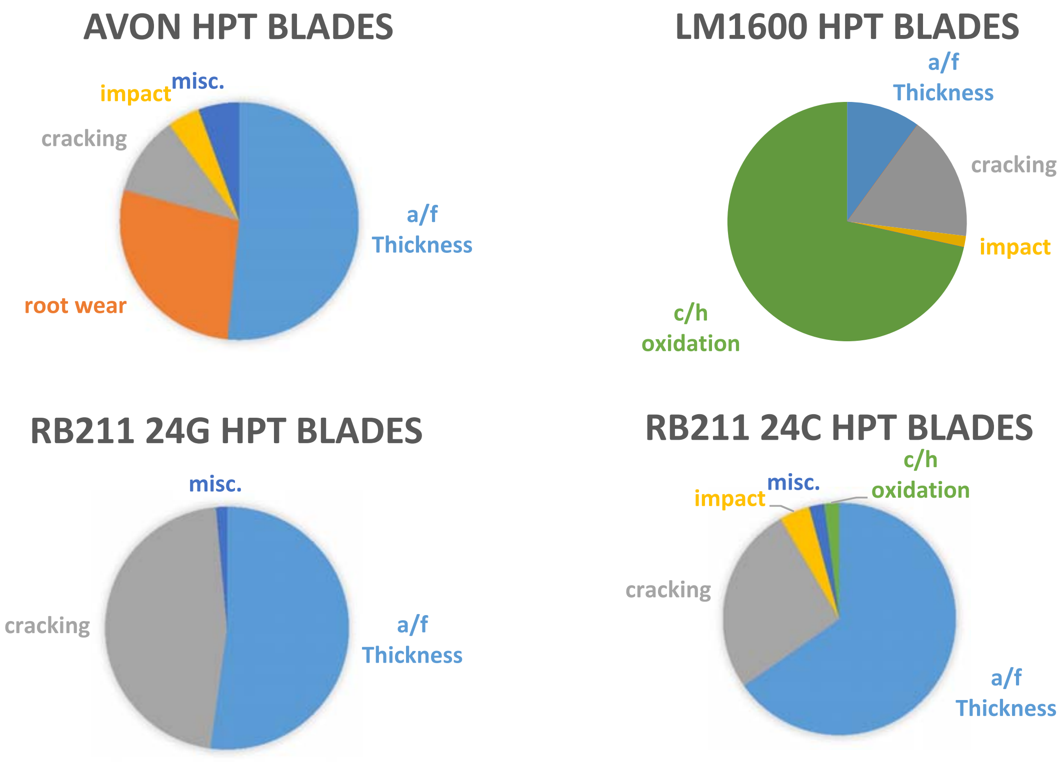

Figure 1: Retirement causes for 4 types of gas turbine blades. The blades had been life extended by rejuvenation heat treatments.

With each repair of gas turbine blades, wall thickness diminishes as coatings are stripped and oxidation damage is removed. **Figure 2** shows the increase in average scrap rate after each repair cycle for RB211 24C HPT blades. The number of blades scrapped for insufficient wall thickness after 2 repairs is typically negligible.

[1] In some cases, multiple retirement causes may exist. Blades which are deemed scrap for the presence of cracking are typically culled from the repair process before wall thickness is assessed. Therefore, the number of blades retired due to insufficient wall thickness has been somewhat underestimated.

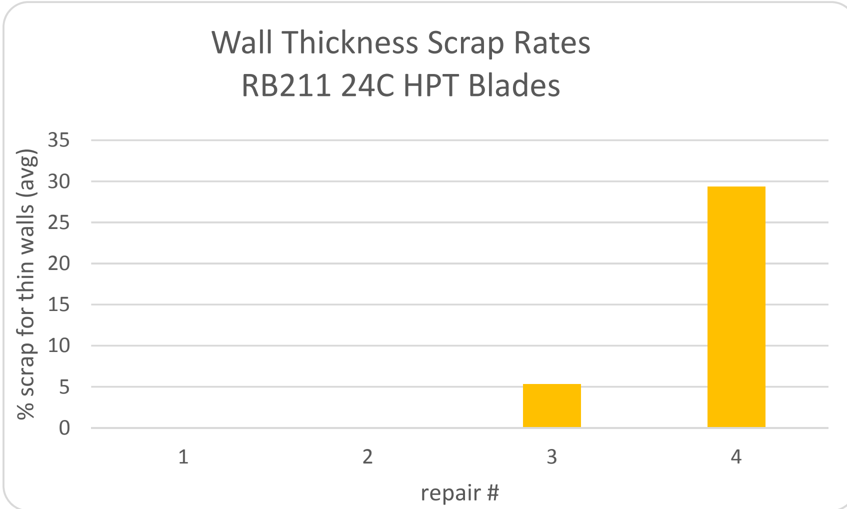

Figure 2: Scrap rates due to thin walls as a function of time (repair cycles) for RB211 24C HPT blades.

