Gas turbines in a carbon-neutral society
10th International Gas Turbine Conference
11-15 October 2021

Paper ID Number: 3-IGTC21

EARLY EXPERIENCE APPLYING PROCESS COMPENSATED RESONANCE TESTING TO NEW AND REPAIRED TURBINE BLADE QUALITY ASSURANCE

John Scheibel[1], Nick Smith[2], Eric Biedermann[3], Richard Livings[3], Garret Gatewood[3]

[1]Electric Power Research Institute, 3420 Hillview Ave. Palo Alto, CA, 650-714-9483, jscheibel@epri.com
[2]Electric Power Research Institute, 1300 West W.T. Harris Blvd., Charlotte, NC 28262-8550, 704-595-2163, nsmith@epri.com
[3]Vibrant Corp., 8916 Adams St. NE, Albuquerque, NM 87113-2710, 505-338-2576, ebiedermann@vibrantndt.com

ABSTRACT

Industrial gas turbine (IGT) blades are subjected to various nondestructive evaluation (NDE) methods to ensure structural integrity and uniform quality. Legacy NDE, like x-ray diffraction and ultrasonic testing, are limited to surface or point-by-point inspection. Process Compensated Resonance Testing (PCRT) is a volumetric ultrasonic resonance method that applies a swept sine excitation and records the component modal response. The resonance spectrum relates to component material, microstructure, geometry, and defects.

PCRT applies advanced statistical analyses and machine learning to the resonance spectrum to identify parts with defective metallurgical conditions. In aerospace, PCRT is the only NDE method to be approved by the FAA to replace cutups for the metallurgical disposition of turbine blades. EPRI and Vibrant are leveraging PCRT's decade-long aerospace success for IGT components. They have scanned over 10,000 blades from various IGT models with PCRT, demonstrating value for owner/operators with efficient receiving inspection, evaluation of component fitness for repair, and quantification of material rejuvenation heat treatment consistency.

The paper summarizes PCRT case studies for aero engine and large IGT blades for metallurgical qualification and defect detection. These studies examine crystal orientation, overtemperature exposure, heat treatment rejuvenation, and casting flaws. Ongoing PCRT evaluations of specific material states are also discussed.

Keywords: Resonance, Ultrasonics, Quality Assurance, Nondestructive Evaluation, Metallurgy, Microstructure

INTRODUCTION

The microstructure of metals is a primary driver of the static and dynamic performance of those materials. In IGT components material microstructure directly affects the useful life, vulnerability to damage mechanisms like creep and fatigue, and the nucleation and propagation of structural defects [1] - [3]. Evaluation of component microstructures is critical for determining the serviceability of IGT components and the effect of repair processes for them. However, reliably evaluating component metallurgy can be difficult. Metallurgical sampling with destructive cut-up requires sacrificing one component from a batch and assumes results of that analysis represent the microstructural state of the remaining parts. This process is expensive, time consuming, and may be inaccurate if the sampled component is not representative of the population. Nondestructive methods enable evaluation of 100% of component populations, and many of them offer speed and cost advantages over destructive sampling.

Several nondestructive methods, like x-ray diffraction and ultrasonic testing, are capable of some amount of metallurgical characterization [4] but they are generally limited to surface or point-by-point inspections. Ultrasonic methods have the advantage of interacting mechanically with microstructure, but traditional ultrasonic scans use fixed frequencies and rely on the effect of the material or a defect other characteristics of the ultrasonic signal [5]. Scanning the ultrasonic resonance frequencies of the component, which are directly affected by the material microstructure and structural flaws, offers far greater capability for metallurgical evaluation. Ultrasonic resonance inspection methods are grouped under the general term Resonance Ultrasound Spectroscopy (RUS) [6].

Resonance inspections have gained traction during the last two decades, particularly in the aerospace industry. RUS methods such as Process Compensated Resonance Testing (PCRT) are full body ultrasonic methods that excite, record, and analyze the resonance frequencies of a component. In doing so they mechanically interact with the microstructure. The mode shapes and frequencies collected from a component serve as a resonance fingerprint and are dependent on the material, microstructure, geometry, and the presence of defects. Resonance methods can both identify defective conditions and the characterize material properties.

PCRT uses a swept sine wave excitation to drive a part to resonate and then records the resonance spectrum. PCRT applies advanced statistical analyses and machine learning to the resonance spectrum to identify diagnostic frequency patterns that indicate defective metallurgical conditions and other flaws. After the PCRT system has been "trained" to recognize the frequency patterns of acceptable and unacceptable components, it provides automated pass/fail inspection capabilities.

The capabilities of PCRT have been demonstrated in the lab, in simulations, and validated operational inspection applications [7] - [9]. PCRT has more than ten years of proven success in the aerospace industry and is the only Nondestructive Evaluation (NDE) method to be granted approval by the Federal Aviation Administration (FAA) to replace metallurgical cut-ups for the disposition of blades that have experienced over temperature exposure [10].

