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MAXIMIZING GAS TURBINE BLADE LIFE WITH COMPUTED TOMOGRAPHY WALL THICKNESS INSPECTION

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Abstract

This paper explains how airfoil wall thickness has become the typical leading cause of retirement for high pressure gas turbine blades. It describes how computed tomography (CT) inspection can be used to accurately measure the remaining wall thickness and therefore, maximize blade life while ensuring safe and reliable operation in service. The paper explores a number of challenges to the CT wall thickness inspection process and the solutions that have been developed to address them based on practical experience. A strategy is developed for how OEM's, operators and component repair vendors can work together to maximize the life of gas turbine blades while retaining confidence in service operations and maintenance intervals.

1 Introduction

Gas turbine blades are rotating components used to harness the energy of the hot gas stream in a gas turbine. Blades operate in the turbine's hot section (after the combustor) and are exposed to high temperatures and stresses. To protect and cool the blades in this challenging environment, designers have utilized coatings applied to airfoil surfaces as well as internal cooling networks that supply cooling air throughout the blade. As a result, modern gas turbine blades are typically hollow bodies with complex internal geometry and protective coatings applied to their airfoil surfaces (Figure 1).

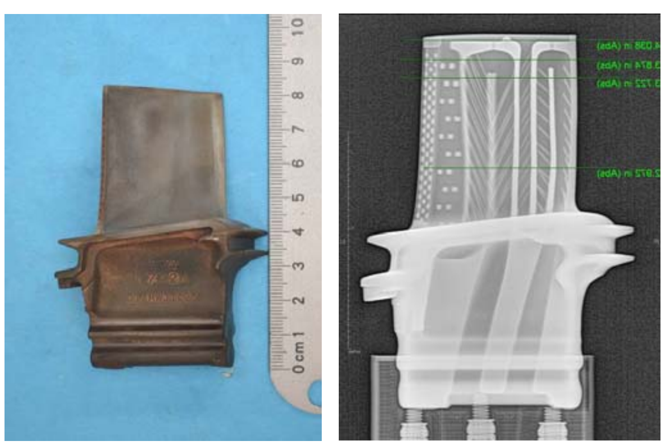

Figure 1 – Photograph & Internal Detail of a Siemens SGT400 CT1 Blade

Gas turbine blade repairs have been performed since the 1960’s to support operators. Repair provides several advantages over new part replacement. Firstly, there are significant cost savings in repairing blades where possible instead of replacing with new components as repairs typically cost a fraction of the new part price. Additionally, repairs are often able to be performed and delivered in a shorter time than new parts can be procured, dependant on new part stock and current market conditions. Finally, there are environmental incentives to repair components for as long as possible as this reduces the environmental impact of scrapping parts unnecessarily.

2 Gas Turbine Blade Life

Gas turbine blade life was originally limited by thermal degradation of the base material. Original Equipment Manufacturers (OEM’s) typically apply life limits to blades to govern the maximum total service hours that a blade can experience. These life limits were largely based on creep damage for rotating components such as blades. Retirement of gas turbine blades typically occurred after two service intervals of 25,000 hours or more each, for a total cumulative life of 50,000 hours or more [3]. A midlife repair is often performed after the first service internal, including removal and replacement of the coatings and replacement of any damaged material at contact surfaces or sealing locations. However the material properties of the base alloy are not typically restored at this time.

Full Solution Rejuvenation® (FSR) is a heat treatment process that reverses the metallurgical damage of the base alloy and returns the material properties to the new part condition. Because of its ability to reset the material properties, FSR is an important tool for extending the life of gas turbine blades [4]. With the introduction of Full Solution Rejuvenation to repair processes, blade life is no longer limited by creep damage. FSR has been successfully employed since the 1970’s to extend the life of gas turbine blades beyond the OEM life limit for many different blade types [1, 2]. FSR is an alloy specific process that uses carefully controlled time and temperature heat treatment parameters to reform the gamma prime precipitates of the specific base material to the as manufactured condition.

However gas turbine blade life cannot be extended indefinitely, even in cases where creep damage is the primary degradation mode. Although FSR can be applied repeatedly to restore the material properties, there are geometric limitations that restrict the continued operation of the blade. These limitations are more governed by the cumulative number of repair cycles and the specific repair processing than the material condition of the base alloy [4]. For hollow components such as high pressure gas turbine blades, one of the most common geometric limitations is airfoil wall thickness. Therefore, the inclusion of Full Solution Rejuvenation in repair processes has shifted the primary cause of blade retirement from creep damage to airfoil wall thickness [3] (Figure 2).

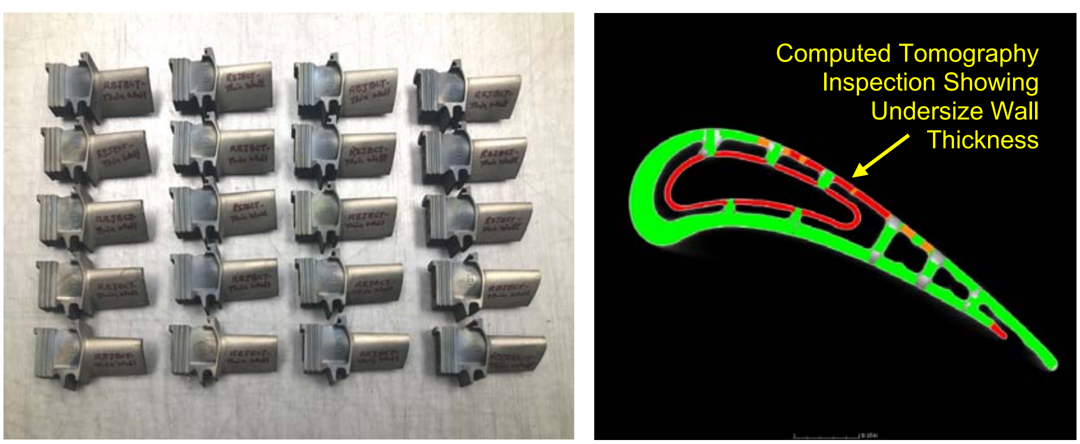

Figure 2 – Rolls Royce 501K34 Stage 1 Blades Rejected For Undersize Wall Thickness

3 Wall Thickness

Wall thickness is defined as the minimum distance from the gas path surface to the hollow internal surface at a given location (Figure 3). Wall thickness measurements are taken after coating removal and before coatings are applied. Internal features (turbulators, cooling pillars) are not included in wall thickness measurements. Although these features likely add some strength to the part, characterizing this added strength is rather complex. Therefore, it is the minimum measurement irrespective of any internal features that is desired when assessing wall thickness. Obtaining such a measurement often requires evaluating the wall thickness over a region and selecting the minimum value obtained.