2 Establishing Safe Wall Thickness Limits for Operation

At what point should a component be retired for insufficient wall thickness? This is a complex question for the repair engineer, as the implications of thinning airfoil walls depend on the specific component in question and the location of the thinning.

The distribution of stress in a rotating airfoil is governed by the combination of centrifugal, aerodynamic and thermal loads. For some internally cooled blades, the steady state stress of the outer wall of an airfoil may be relatively low as a result of the thermal contribution of stress - the hot periphery of the airfoil is constrained from expanding by the colder blade core, which results in a thermally induced compressive stress in the outer wall and a tensile stress in the core. In these cases, a thinning airfoil may not significantly jeopardize the load bearing capacity of the blade under steady state conditions.

Even in cases where the *steady-state* stresses on the hot outer walls of a turbine blade airfoil are relatively low, thin walls may be subject to damage related to thermal cycling (*transient* stresses). Engine start-up and shut-down results in heat-up and cool-down rates which are dependent on the local thickness of the component. For example, the relatively thin trailing edges will expand and contract at a faster rate than the core of the airfoil [3, 4]. For vanes, this effect is exacerbated by the physical constraint of the outer shrouds, while rotating blades are relatively more free to expand radially. **Figure 3** depicts how thermal cycles result in thermal mechanical fatigue (TMF) cracking of the trailing edge airfoil of a turbine vane.

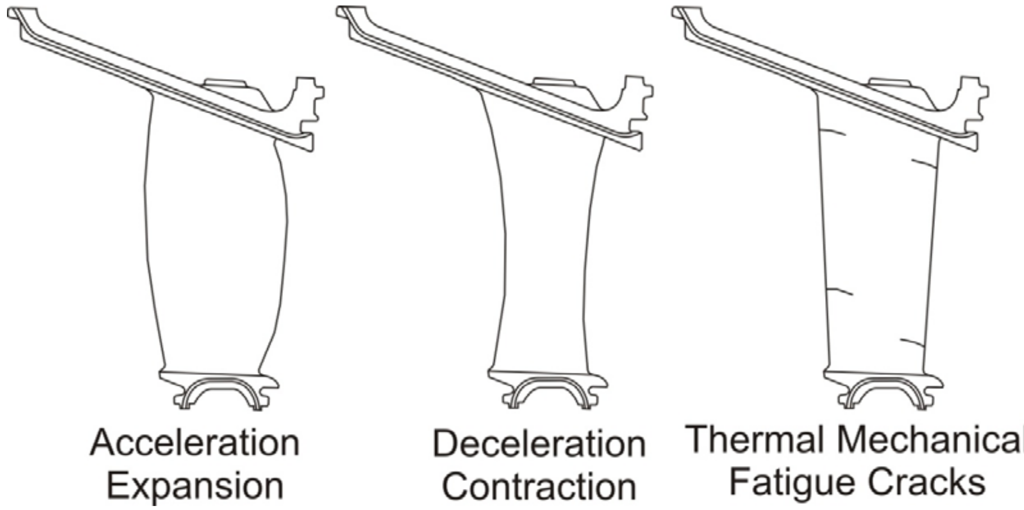

Figure 3: Mechanism for thermal mechanical fatigue of turbine vanes.

2.1 Case Study: Cracking of Thin Airfoil Walls Under Transient Loading

Figure 4 shows an aero derivative turbine blade which developed cracks in service through a thin region of the airfoil, in some cases leading to an airfoil breach. The cracks were prevalent in a population of blades exhibiting relatively thin airfoil walls. Four blades were found to be cracked in the set of 102 blades. Three of the four cracks were through the thinnest walls in the blade set. The fourth crack was in the lower quintile of the wall thickness distribution.

The cracks were oriented radially (parallel to the cooling passage) suggesting thermal stresses were prominent in their formation; had the centrifugal load been dominant, the cracks would be expected to occur in the axial (perpendicular to cooling passage) direction.