The experience accumulated in aerospace PCRT applications can be leveraged for improved metallurgical inspection in the power generation industry. Although PCRT analysis of industrial gas turbine blades is in the nascent stage, it has already proven to be useful for multiple power generation Industrial Gas Turbine (IGT) owners by providing an efficient incoming spare and in-service blade inspection, evaluating a component's fitness for repair, and evaluating the consistency of rejuvenation.

This paper summarizes case studies of PCRT evaluations of aerospace turbine blades and materials for metallurgical qualification and defect detection. These studies examine crystal orientation, overtemperature exposure, and casting flaws among other things. In addition to the aerospace case studies, this paper presents the early experiences scanning and analyzing IGT blades with PCRT. The ongoing work of quantitative, nondestructive metallurgical analysis of IGT blades is also presented and discussed.

NOMENCLATURE

α	Primary crystallographic orientation angle
γ	Matrix phase in nickel-base superalloy
γ'	Precipitate phase in nickel-base superalloy
FAA	Federal Aviation Administration
HIP	Hot Isostatic Pressing
IGA	Intergranular Attack
IGT	Industrial Gas Turbine
MTS	Mahalanobis-Taguchi System
NDE	Nondestructive Evaluation
OEM	Original Equipment Manufacturer
PCRT	Process Compensated Resonance Testing
PTI	Part-to-Itself examination
RUS	Resonance Ultrasound Spectroscopy
SX	Single Crystal alloy
VIPR	Vibrational Pattern Recognition

1 NDE Background

Nondestructive Evaluation characterizes components and detects defects without affecting the future usefulness of the component. Multiple NDE methods have been developed based on different underlying physical principles. All methods strive to detect defects and measure properties, as well as monitor processes, structures, and equipment. Each method has pros and cons. Often multiple techniques are used in conjunction to achieve detection/characterization goals [11]. The end user, therefore, must be knowledgeable concerning which method(s) to use in which situation. Metaphorically speaking, each industry and business needs an NDE toolbox with appropriate tools at their disposal. PCRT is an established tool in the aerospace and automotive industries and is now being demonstrated in power generation.

1.1 PCRT Background

Process Compensated Resonance Testing is an NDE method that utilizes a part's resonance spectrum to detect material defects or damage. The fundamental principle behind PCRT is that any rigid, elastic body will resonate at specific frequencies that are a function of geometry, mass, material properties, and defects/damage. Differences in a part's resonance signature from the nominal are attributable to changes in geometry, material condition, or defect/damage state. PCRT identifies parts with unacceptable deviations in the presence of normal, acceptable production and process variation.

The application of PCRT for NDE is described by several ASTM Standard Practices [12] - [14]. PCRT capabilities for metallurgical evaluations, such as microstructural changes due to overtemperature exposure, crystal orientation, and elastic constants have also been described in several recent publications [15] -[18].

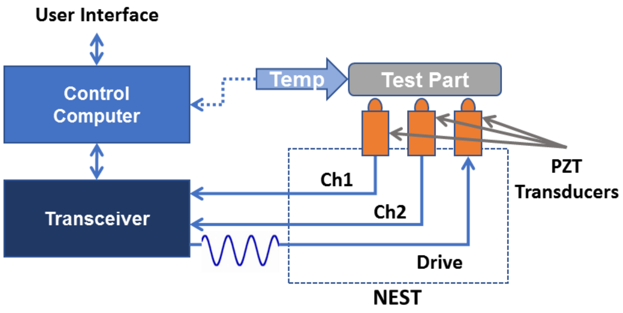

FIGURE 1: PCRT SYSTEM SCHEMATIC.

2 PCRT System

A PCRT system comprises three basic components: the transceiver, the nest, and a computer (FIGURE 1). The transceiver is a combination signal generator and spectrum analyzer. A nest comprises piezo-electric transducers (typically three for optimal part stability and mode shape coverage), tooling/mechanisms for part fixturing and handling, and a thermocouple to measure part temperature. Part temperature variation alters component elastic constants and can cause frequency shifts greater than the standard measurement repeatability. PCRT systems measure the part temperature and automatically compensate for temperature-driven frequency variations.

PCRT excites resonance modes by impinging on the component with a swept sine wave through the drive transducer. The system records the surface displacement with the receive transducers. Generally, one piezoelectric transducer transmits while two other transducers receive. The swept sine excitation covers a broadband frequency range that is dependent on the part type and is configured in the initial phase of a project. Standard PCRT transducers and transceivers can scan and receive over a frequency range from less than 1.0 kHz to more than 10.0 MHz. A resonance spectrum is collected for each part in the population and individual resonance modes are identified with derivative spectral decomposition [19]. Once the component resonant frequencies are collected, they are analyzed with machine learning and statistical scoring tools to detect damage/defects or to characterize the population with respect to itself or previously collected populations. In operational inspections, PCRT typically requires less than one minute to scan a component and return an automated pass or fail result.