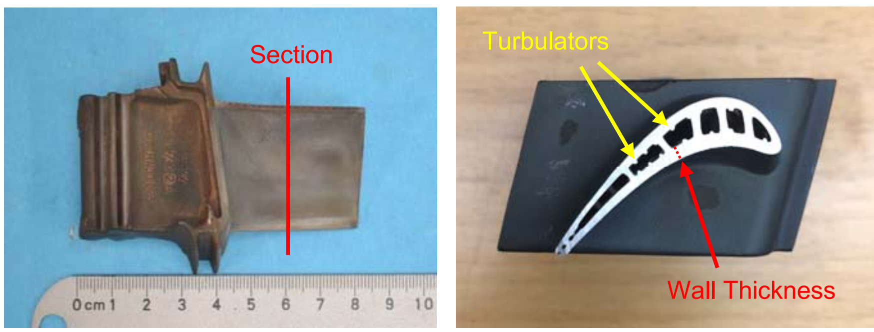

Figure 3 – Cross Sectional View of a Siemens SGT400 CT1 Blade

3.1 Importance

Wall thickness is an important consideration for cooled gas turbine components. Together with any webs (internal walls), the wall thickness is responsible for carrying the mechanical load on the hollow airfoil. For stationary components (vanes), the mechanical load is caused by the incident force of the hot gas path. For rotating components (blades), the mechanical load is a combination of the hot gas path incident force and the circumferential forces caused by rotation. Therefore, wall thickness is especially important for ensuring the mechanical strength of rotating blades.

In addition to the mechanical load that a part's wall thickness must carry, there are also thermal considerations. Due to the transient thermal nature of gas turbine components during start up, shut down and varying operating conditions, the hollow airfoil must cycle through a range of temperatures. Reduced wall thickness can contribute to these thermal changes, either increasing or decreasing the surface temperatures. Thinner walls heat up and cool down faster than thicker walls, which can cause increased thermal strains and lead to low cycle fatigue cracking, distortion and failure. Mechanical and thermal modelling can be performed to understand and evaluate these considerations (Figure 4).

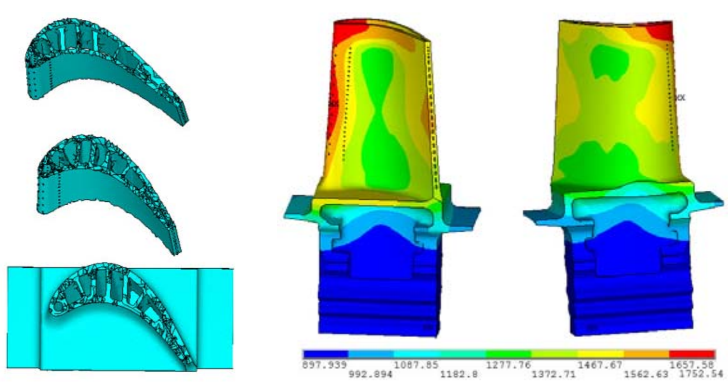

Figure 4 – Mechanical & Thermal Modelling of a General Electric LM2500 Single Shank HP1 Blade

Intuitively there exists a functional limit to wall thickness for proper operation of the part. Operating below this functional limit can cause the formation of life limiting damage, which can lead to premature removal of the components from service or failure. This damage typically starts as thermal mechanical fatigue (TMF) cracks and can eventually progress into airfoil breaches. The exact progression of this damage is often component specific and difficult to predict.

A history of metallurgical analyses and service experience combined with evaluation of operating conditions and borescope findings has produced an understanding of the progression of this damage on Siemens SGT A35 (Rolls Royce RB211) 24C HPT Blades. If a thin walled blade of this type is put back into service, it can progress through the following phases of damage (Figure 5).

1. Radial cracks develop in thin walled location (typically mid concave airfoil)
2. Airfoil breaches form in locations of radial cracks which undermines the cooling scheme and allows hot gas to enter the blade
3. Axial cracks form adjacent to airfoil breach which can grow and eventually cause liberation

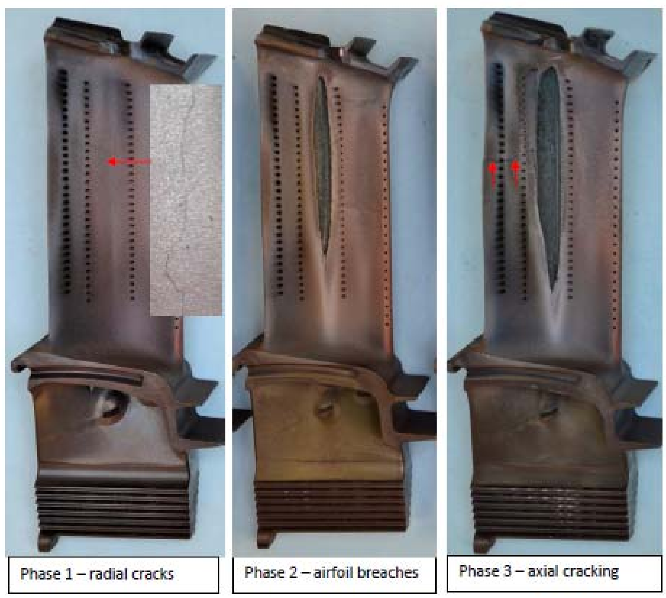

Figure 5 – Damage Progression of Undersize Wall Thickness on Siemens SGT A35 24C HPT Blades

3.2 Loss During Service

The importance of wall thickness means that it is valuable to understand how it changes during a blade's life including both service and repair. Most modern gas turbine blades have coating applied to their airfoil surfaces to protect the underlying base material from direct service exposure. The intention of this arrangement is that the part itself is not exposed to the hot gas path and therefore, does not undergo erosion or oxidation during service. During normal operation (absent of over temperature conditions or air or fuel contaminants), wall thickness will therefore not be lost during service. Ideally, coatings are not fully consumed (or just consumed) during a service interval and so the base material is never directly exposed to the adverse effects of the hot gas stream.

In contrast to the above, if operation is abnormal (hotter or longer than intended, containing air or fuel contaminants), or if the coating choice is not suitable for the service application, base material and therefore wall thickness can be lost from the blade during service. Two common examples of how this base material loss can occur directly in service are erosion and oxidation.