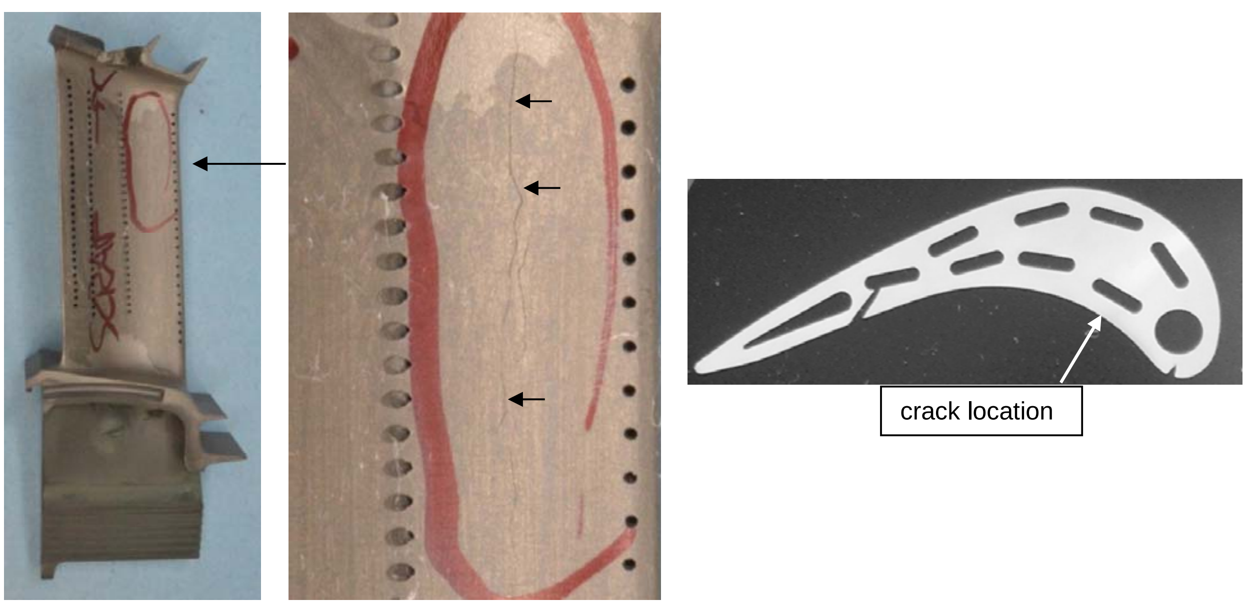

Figure 4. Radial cracking (right image) from a set of aero-derivative turbine blades.

The crack was examined in cross section by optical microscopy (**Figure 5**). The crack path was straight and transgranular. The width of the crack tapered significantly along its length. These crack features are typical of thermal mechanical fatigue (TMF) cracking.

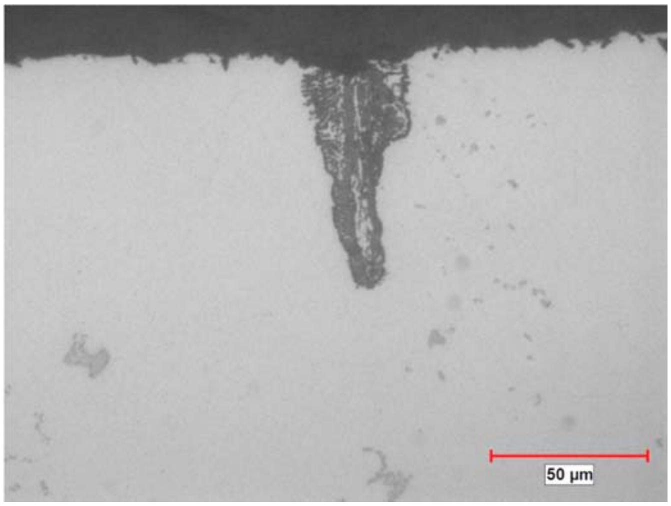

Figure 5: Optical micrograph of radial airfoil cracking through a thin airfoil wall.

A mechanism for the observed cracking is depicted in **Figure 6**. On heating, the thin wall between the external surface and the cooling passage expands. The relatively bulky regions near the thin wall take longer to heat, constraining the thin wall leading to a compressive stress. Following shut down of the engine, the thin wall cools more rapidly than the surrounding metal, which generates a tensile stress perpendicular to the observed crack.

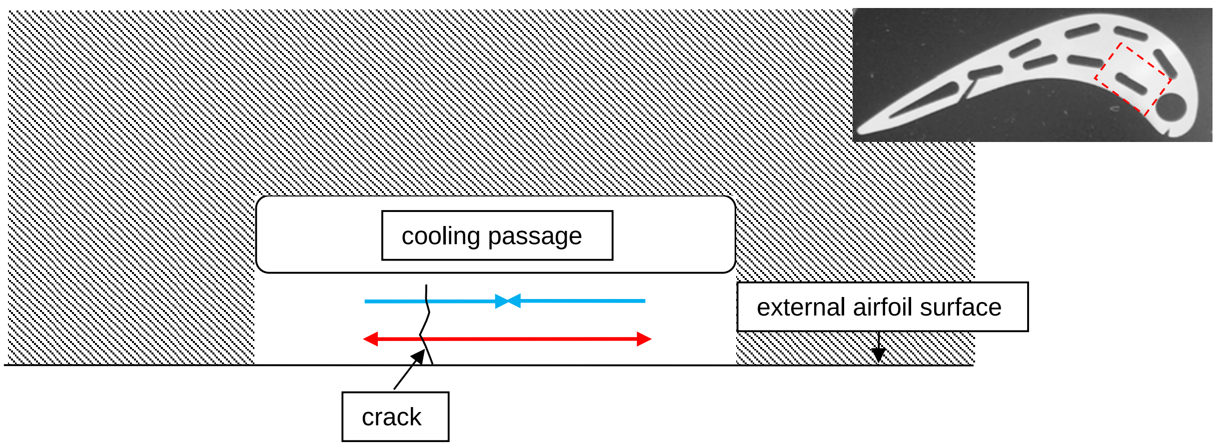

Figure 6: Schematic showing the mechanism for thin wall cracking during transient thermal loading. The thin wall expands (red arrow) and contracts (blue arrow) faster than the surrounding metal (hatched area) which generates stress cycles perpendicular to the observed crack.