3 PCRT Analysis Methods

Vibrant PCRT offers multiple methodologies for the analysis of resonance spectra. The three that have been primarily applied to IGT blades are described below. Using these three methods, PCRT can characterize part populations, identify outliers, sort for specific defects, and characterize processes such as component repair. These methods use statistics and machine learning and thus require a training set or reference population. Ideally, the reference population are statistically significant sets of resonance spectra from nominal components with a representative range of acceptable process variation and unacceptable components with the defects/material states of interest. Historically, the training set spectra have come from physical components. However, Vibrant has also demonstrated the generation of resonance spectra with physics-based simulation to augment physical component populations in cases where physical component availability is limited [15]-[18]. A lack of process variation in the reference set will reduce the accuracy of the characterization. For widely used IGT models, EPRI and Vibrant are building a global parts database initially focused on blades that will eventually capture the full life cycle process variation for each blade design.

3.1 Population Characterization & Outlier Identification

A quantitative characterization of variation within and between populations is accomplished with a Z-score statistical analysis. The Z-score statistic specifies the normalized distance between a given part and the central tendency of the population. This analysis is particularly useful for quantifying variation between subgroups, such as casting lots, and identifying outliers.

Outlier parts are those that exhibit a significantly different resonance signature in a similar manner to the Six Sigma approach. They typically fall outside the 99% confidence bounds of the population and have a significant separation from the majority cluster. Several factors in addition to damage/defects can cause the appearance of outliers: lot-to-lot material variations, geometry differences, differing thermal histories, or inadequate representation of a process variation in the reference set. Collecting resonance spectra and characterization information (e.g. casting lot, etc.) from additional components that are known to be acceptable will help quantify the true variation among serviceable components.

Outlier Screening inspection is often used as an initial PCRT capability in the absence of well-characterized training sets of components needed for Targeted Defect Detection methods described in Section 3.2. In a production setting, outlier screening can be configured as an automated pass/fail inspection. ASTM Standard Practice E3081 describes the setup and operation of PCRT Outlier Screening inspection. [13].

3.2 Targeted Defect Detection

Targeted defect detection increases the sensitivity of PCRT beyond basic Outlier Screening. Proprietary Vibrational Pattern Recognition (VIPR) machine learning algorithms identify the resonance peaks that are most diagnostic for a defect of interest and produce a PASS/FAIL PCRT inspection targeting that defect. VIPR-based inspections use the Mahalanobis-Taguchi System (MTS) statistical scoring and optimization method [20] to optimize the diagnostic peak patterns and score components for their similarity to the central tendencies of good and bad training sets. In operational inspections, the VIPR-MTS tools evaluate the diagnostic resonance frequencies and return a statistically based pass or fail result that does not require interpretation by a technician. Multiple VIPR solutions can be implemented to sort for various defects. ASTM Standard Practice E2534 describes the setup and operation of Targeted Defect Detection inspections [12].

For the optimization routine to produce a robust solution, a VIPR analysis needs statistically significant, characterized training sets of acceptable and unacceptable components. The acceptable population must be representative of normal, acceptable process variation. The unacceptable population must include representative variation in the defects of interest (e.g. size, severity, location).

Since a VIPR analysis is a trained statistical method, small training populations, lack of acceptable process variation, and/or inaccurate classifications (parts classified as good that have defects or parts classified as bad that are defect free) will degrade VIPR accuracy. If a representative 3D solid model, accurate material properties, and methods for modeling defects of interest are available, physics-based simulations of components can be used to generate resonance spectra that can augment physical component populations in VIPR training sets.

3.3 Part-to-Itself Analysis

A Part-to-Itself (PTI) analysis compares the resonance spectrum of a part in a one state (e.g. post-repair) to the resonance spectrum of the same part in a previous state (e.g. new). The frequency change between the states is quantified to evaluate the effect of in-service loads/damage and monitor manufacturing or repair processes. Comparing a part to itself in two different states increases the sensitivity to changes in a component by removing the influence of part-to-part variations. A PTI analysis is particularly useful for identifying turbine blades that have not been repaired properly or have suffered unacceptable degradation in service.

In a PTI analysis, diagnostic resonance peaks are identified, and limits are placed on the variation for each peak based on an examination of the before and after states of a training set. The training set comprises a statistically significant population of parts with acceptable process variations in both states as well as a statistically significant population of parts with unacceptable process variation in the second state. ASTM Standard Practice E3213 describes the setup and operation of PTI inspections [14].

4 Case Studies in Aerospace

4.1 Overtemperature Exposure

Exposure of nickel-based superalloys to overtemperature conditions will change the volume fraction and distribution of γ’ precipitates. This in turn reduces the part strength and creep resistance, which are two mechanisms leading to early failure [21] - [22]. PCRT was applied to a fleet of aerospace turbine blades from Delta TechOps, the maintenance arm of Delta Airlines. The blades for the JT8D-219 engine had an elevated risk of exposure to overtemperature conditions. Multiple in-field failures occurred each year until the implementation of a PCRT Targeted Defect Detection inspection [8].