Erosion occurs when exposed base metal is eroded away by contaminants or the force of the hot gas stream. The Solar Centaur T60 Stage 1 Blade shown below (Figure 6) is an example of base material loss through erosion. In this case, the platinum aluminide coating was fully consumed at the leading edge, likely due to an overly hot service exposure. The underlying base material was exposed and eroded, leading to leading edge material loss in the area of coating consumption. A corresponding reduction in wall thickness was confirmed by sectioning of the blade for metallurgical analysis.

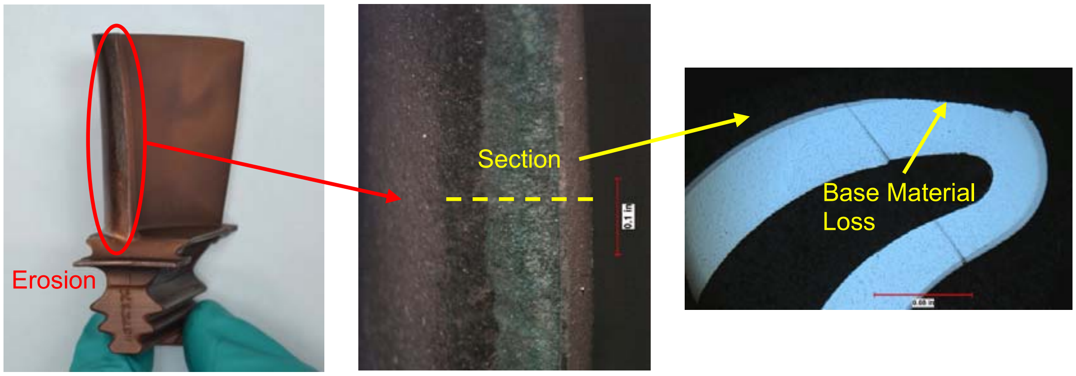

Figure 6 – Leading Edge Erosion on a Solar Centaur T60 Stage 1 Blade

In addition to erosion, oxidation is another method in which base material can be consumed during service. Oxidation occurs when the exposed base metal reacts with oxygen in the hot gas stream and causes some of the metal to corrode (oxidize) forming metal oxides on the surface. Although oxidation does not directly remove base material at the time of exposure in the way that erosion does, the oxidized metal must be removed during subsequent repair as recoating will not properly adhere to the oxidized surface. This makes oxidation an indirect base material loss mechanism as it creates a damaged (oxidized) metallic layer that must then be removed at the next repair interval, compared to erosion that directly removes material at the time of service exposure.

The Siemens SGT A35 (Rolls Royce RB211) 24G HPT Blade shown below (Figure 7) is an example of base material loss from oxidation. In this case, the platinum aluminide coating was fully consumed at the concave airfoil hot spot as shown. The underlying base material was then exposed and oxidized through interaction with the hot gas stream. It was necessary to then remove this oxidized layer of metal during the next repair cycle to ensure a successful reapplication of the airfoil coating. Sectioning of the blade for metallurgical analysis showed the oxidized material layer that must be removed and the expected corresponding reduction in wall thickness.

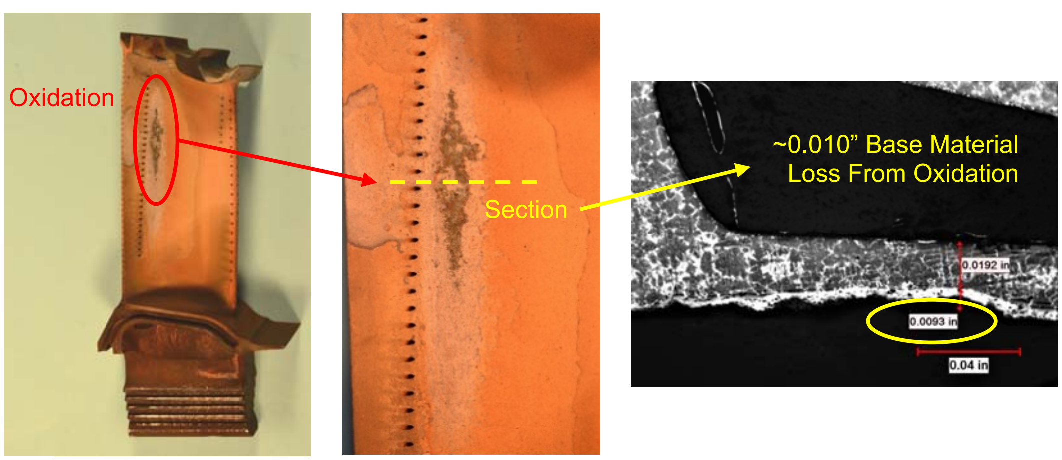

Figure 7 – Concave Airfoil Oxidation on a Siemens SGT A35 24G HPT Blade

3.3 Loss During Repair

In addition to the wall thickness loss that can occur during service, wall thickness can also be consumed during various repair processes. Chemical stripping is used to remove coatings before the components are inspected and inducted into repair. This stripping involves a controlled interaction between the coating and a chemical bath that is specially formulated to preferentially remove the coating without affecting the underlying base material. This chemical interaction occurs at a specific temperature and for a limited time to adequately remove the coating. These stripping parameters are specific to the base alloy of the blade and the coating type to be removed. The two most common types of coatings applied to gas turbine blades are diffusion coatings and MCrAlY coatings.

Diffusion coatings such as aluminide and platinum aluminide have both an additive layer that sits above the original substrate and a diffused layer where the coating has been diffused down into the underlying base metal. As a result, when a blade with a diffusion coating is chemically stripped, the entire coating is removed including both the additive layer and the diffused layer. This means that the application and removal of diffusion coatings will always consume a small amount of base material and therefore wall thickness. The amount of base material loss is typically around half of the applied coating thickness. It is therefore important to properly control coating thickness at both new part manufacture and repair to ensure an overly thick coating is not applied. This would lead to increased base material loss and wall thickness reduction during chemical stripping at the next repair interval.

MCrAlY coatings on the other hand do not have a diffusion zone. Instead, they are overlay in nature and are applied in such a manner that they rest on top of the original substrate surface. Therefore, they typically have a minimal diffusion zone and do not consume wall thickness at subsequent chemical stripping in the same way that diffusion coatings do. However, MCrAlY coatings are typically more difficult to remove through chemical stripping which means there is more often a requirement to remove remaining coating through mechanical means such as blending (manual material removal with hand tools). This process is often not easily controlled so there is a greater risk of removing excessive material along with the remnant coating and diffusion zone during residual coating removal efforts.