3 Control of Wall Thickness at Original Manufacture

Maximizing component life in terms of wall thickness requires not only minimizing the reduction in thickness over time but also control over the initial thickness. While some recent studies have shown that wall thickness variation at manufacture has little impact on initial component performance, these studies only consider wall thickness variation of the reported manufacturing tolerances (typically 5% for wall thickness) [5, 6]. In practice, it can be shown that much more significant variation in the original manufacturing process can exist, resulting in a significant reduction in long term life of the component.

3.1 Case Study: Casting Core Shift

The complex internal passages of modern turbine components are created by supporting ceramic cores in the molten metal. Positioning of the cores is critical in ensuring proper airfoil dimensions.

Figure 7 shows cross sections of aero turbine blades of the same type after service. The airfoil thickness near the trailing edge of the blade was found to be relatively thin (~40% below nominal) on the pressure side and thick on the suction side. Comparing the blade cross section to nominal it is apparent that the trailing edge cooling passage of the blade was shifted relative to the other cooling passages. This suggests the relatively thin wall was the result of casting core shift at manufacture. The common causes of thinning (service damage, material loss during repair) would not account for the thin wall.

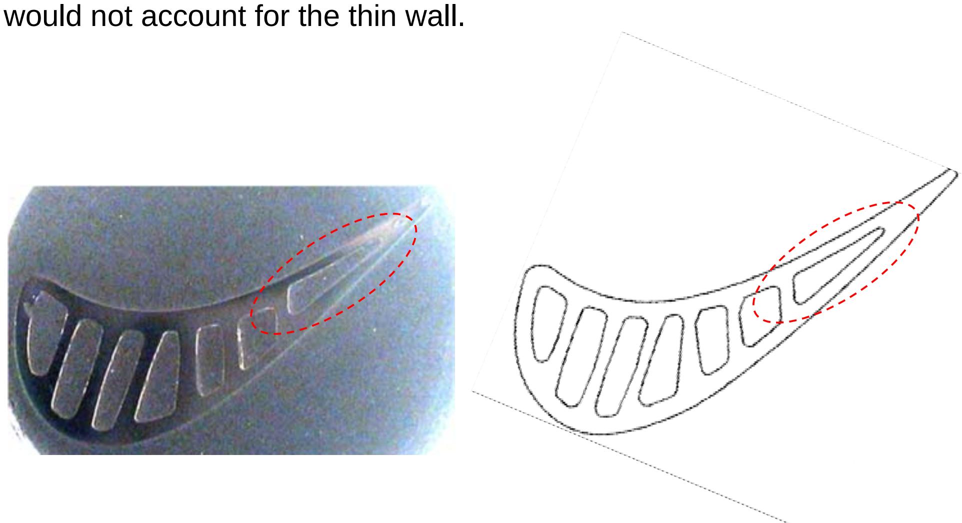

Figure 7: Thin airfoil wall due to casting core shift of the trailing edge passage (image left). Proper alignment of the cooling holes is depicted image right.

3.2 Case Study: Hole Drilling

A set of turbine blades had a significant scrap rate due to thin airfoil walls following 3 service intervals. Cross sections of the airfoil revealed the thin airfoil region to be associated with a cooling hole which was misplaced relative to the camber line by approximately 0.020-inches. **Figure 8** shows two sectioned airfoils, one with a misplaced trailing edge cooling hole (thin wall, pressure side) and one from another set of blades, with the cooling holes centred on the camber line.