The original analysis approach (defined in the component maintenance manual by the OEM) was to section one blade from an engine set with suspected overtemperature exposure, making the assumption that sample was representative of the full engine set, and then disposition the entire set based on the metallurgical results. Components still failed in-service. PCRT offered the ability to nondestructively inspect every blade in an engine set for individual disposition. A PCRT feasibility study was performed. [8]

FIGURE 2 shows the Z-score characterization of a population of service-run turbine blades with some suspected incidences of overtemperature exposure (as determined by monitoring the operating temperature of the engine). In this plot, green represents acceptable components, red represents components with overtemperature microstructure; the rhombi represent the assumed classifications, and the circles represent the confirmed classifications. As the component was exposed to increasing temperatures, the changes in the microstructure also increased. This is indicated by the increased separation of the overtemperature components from the central tendency of the nominal population. Several parts from the outlying and inlying region of the Z-score were sent to a third-party lab for verification. All inlier blades exhibited acceptable microstructures like the one shown in FIGURE 3, indicating they remained below the temperature limit of 2050 deg F specified by the OEM maintenance manual, while the outliers exhibited microstructures that were exposed to 2050 deg F or greater like the one shown in FIGURE 4 [8].

After the initial validation of PCRT results with metallography, a Targeted Defect Detection inspection was configured and implemented to detect defective microstructures. Validation with metallography continued and resulted in confirmation of PCRT results for more than 200 blades. This led to FAA approval of PCRT to replace destructive cut-ups for the detection of overtemperature microstructures [10]. As the number of blades inspected with PCRT increased, the number of in-service failures reduced until the PCRT inspection made its way through the entire blade population. There has not been a failure of a blade inspected by PCRT, and Delta TechOps salvaged a population of blades that were quarantined by the previous method, saving millions of dollars in spares purchases [8].

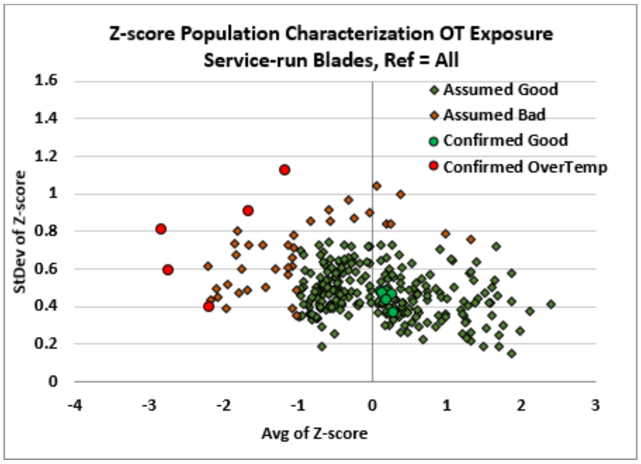

FIGURE 2: Z-SCORE CHARACTERIZATION OF TURBINE BLADES EXPOSED TO OVERTEMPERATURE.

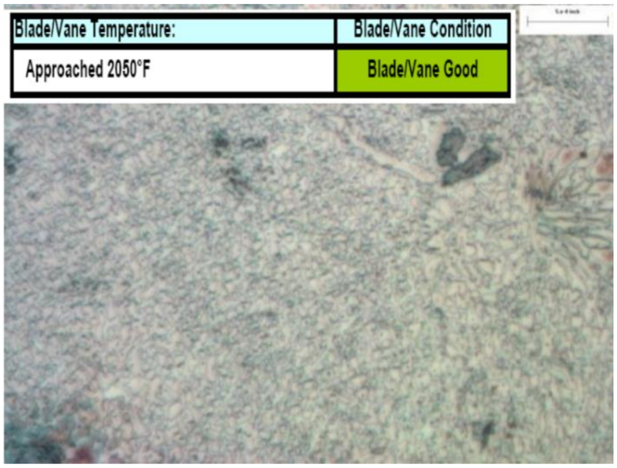

FIGURE 3: MICROSTRUCTURE OF TURBINE BLADE THAT APPROACHED, BUT REMAINED BELOW 2050°F.

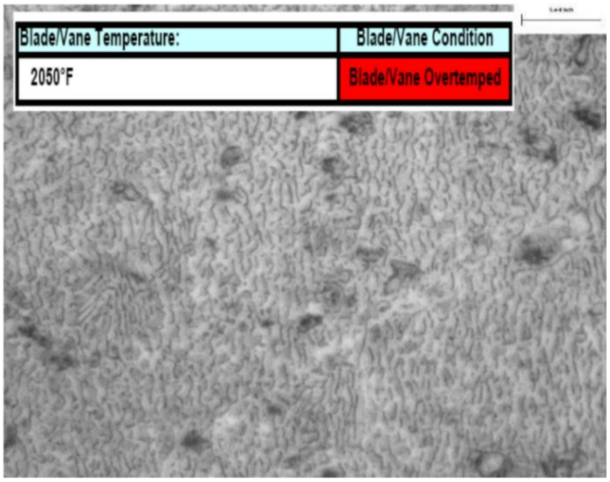

FIGURE 4: MICROSTRUCTURE OF TURBINE BLADE THAT WAS EXPOSED TO 2050°F.