Mechanical means such as blending can also consume wall thickness during removal of local defects (erosion, dents, FOD) and finishing of repair material (weld or braze). If a blade has a local defect that is within blending limits, it can be locally thinned in exchange for removing the defect. General Electric LM1600 HPT Blades often exhibit airfoil cooling hole erosion upon receipt from service (Figure 8). By blending around the cooling holes to an adequate depth to remove the erosion and finishing the resultant surface to match the adjacent airfoil area, the defect is removed in exchange for reduced wall thickness in the area of the blending. Subsequent wall thickness inspection in the blended area is required to ensure the blade still meets minimum wall thickness limits.

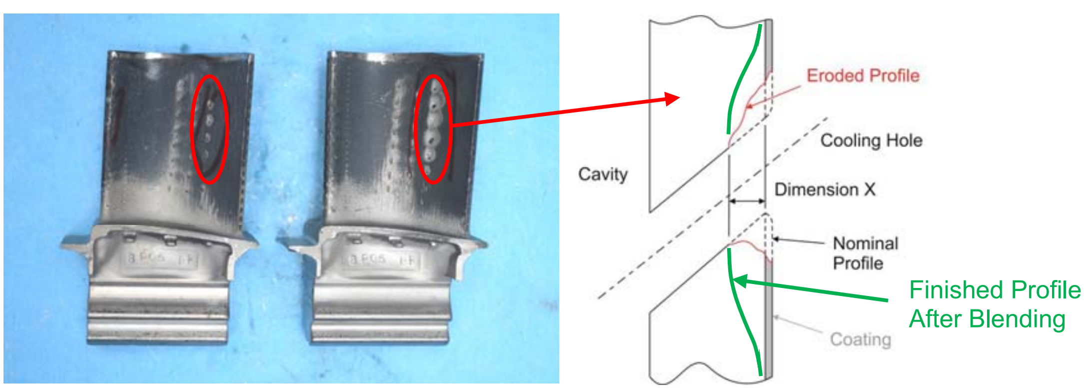

Figure 8 – Airfoil Cooling Hole Erosion & Finished Profile on General Electric LM1600 HPT Blades

3.4 Repair Options

With the demonstrated loss of wall thickness that can ensue during both service and repair, a natural question that arises is if wall thickness can be replaced. The answer to this question depends on the nature of the component, with two main answers depending on if the component is rotating (blades) or stationary (vanes). On stationary components such as vanes, wall thickness can be restored during repair using a modified wide gap brazing process called Liburdi Powder Metallurgy® (LPM). In this process, material is added over the surface to be thickened and heat treated to consolidate it in place. Excess material is then machined or blended down to the nominal shape and size. The remaining wall thickness is then measured to ensure the minimum wall thickness limits are met after repair.

However for rotating components such as blades, airfoil wall thickness cannot be replaced. This difference is due to the fact that the base materials used for casting blades and vanes are of different mechanical properties. On vanes, base materials are of lower strength and repair materials can be added in a manner that makes the repaired area of equal or greater strength than the underlying part. However on blades, base materials are of higher strength and repair materials cannot be added in a manner that makes the repaired area of equal or greater strength than the underlying part. Due to the circumferential forces present on rotating blades, lower strength areas are not permitted below a certain airfoil height. This means that repair materials can be added to blades near the tip, but not in the bulk of the airfoil as would need to be done to restore the overall wall thickness (Figure 9).

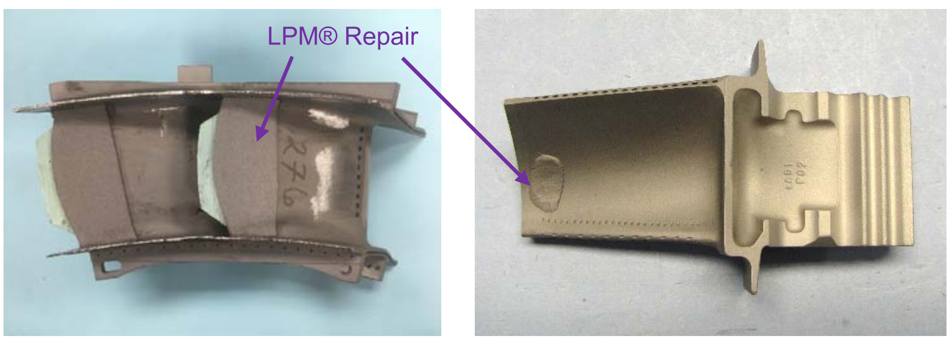

Figure 9 – Repair Materials Applied to Vanes (Full Airfoil Wall Thickening) & Blades (Local Tip Only)

This conclusion means that preserving wall thickness on blades is of critical importance for extending blade life. A blade's wall thickness is a non-renewable resource that only decreases from the new part condition until it eventually passes below minimum wall thickness limits and is declared scrap. Modern gas turbine blades are being designed with ever thinner nominal wall thicknesses, particularly on aerospace and aeroderivative designs. The result is a thinner starting condition and less potential for reduction before the part is rejected. This makes the inspection process described herein (CT wall thickness) and the strategy for maximizing blade life given in a later section, ever more important in today's gas turbine market for extending blade life and realizing the associated benefits of repair.

3.5 Measurement Techniques

As important as preserving wall thickness is for extending blade life, the ability to accurately and reliably measure the wall thickness is of equal importance. Historically, wall thickness has typically been measured using the ultrasonic thickness (UT) technique (Figure 10). In this technique, a probe is held on the surface of the part in the area of the desired wall thickness measurement. The probe emits a sound wave at a known speed that travels through the metallic substrate to the cavity inside, then reflects back and is received again by the probe. The time between incidence and return of the sound wave is measured and knowing the speed of the wave, the distance travelled can be calculated.