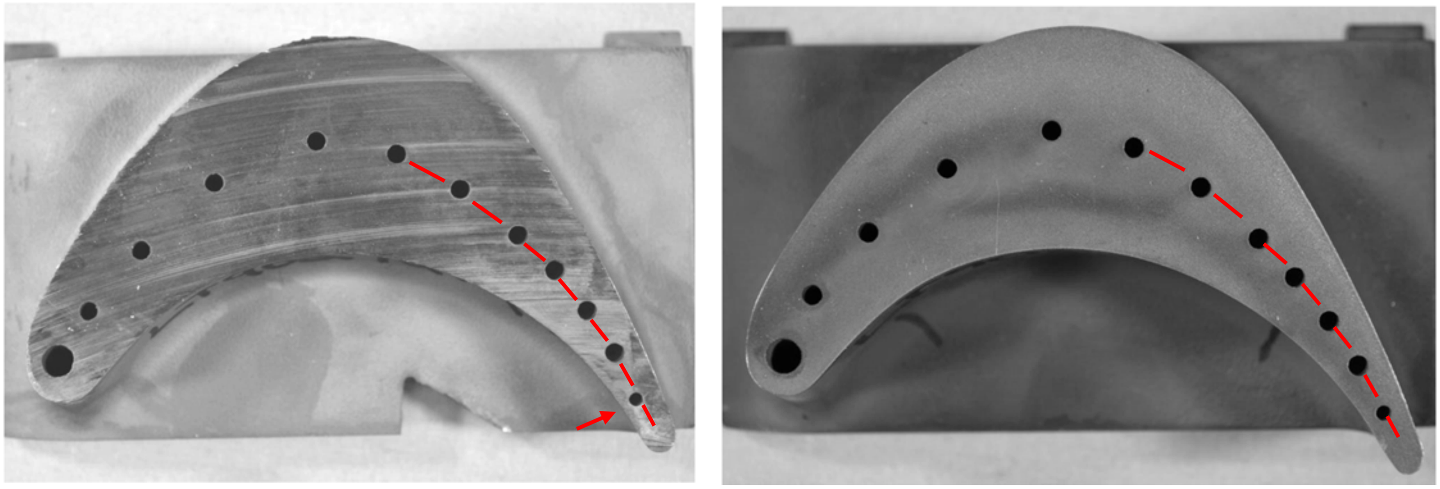

Figure 8: Misplaced trailing edge cooling hole (arrow). The airfoil section on the right shows a proper alignment of cooling holes along the camber line (dashed line).

The airfoil cross sections also revealed a discrepancy in the diameter of the cooling holes. The cooling holes at the cross sectioned locations were found to be oversized by approximately 0.010-inches relative to measurements of the holes taken at the tip. **Figure 9** shows cooling hole diameters at the tip (exit) and root (entry) and at two locations further within the blade. Three blades were measured; one after 3 service intervals (3 repairs) and two blades after 1 service interval (no repairs). In each case, the cooling holes were restricted (smaller) at the tip and root, by approximately 0.010-inches. Also, the cooling hole diameter of the blade which had undergone 3 repairs was oversized as a result of multiple strip and recoating cycles applied to the internal surfaces.

Blade Set#	Location	Hole Diameter*
1 (3 repairs)	1	110
	2	120
	3	187
	4	175
2 (no repairs)	1	96
	2	106
	3	174
	4	162
3 (no repairs)	1	n/a
	2	102
	3	171
	4	159

* in mils, average.

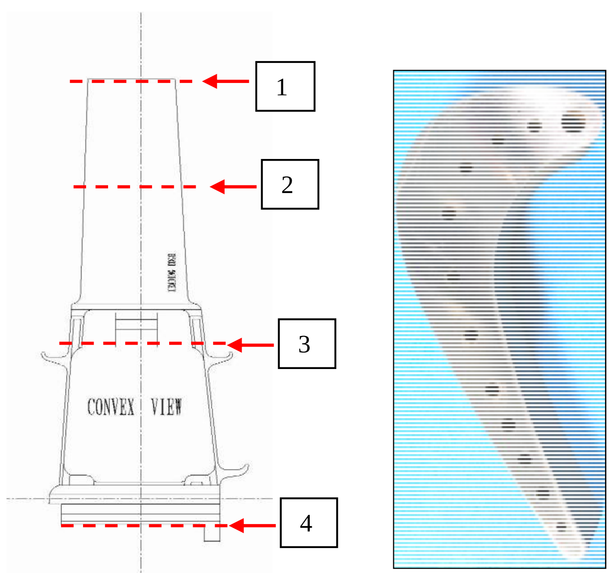

Figure 9: Cooling hole diameters (in mils) of industrial turbine blades from three different sets.

The cooling holes are produced at original manufacture by a shaped tube electrolytic machining (STEM) process. The STEM drills holes from the tip which meet up with larger holes drilled from the root end of the blade. The STEM process is controlled by feed rate of the electrode and voltage. Variation of these parameters may result in corresponding variation in the diameter of the hole [3]. Accordingly, the restrictions of the cooling holes noted in Table 1 were likely produced by variation of the STEM process.

It was unlikely the cooling holes were intended to be larger within the blade while relatively restricted at the tip. The flow of cooling air in service would be metered by the restrictions. Therefore, any increase in cooling hole diameter within the blade reduces the wall thickness of the blade with no corresponding practical increase in cooling. A cooling hole with consistent diameter could be made 0.010-inches smaller and flow the same quantity of cooling air. The smaller hole would save 0.005-inches in wall thickness which would likely extend the life of the blade by at least one service interval.

4 Minimizing Reductions in Wall Thickness from Service Exposure

The wall thickness of a hot-section turbine component can diminish during service exposure under particular conditions. The most common mechanism of wall thinning during service is high temperature oxidation. Wall thickness reductions may also occur due to hot corrosion or heat erosion (oxidation and solid particle erosion), although these mechanisms are much less prevalent.

In cases where the service demands (time, temperature, engine cycling) are fixed, reductions in oxidation rates can be achieved through the use of protective coatings, typically diffusion aluminides (internal and external) or overlay coatings (external).