4.2 Intergranular Attack

Intergranular attack (IGA) corrosion is generally difficult to detect in the internal cooling passages of turbine blades. This is due to the obstacles preventing thorough inspection of the internals with standard NDE methods such as penetrant testing or magnetic particle testing. Even borescope inspections suffer from limited inspection capabilities. Previous work examining aerospace turbine blades with PCRT yielded excellent IGA detection results.

The majority of IGA cases exhibited outlying resonance responses compared to the nominal components. This was attributable to the loss of stiffness due to the layer of IGA products in the internal passages. Nascent IGA may not have a large effect on the resonance. In cases where there is not an extreme, observable difference in behavior in Z-space, a Targeted Defect Detection inspection can be implemented. FIGURE 5 shows the results from a PCRT inspection for IGA. All of the IGA components failed while all nominal components passed. FIGURE 6 shows a visual micrograph of internal IGA detected with a PCRT analysis.

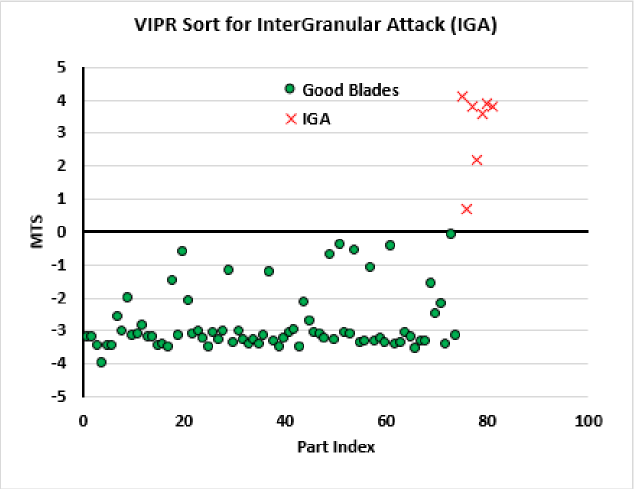

FIGURE 5: TARGETED DEFECT DETECTION OF IGA IN TURBINE BLADES.

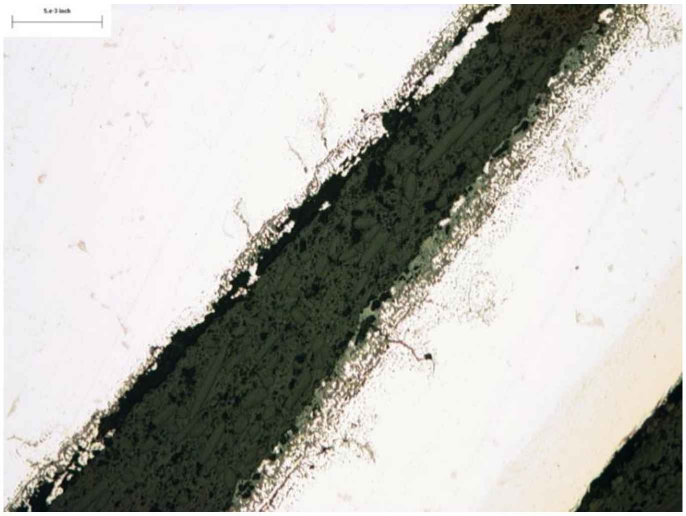

FIGURE 6: VISUAL MICROGRAPH OF IGA IN TURBINE BLADE FAILED BY PCRT FOR IGT.

4.3 Casting Defects

PCRT also offers advantages for detection of metallurgical defects formed during casting, forging, and other manufacturing processes. These defects, like internal casting shrinkage, cause failures in service and are difficult, time-consuming and/or costly to inspect with legacy NDE. The resonance frequencies scanned with PCRT are directly influenced by the component metallurgy, so it is sensitive to internal casting defects. PCRT's fast testing speed (less than one minute for an automated pass/fail inspection), offers advantages over radiographic methods with slower scan times and subjective interpretation by operators.

Multiple PCRT inspections have been implemented in production settings including for Pratt & Whitney Canada. These inspections have been validated by follow-on characterization and by reducing the occurrence of in-service failures [9]. FIGURE 7 shows an example of a component with radiographically confirmed shrinkage porosity.

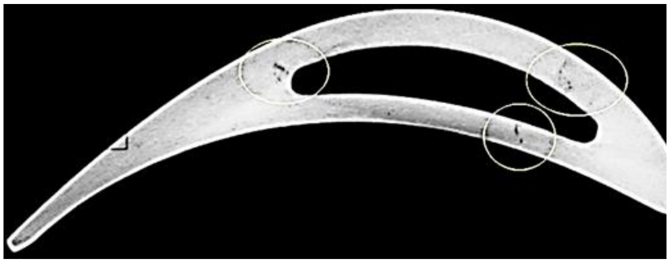

FIGURE 7: EXAMPLE OF SHRINKAGE POROSITY DETECTED DURING PCRT INSPECTION OF PRATT & WHITNEY TURBINE BLADES.