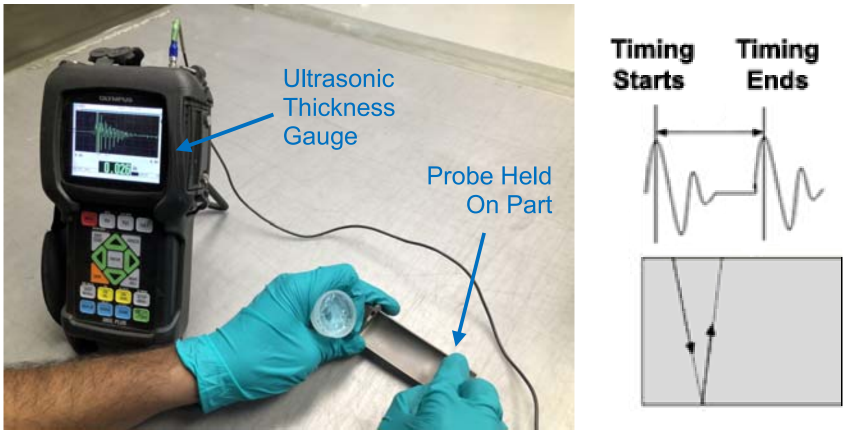

Figure 10 – Ultrasonic Wall Thickness Measurement of a General Electric LM1600 LPT Blade

When applied to simple, mostly flat geometries, the UT method produces reasonable results. However challenges were encountered when trying to apply this process to more complex geometries including curves, radii and non parallel surfaces. Production experience with using the UT method to measure wall thickness on modern gas turbine blades has identified a number of process limitations [4].

1. Obtaining the minimum wall thickness over a certain region
2. Obtaining accurate readings on concave and convex surfaces
3. Obtaining readings on the rounded leading edge
4. Material variation in equiaxed castings results in varying sonic velocities which leads to challenges in calibration of the equipment before taking measurements
5. Obtaining accurate measurements on wall thicknesses below ~0.030” (Typical detectors have a tendency to report double or triple the actual wall thickness measurement in this range)

Given the challenges above, a new inspection technique was necessary to accurately and reliably measure the wall thickness on modern gas turbine blades. To support the desired extension of blade life, computed tomography (CT) was chosen as the alternate wall thickness inspection process.

4 Computed Tomography (CT)

Computed Tomography (CT) is an imaging procedure that uses X ray equipment to generate detailed pictures and geometric information about the internal features of a physical body. It is used extensively in medical applications for imaging and diagnostic purposes. The proceeding section will discuss the use of computed tomography to inspect the internal features of modern gas turbine blades.

4.1 Equipment

The typical components of an industrial computed tomography system include an X ray source, a kinematic system for positioning the sample, a detector, a reconstruction algorithm and display and post processing software. The source generates X rays which pass through the sample. The material of the sample attenuates the X rays before they are received by the detector. The kinematic system rotates the sample to different angles as the X rays pass through it which generates numerous 2D images. These 2D images are compiled by a reconstruction algorithm into a 3D voxel model (a voxel is the 3D analogue of a pixel in 2D) with each voxel having a grey value related to the absorptivity of the material. The display and post processing software then determines the edges of the material based on the grey value to create a 3D model of the sample including any internal detail [4].

4.2 Process

To measure the wall thickness on production gas turbine blades, the blades are first loaded into a holding system which is typically a flat plate with multiple cut outs placed on top of a hollow bin. The bin is loaded into the CT machine and the door is safely closed. A robotic gripper arm picks up the first blade and passes it slowly through the X ray beam being emitted by the source and received by the detector. This creates a digital radiography (DR) shot of the blade which is similar to a conventional 2D X ray image. This DR shot is later inspected by a certified X ray technician to check for any internal blockages or other relevant X ray criteria. The same blade is then positioned within the X ray beam at the required measurement heights and rotated about its axes. This creates a cross sectional scan at each measurement height that is then post processed into numerical wall thickness results and a cross sectional image of the blade including internal detail. The first blade is then returned to the bin and the process is repeated for the rest of the blades in the set (Figure 11).

Figure 11 – Bladeline Computed Tomography Machine and Part Holding Bin with Robot Gripper

After the blades are scanned, analysis software is then used to analyze the data gathered at each measurement height. Measurement regions are drawn in the areas of the desired measurements and the software returns the minimum wall thickness value within each region with a typical accuracy of +/-0.002”. The results are then compiled into an excel file and transferred into a formatted inspection worksheet containing the wall thickness limits for the blade being inspected. Conditional formatting is used to flag any results that are below the minimum wall thickness limits. The wall thickness results and cross sectional images are reviewed for each measurement height to look for any abnormalities or incorrect readings. Finally, the wall thickness results are dispositioned and each blade is deemed to be serviceable or unserviceable based on its wall thickness condition (Figure 12).

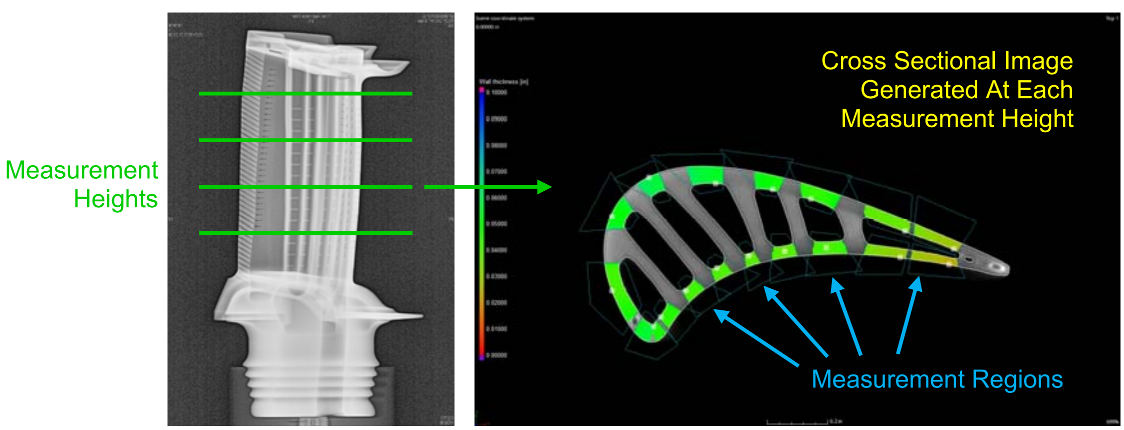

Figure 12 – Digital Radiography (DR) Shot & Cross Sectional Image of an SGT A35 24G HPT Blade

4.3 Challenges & Solutions

The CT wall thickness inspection technique described previously has been shown to address a number of the process limitations that were encountered with the UT method [4]. However, several challenges have been encountered with the CT wall thickness process through practical experience in applying the process to various blade types in production. Through engineering development and verification, solutions have been developed to address these challenges that allow continued use of the CT wall thickness technique and the benefits it provides in wall thickness measurement.