4.1 Case Study: High Temperature Oxidation of Uncoated Blades

A set of industrial turbine blades was examined after a service interval consisting of approximately 50,000 hours of service under base load conditions (44 starts). Metallurgical examination of airfoil cross sections revealed the airfoil surfaces to be significantly oxidized. The oxidation damage resulted in an alloy depleted layer up to 170 microns thick at the trailing edge of the airfoil (**Figure 10**).

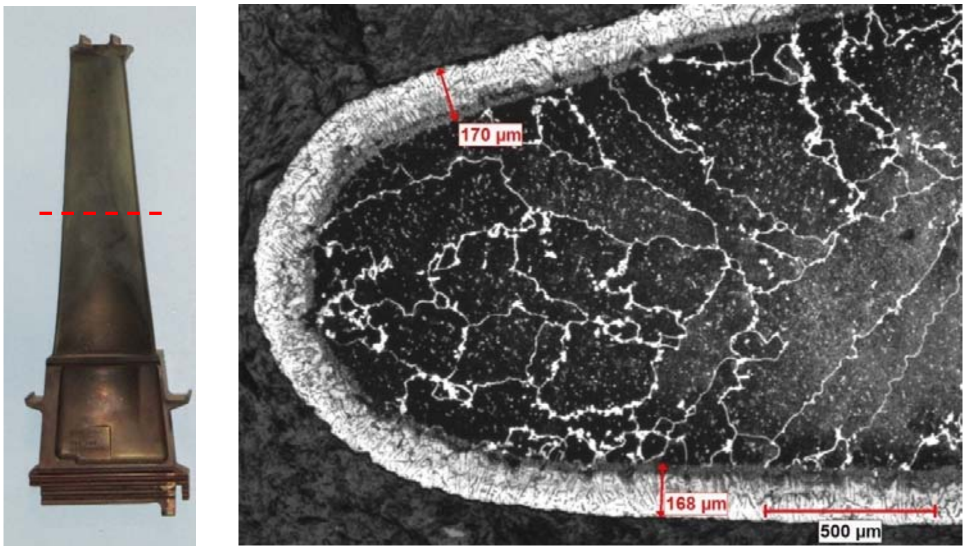

Figure 10: Alloy depleted layer (arrows) at the surface of a gas turbine blade airfoil.

The effective load bearing cross section of the airfoil would not include the depleted layer, as this layer was lacking the alloying elements (aluminium, titanium) responsible for strengthening the blade material.

The blade lacked a protective coating on all surfaces examined. The absence of coating was not the result of consumption during service, as the relatively cool regions of the lower airfoil were also lacking a coating.

Operation of the subject blade without a coating resulted in a significantly diminished life-span relative to a coated component.

<u>4.2 Case Study: Oxidation of Internal Surfaces</u>

Two sets of industrial turbine blades of the same type were subject to metallurgical examination after service. Both sets had operated under peak conditions. The first set had operated for approximately 24,000 equivalent operating hours (EOH) since new while the second set had operated for two service intervals of 24,000 EOH, each. The second set had been subject to repair following its first service interval which involved external coating replacement and tip repair. The internal coating was not replaced as a part of the repair.

The internal surfaces of the first (non-repaired) blade set are shown in **Figure 11.** The internal surfaces showed sporadic coverage of the aluminide coating. Where coating was present, negligible degradation was observed. Regions without coating showed only minor alloy depletion, approximately 0.001-inch in depth.

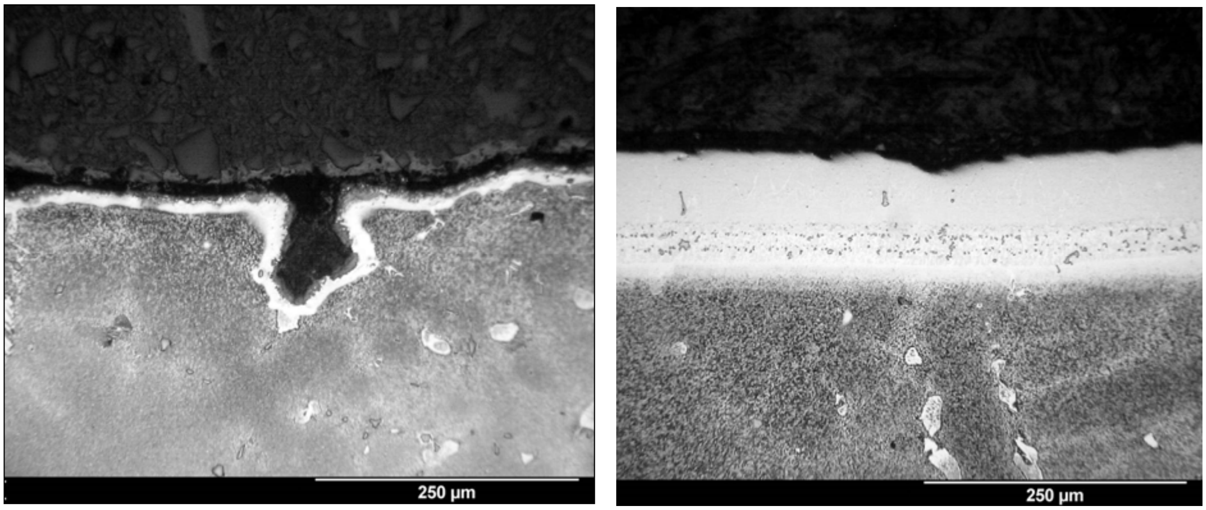

Figure 11: The range of internal surface condition of an Industrial turbine blade after one service interval; base alloy depletion (white layer, left image) and undepleted coating (right image).