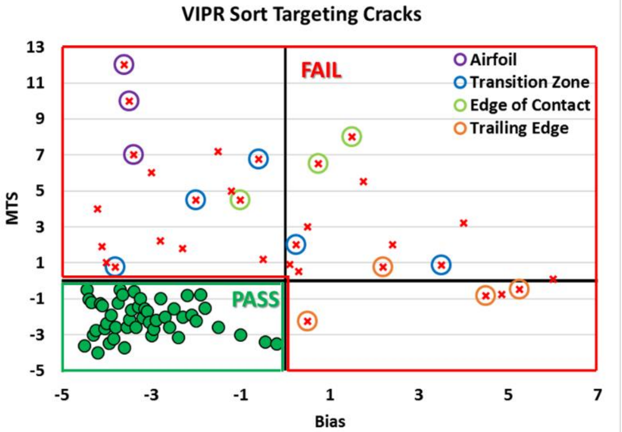

FIGURE 8: TARGETED DEFECT DETECTION OF MULTIPLE DEFECT TYPES IN DELTA TURBINE BLADES.

FIGURE 8 presents the results of a Targeted Defect Detection inspection for as-received spare turbine blades with casting defects at Delta TechOps [8]. The defects include cracks at multiple locations in the turbine blade. The maximum allowable crack size for a nominal part was determined by Delta and is proprietary. With this sort, all of the nominal components passed, and all of the defective components failed. Several of the components that failed the sort were examined metallographically and were found to have defects. Since implementation, there have been no in-service failures of blades passed by PCRT inspection.

5 Early IGT Experiences

5.1 Crystal Orientation

Previous experience from aerospace indicated that Z-score outliers in an SX population with high standard deviations may be due to crystallographic misorientations. Early experience with IGT blades yielded two SX populations with possible crystal misorientation issues. FIGURE 9 shows a Z-score population characterization of first stage Advanced F-Class blades with suspected instances of crystal misorientation. Of the IGT SX populations examined, 2-10% of the components exhibited signs of crystal misorientation.

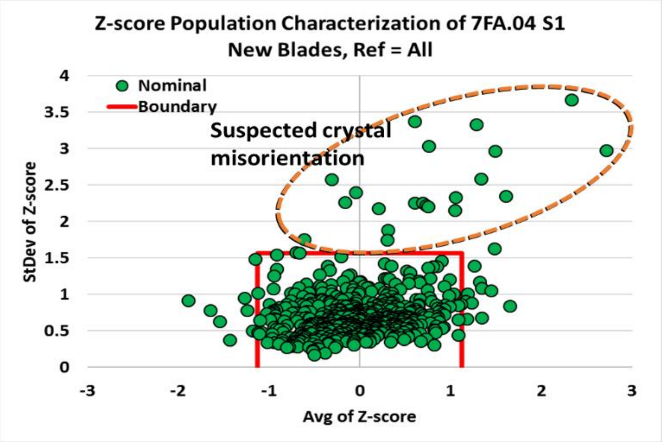

FIGURE 9: Z-SCORE CHARACTERIZATION OF NEW FIRST STAGE ADVANCED F-CLASS BLADES WITH SUSPECTED EXCESSIVE CRYSTAL MISORIENTATION INDICATED.

5.2 Process Variation

Process variation in IGT blades has many underlying causes including variations in alloy composition, casting, geometry, manufacturing heat treatment, run conditions, repair processes, Hot Isostatic Pressing (HIP), and repair heat treatments. Some of the manufacturing process variations are encoded in the serial number prefix (indicated by A, B, C, and D) while the variations are expressed by serial number groupings in other cases. The discussions on the resonance effects of process variation are qualitative in nature since little to no information regarding the variations in the manufacturing or repair processes was available.

Based on initial experiences with IGT blades, process variations often result in distinctive resonance behavior or differing central tendencies at the very least. Several examples are presented here. FIGURE 10 shows a population of second stage F-Class blades in the new condition that exhibits nearly distinctive resonance behavior between the prefix groups A and B. This type of separation indicates that the B blades exhibit a significantly higher effective stiffness.

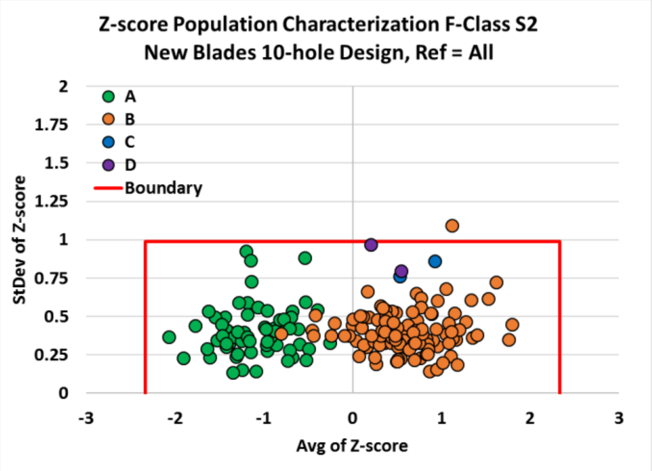

FIGURE 10: Z-SCORE CHARACTERIZATION OF SECOND STAGE F-CLASS BLADES GROUPED BY SN PREFIX.