<u>Challenge 1 – Core Shift</u>

One of the first challenges identified by CT wall thickness inspection is casting core shift. Casting core shift occurs when the casting core placed inside the blade mold at manufacture to form the internal cavity is shifted to one side or misplaced within the mold. This causes a locally thin spot or an entire side of the airfoil to be thin where the casting core has shifted too close to the external profile.

The Rolls Royce 501K34 Stage 1 Blade shown below (Figure 13) is an example of core shift. In the CT cross sectional images, there is a distinct difference between the left and right pictures. The left picture shows a uniform wall thickness all around the airfoil profile with no locally thin spots. The right picture shows that the entire convex surface is significantly thinner than the concave surface. These blades had no previous repair and experienced minimal material removal from chemical stripping and residual coating blend so it is highly unlikely that the uniformly thinned area was caused by service or repair. Therefore, the observed condition was likely caused by casting core shift at manufacture.

Even with the understanding that this condition was likely caused by core shift and therefore has existed since the beginning of this blade's life, the wall thickness is now below acceptable limits and the blade must be rejected. In these cases, the reason for rejection (core shift) is explained to the customer in hope that this feedback can be shared with OEM's to reduce core shift in the future.

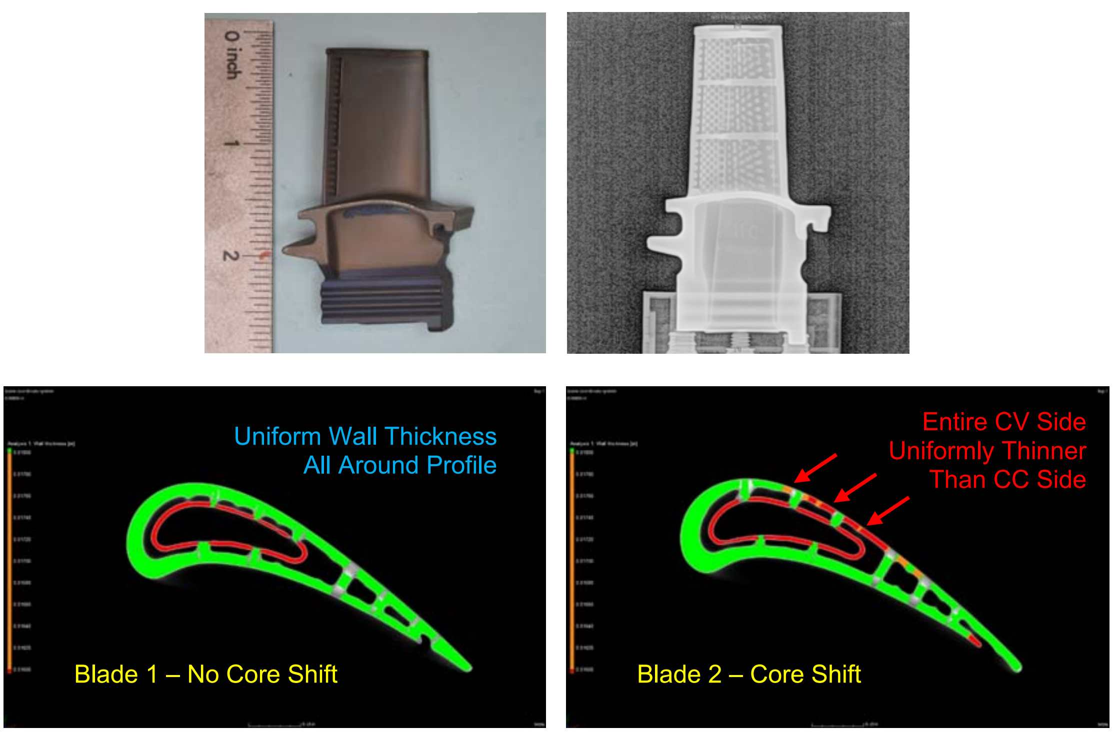

Figure 13 – Casting Core Shift on Rolls Royce 501K34 Stage 1 Blades

<u>Challenge 2 – Cooling Holes</u>

Another challenge with CT wall thickness inspection occurs when a measurement height passes partially or fully through an airfoil cooling hole. When this occurs, a locally thin area caused by the cooling hole intersection can be incorrectly registered as the wall thickness measurement. If the disposition of this blade is done based only on the numerical result without knowledge of the cooling hole intersection, an otherwise acceptable blade could be rejected for undersize wall thickness.

In the Siemens SGT A35 24C HPT Blade shown below (Figure 14), the measurement heights are set by an external repair scheme. Experience has shown that there is variation in the vertical position of the airfoil cooling holes both from part to part within a set and from one set to the next. This variation means that when multiple blades are scanned using the CT process at the same measurement height, the cross sectional images showed that some blades were intersecting cooling holes whereas others were not. The blades that intersected cooling holes showed a falsely undersize measurement at the locally thinned area adjacent to the hole, however it is clear from the cross sectional images below that this is not an accurate measurement of the wall thickness.

The solution to this problem is to draw measurement regions that reliably dodge cooling holes, based on the expected location and positional tolerance of cooling holes that has been observed historically. In this manner, the local wall thickness of interest can still be obtained while avoiding the incorrect measurements that result from locally thinned areas adjacent to cooling holes. Additional production experience allows this strategy to be further refined and improved.