The second blade set (two service intervals, one repair) showed significantly greater base alloy damage of the internal surfaces (**Figure 12**). The effective wall thickness had been reduced by approximately 0.010-inches as a result of the oxidation.

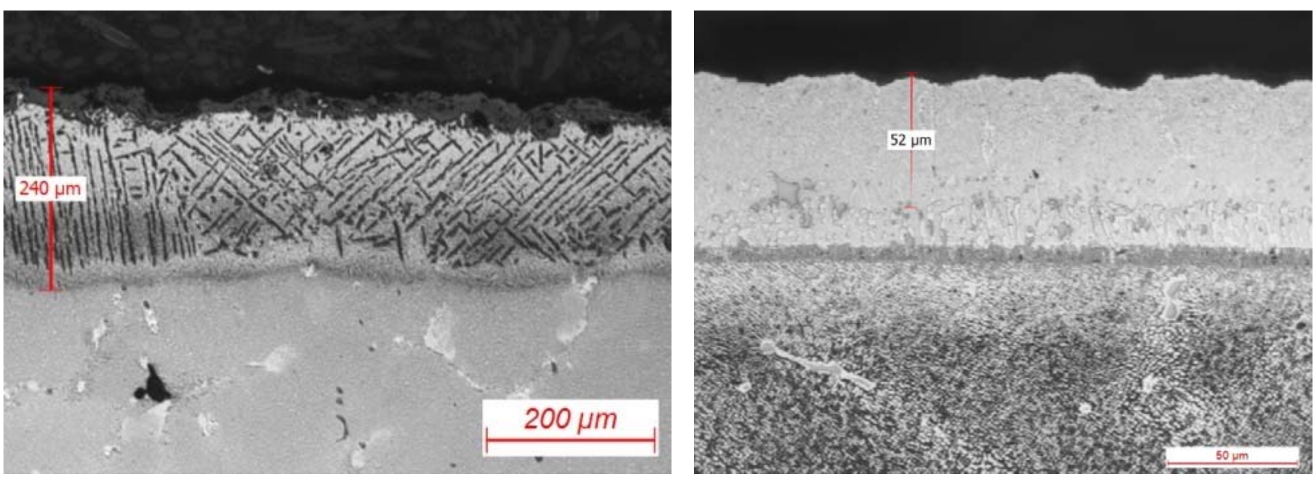

Figure 12: The range of internal surface condition of an industrial turbine blade after two service intervals (no re-coat); base alloy depletion (left) and undepleted coating (right).

The internal coating protected the internal surfaces adequately for a service interval of 24,000 EOH, based on the degradation rate of the first blade (one service interval). Accordingly, the base alloy damage of the second blade (two service intervals) would have been substantially less had the internal surfaces been recoated as a part of the repair.

5 Control of Material Removal During Repair

Each repair cycle involves the removal of base alloy. Processes designed to remove coatings and clean the surfaces inherently involve some degree of airfoil thickness reduction. Minimizing material loss during repair requires stripping and cleaning processes which are highly selective – removing unwanted material (coating, oxides) while preserving the base alloy.

A chemical stripping process which is too aggressive will result in corrosion of the base material. If the chemical strip is too mild, coating will remain and the repair vendor will typically resort to mechanical grinding of the coating [8]. Surface grinding removes coating and base material indiscriminately. In this sense, grinding is not a selective process and typically results in a relatively high degree of wall thickness reduction.

5.1 Case Study: Base Alloy Attack During Coating Stripping

A set of industrial gas turbine blades were examined after the coating was stripped by an unknown party. The blades were deemed to be scrap due to insufficient wall thickness. The blades exhibited visual signs of grinding (lustrous, metallic appearance) of the external surfaces (**Figure 13**).

Figure 13: As received condition of the blade. Note the bright surfaces.

One blade was sectioned axially through the airfoil, polished and examined by optical microscopy. The internal surfaces were found to exhibit deep pitting (up to 0.008-inches); no evidence of high temperature oxidation attack was observed over the pitted internal surfaces (**Figure 14**). The external surfaces were smooth and free of oxidation and pitting. The apparent grinding of the external surfaces may have removed evidence of damage.