FIGURE 11 shows a similar plot but for third stage blades in the repaired condition. Utility 1 used the same repair vendor (Rep1) for all of the blades shown here while Utility 2 used a different vendor (Rep2). In addition to the nearly distinctive behaviors exhibited by the A, B, and C prefix groups (attributable to OEM variations), the effect of variations in repair and/or service conditions could be observed for the two different B populations. The behavior exhibited by the blades from Utility 1 again indicates a difference in the effective stiffness of the components based on the SN prefix. The observed difference between the two B groups indicates not only a different effective stiffness, but also a significant variation in the resonance pattern. This may be due to differences in repair or residual effects from the service interval.

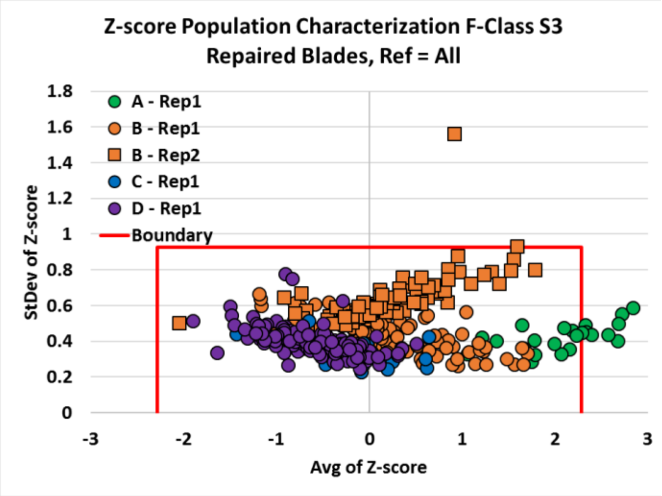

FIGURE 11: Z-SCORE CHARACTERIZATION OF THIRD STAGE F-CLASS BLADES GROUPED BY SN PREFIX.

FIGURE 12 shows a population of first stage E-Class blades in the repaired condition. Disk 1 and Disk 2 have been through a different number of repairs, yet some of the blades from Disk 1 exhibited similar behavior to the blades from Disk 2. This is indicative of a residual process variation that likely occurred during casting, such as a change in alloy composition or the formation of different microstructures. The distinct behavior shown in this plot corresponds to blade serial number where the components in the left cluster have low numbers and the components in the right cluster have high numbers.

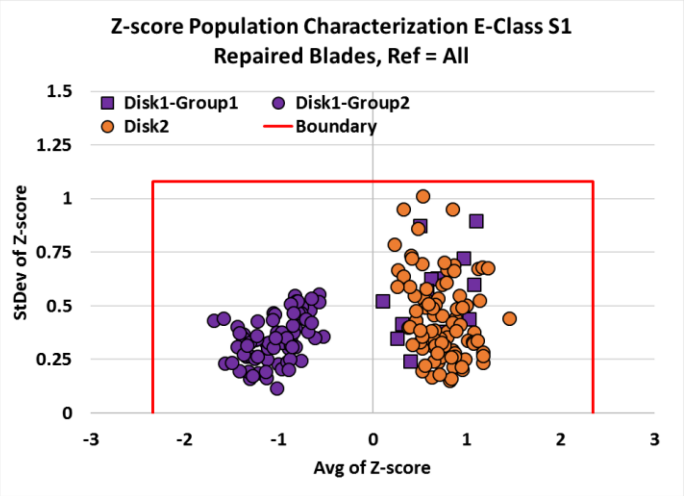

FIGURE 12: Z-SCORE CHARACTERIZATION OF FIRST STAGE E-CLASS BLADES GROUPED BY SN PREFIX.

5.3 Heat Treatment Variation

A preliminary analysis of the sensitivity of PCRT to variation in the soak temperature during a solutioning heat treatment was performed using four F-Class third stage blades. These blades had spent approximately 65k hours in-service under nearly identical conditions before the rejuvenation process. After HIP, each blade was subjected to a different heat treatment (1975°F/4hrs, 2050°F/2hrs, 2125°F/2hrs, 2200°F/2hrs) followed by an Argon quench.

A PTI analysis compared spectra for each blade in the post-HT state to the same blade in the service-run state. FIGURE 13 shows the percent frequency change due to solutioning for each of the four blades. The majority of peaks reduced in frequency between 0.5 and 1.5%. The overall reduction in frequency indicated that the heat treatment reduced the effective stiffness of the blades, the expected result of reversing the aging precipitates.