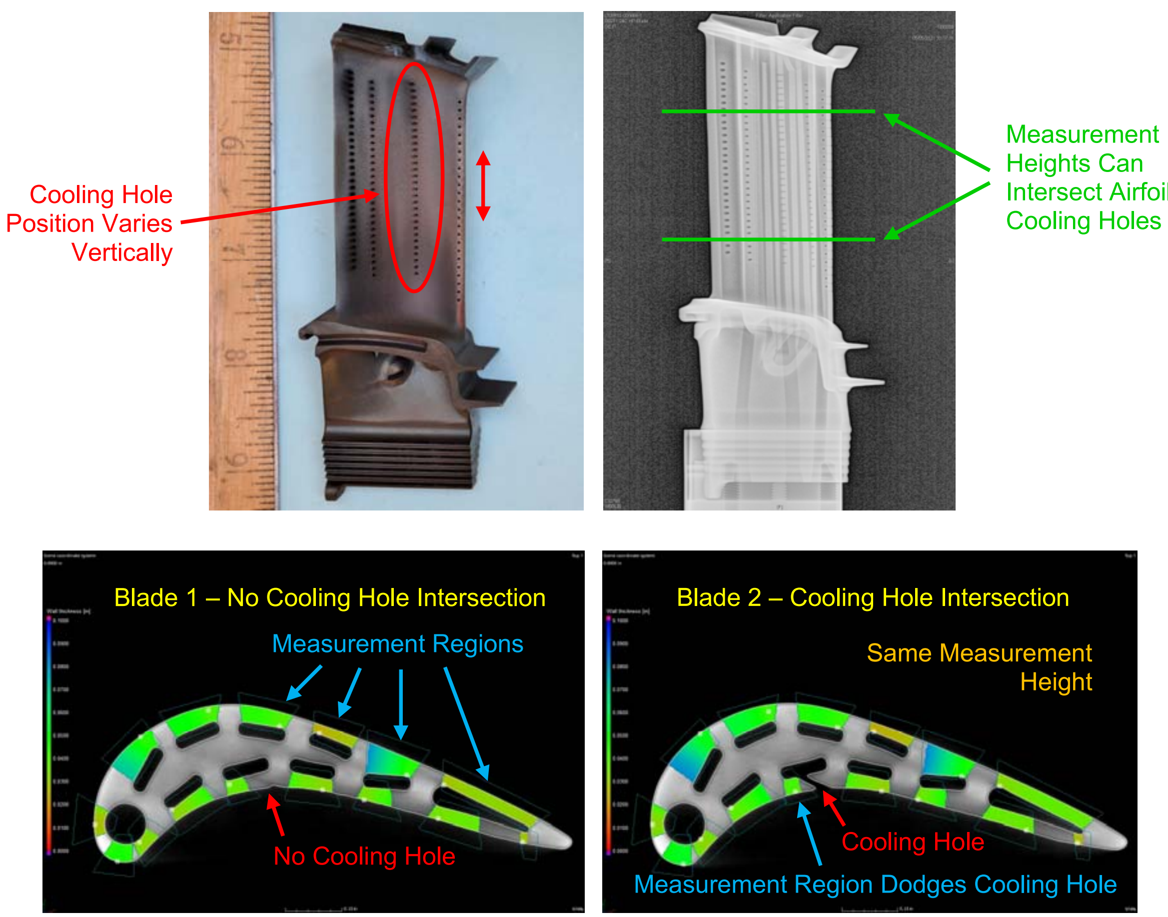

Figure 14 – Cooling Hole Intersection & Measurement Regions on SGT A35 24C HPT Blades

Challenge 3 – Turbulators

A third challenge encountered with CT wall thickness inspection is horizontal turbulators. A turbulator is an internal rib or protrusion on the inner surfaces of gas turbine blades. Turbulators are designed to increase flow turbulence and surface area, which increases heat transfer between the hot airfoil walls and the cooler air flowing through the internals. Turbulators can be horizontal (parallel to the engine centreline), vertical (perpendicular to the engine centreline) or angled. Vertical and angled turbulators do not pose a problem for CT wall thickness inspection since they simply show up as bumps in the cross sectional scan. Therefore, the software does not measure on the turbulator when extracting the minimum wall thickness value over the region. Horizontal turbulators however are problematic as they are roughly parallel to the measurement plane and therefore, can incorrectly inflate the wall thickness measurement. If the measurement height lands directly or partially on a turbulator, the wall thickness value returned will include some or all of the turbulator height. This is not a valid measurement as it was stated previously that internal cooling features such as turbulators do not add significant strength to the part and should therefore be omitted from wall thickness measurements.

The problem of horizontal turbulators is especially dangerous as it may not be evident from the cross sectional image that the measurement plane has landed on a turbulator. The entire cross section is affected and so there is no visual evidence of the turbulator (bump) as is seen with vertical or angled turbulators. This can lead to wall thickness values being returned that are thicker than the turbulator free measurement and creates the risk of accepting parts with undersize wall thickness.

In the General Electric LM1600 HPT Blade shown below (Figure 15), the lower height H2 has horizontal turbulators and is at risk of having its wall thickness values incorrectly inflated by the turbulator height. To solve this problem, a process was developed using two separate measurement heights H2A and H2B spaced slightly above and below the desired H2 height. The wall thickness is measured at both the H2A and H2B heights and the values are compared to select the minimum at each location around the profile. This collection of local minimums is then assessed as the final wall thickness numbers at the desired H2 height. The spacing of the H2A and H2B heights above and below the desired H2 height is set as half the turbulator pitch to ensure that at least one measurement at each location will fully dodge the turbulator. In this way, the final wall thickness numbers will be free of any incorrect inflation from turbulator height and are therefore suitable for disposition.

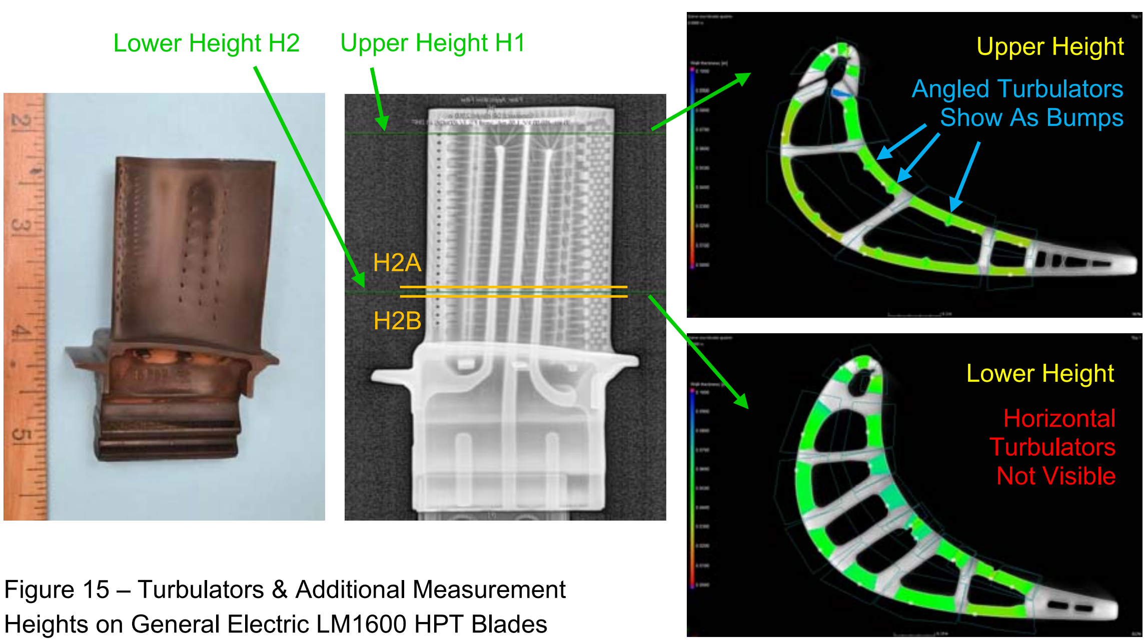

Figure 15 – Turbulators & Additional Measurement Heights on General Electric LM1600 HPT Blades

5 Discussion

The use of CT (computed tomography) has significantly improved the wall thickness inspection capability of gas turbine blades over the traditional UT (ultrasonic thickness) method. The following improvements have been achieved with use of the CT wall thickness inspection method [4].