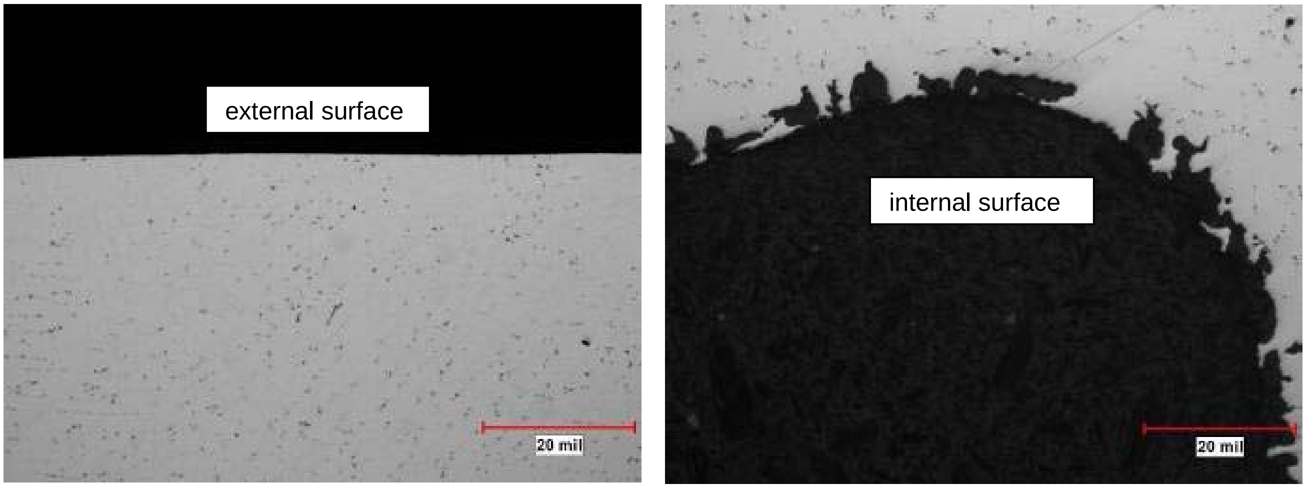

Figure 14: micrographs showing the external and internal surface condition of a blade stripped by an unknown party.

The absence of high temperature oxidation or hot corrosion scales suggests the cause of pitting was aqueous corrosion. The most common source of aqueous corrosion of a turbine blade is chemical stripping.

Pitting of the airfoil surfaces resulted in a reduction in the effective wall thickness of the blade, resulting in the early retirement of the subject blade set.

6 Conclusions

The wall thickness has been shown to be an important factor in the serviceability of a gas turbine blade. Thin airfoil walls may be subject to increased transient loading, resulting in a higher susceptibility of cracking by thermal mechanical fatigue (TMF).

Maximizing the lifespan of the turbine blade requires control and preservation of the blade's wall thickness. The manufacturer, operator and repair vendor all influence the life of a turbine blade. **Table 1** summarizes a strategy for managing the wall thickness of a component over its life, in terms of the various parties involved.

Table 1: Wall Thickness Management Strategy

Original Manufacture	Operation	Repair
quality control • hole positioning. • hole diameter.	overhaul components before coating consumption.	minimize base material loss during removal of coatings and damaged base alloy.
application of coatings (internal and external) where required.		measure residual wall thickness to determine serviceability.
		develop wall thickness acceptance criteria.
		coating life assessment and coating application (external and internal).

References

[1] Liburdi J, and Stephens J. Mechanical and Metallurgical Considerations in Extending the Life of Turbine Blades. *NRC Symposium on Gas Turbine Operations and Maintenance*, Toronto, September, 1981.

[2] Liburdi J, Lowden P, and Nagy D. Practical Experience with the Development of Superalloy Rejuvenation. *ASME Turbo Expo*, Orlando, FL, Paper # GT2009-59444, 2009.

[3] Mazur Z, Perez-Hernandez E, Garcia Illescas R. Gas Turbine Nozzle Life Assessment Due to Thermal Fatigue. *ASME Turbo Expo*, Vancouver, BC, Paper # GT2011-45247, 2011.

[4] Cunha F, Dahmer M, Chyu M. Analysis of Trailing Edge Heat Transfer and its Significance in Thermo-Mechanical Design and Durability. *Transactions of the ASME*, Vol, 128, pp 738 – 746.

[5] Bunker R. The Effects of Manufacturing Tolerances on Turbine Blade Cooling. *Journal of Turbomachinery*, Vol. 131, 2009.

[6] Arkhipov A, Krasnovskiy Y, Putchkov I. Probabilistic Life Analysis of Turbine Vanes. *ASME Turbo Expo*, Vancouver, BC, Paper # GT2011-45841, 2011.

[7] Mohan S, Shan H. A review of electrochemical macro to micro-hole drilling processes. *International Journal of Machine Tools and Manufacture*, Vol. 45, pp 137-152, 2005.

[8] Daleo J, Ellison K, Boone D. Metallurgical Considerations for Life Assessment and the Safe Refurbishment and Requalification of Turbine Blades.