1. Ability to obtain the minimum wall thickness measurement over a region
2. Ability to obtain accurate readings on curved surfaces such as concave and convex airfoils
3. Ability to obtain readings directly on leading edges
4. A cross sectional picture of the CT scan is provided at each measurement height which can be reviewed to ensure the minimum value was obtained and that the reading was valid
5. Elimination of the doubling or tripling effect that is sometimes observed when the UT method is used to inspect wall thicknesses below ~0.030”

An improved inspection process is not the only requirement to meet the overall goal of maximizing blade life. The wall thickness limits against which to disposition the blades are critically important, and these limits should be set as low as possible to maximize yield while still ensuring the safe operation of the part in service. Additionally, the right approach is required among OEM’s, operators and component repair vendors in order to maximize blade life.

5.1 Wall Thickness Limits

Once accurate and reliable wall thickness measurements are obtained, the next step is to disposition these results against acceptable wall thickness limits. Setting these limits can be a complex exercise involving analytical methods such as mechanical and thermal models as well as previous experience on similar components. Wall thickness limits can be set by the OEM, the operator or the component repair vendor, or a combination of these entities working collaboratively to establish an agreed upon acceptance criteria and corresponding level of risk. The setting of wall thickness limits is a very important decision that ultimately determines the fate of a significant number of blades. If accurate measurements are obtained but the acceptance limits are not well founded, there can be a high number of blades rejected that could be otherwise repairable with a lower wall thickness limit.

It is preferrable where possible to use analytical methods as part of the exercise for setting acceptable wall thickness limits. These methods typically use computer simulations and finite element analysis to model certain wall thickness reductions and their effect on mechanical and thermal stresses in service (Figure 16). Additionally, any high stress locations on the blade are identified as critical inspection locations. This approach often results in recommended wall thickness reductions that can be applied to a nominal thickness or new part measurement to produce wall thickness limits for repair.

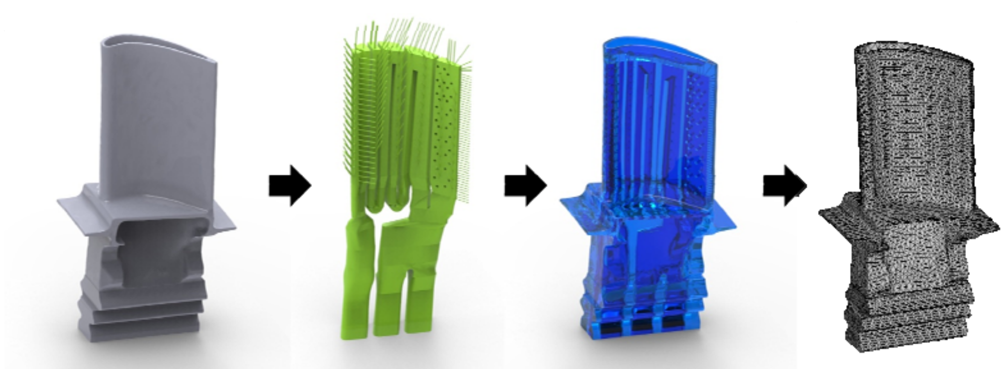

Figure 16 – Analytical Wall Thickness Modelling of a General Electric LM5000 HP1 Blade

5.2 Strategy For Maximizing Blade Life

It has been shown that properly managing wall thickness is critical for extending the life of gas turbine blades. How can OEM's, operators and component repair vendors work together to maximize blade life and realize the associated benefits? The strategy presented below gives recommended actions and considerations for each entity to take in a combined effort to achieve this goal.

<u>OEM's</u>

- Maximize nominal wall thickness within design and performance goals (provides more wall thickness as a starting point which subsequently increases a blade's potential life)
- Accurately control wall thickness at manufacture by reducing casting core shift (prevents locally thin regions that are subsequently rejected at repair)
- Choose and apply coatings (internal and external) that are properly suited to the intended service and will provide adequate protection for the base material
- Provide reasonable wall thickness limits where applicable, ideally including consideration from analytical methods (mechanical and thermal models)

<u>Operators</u>

- Perform overhauls before coating consumption to prevent base material loss (adequately follow design service intervals, use borescope inspections where applicable)
- Refrain from running engines hotter or longer than the intended service conditions (can cause premature coating loss and potential base material damage)
- Ensure fuel and air filters are free of contaminants and meet the applicable guidelines

<u>Component Repair Vendors</u>

- Minimize base material loss during repair by properly controlling repair processes (chemical stripping, mechanical removal of residual coating and defects, coating reapplication)
- Use CT (computed tomography) to measure the wall thickness instead of the traditional UT (ultrasonic thickness) method
- Develop reasonable wall thickness limits where applicable, ideally including consideration from analytical methods (mechanical and thermal models)
- Conduct coating assessments on incoming blade condition and recommend coating upgrades or replacement where applicable (metallurgical analysis)

Figure 17 – Post Service (Left) & Fully Repaired (Right) Condition of a GE LM2500 HP1 Blade

6 Conclusion

Maximizing gas turbine blade life is desirable for several reasons. These include significant cost savings for the operator, reduced outage time due to supply limitations of new blades, and reduced environmental impact from minimized scrap rates. Airfoil wall thickness was shown to be a leading cause of retirement for modern gas turbine blades and there is no repair option for replacing wall thickness on rotating components such as blades. Therefore, preserving and accurately measuring the remaining wall thickness is critical for achieving maximum blade life. An understanding was developed of how wall thickness is lost during both service and repair and how it is measured. It was shown that CT (computed tomography) is strongly preferred over the conventional UT (ultrasonic thickness) method. Some of the unique challenges of CT wall thickness inspection were explored as well as the solutions that have been developed to address them. The importance of setting reasonable wall thickness limits was demonstrated and some methods for doing so were discussed. A strategy was developed for how OEM's, operators and component repair vendors can work together to achieve the maximum possible life of gas turbine blades.

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