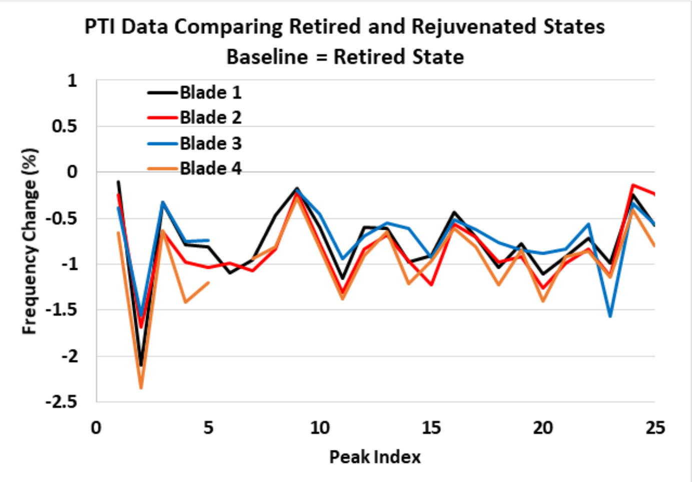

FIGURE 13: PTI ANALYSIS OF ADVANCED F-CLASS THIRD STAGE BLADES COMPARING THE REJUVENATED AND SERVICE-RUN STATES.

FIGURE 14 shows four example correlations where the vertical error bars represent the repeatability and the horizontal error bars represent a ±25°F tolerance in temperature. These four resonance modes were the most diagnostic of the modes examined, but many additional peaks offered similar distinguishing capabilities. All four modes exhibited excellent correlation with solutioning temperature. The sensitivity of resonance to the solutioning conditions is represented by the slope of the linear fits while the distinguishability is represented by the lack of overlap by the vertical error bars.

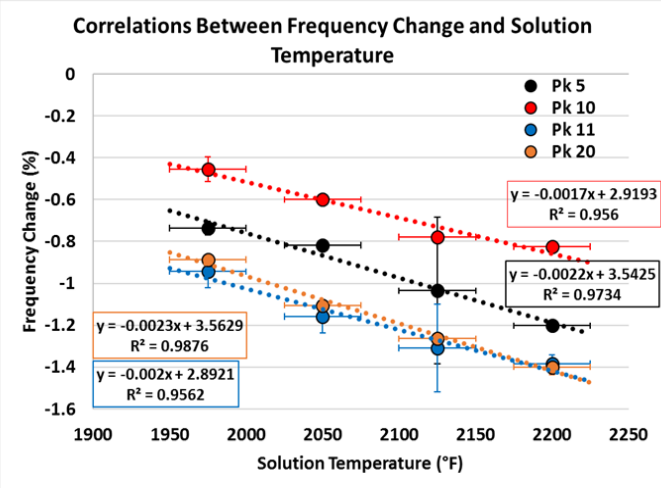

FIGURE 14: MEASURED CHANGE IN RESONANCE FREQUENCIES VS. SOLUTIONING TEMPERATURES.

Based on previous experience, these sensitivities are measurable and significant. This data demonstrates the potential of using PCRT to monitor the heat treatment process with the possibility of distinguishing between various conditions or estimating the solutioning temperature. Using multiple independent temperature estimates weighted by their correlation strengths could potentially serve as an additional monitoring step in the repair/rejuvenation of IGT blades.

5.4 Differing Degradation Behavior

Component degradation is influenced by geometrical design, run conditions, and metallurgical aspects. Initial examinations of service-run IGT blades yielded some cases where distinctive behavior corresponding to serial number (SN) prefix was observed in service-run blades. For each of the cases presented, the service-run blades shown are the same drawing number and experienced the same run conditions. Therefore, the distinct resonance behavior exhibited by the service-run sets was attributable to residual differences from the manufacturing process variations (Section 5.2).

FIGURE 15 shows three populations of third stage Advanced F-Class blades: new, 10k service hours, and 30k service hours. The 30k population formed two distinct clusters. These clusters corresponded to SN prefixes (A – left and B – right). The new population comprised both A and B SN prefixes yet there was little to no distinguishable behavior between those two groups. Movement of the SN prefix groups in different directions due to the same in-service loading indicates that the two groups are degrading differently and that those differences are attributable to a manufacturing process variation.

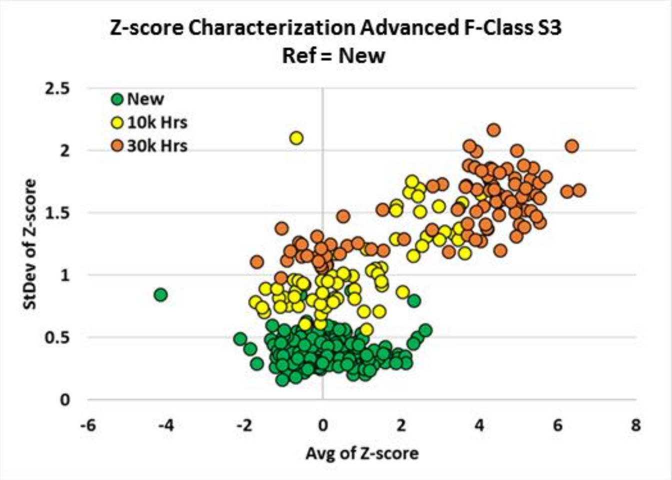

FIGURE 15: Z-SCORE CHARACTERIZATION OF THIRD STAGE ADVANCED F-CLASS BLADES COLORED BY CONDITION.

FIGURE 16: Z-SCORE CHARACTERIZATION OF THIRD STAGE F-CLASS BLADES COLORED BY SN PREFIX.

FIGURE 16 shows two populations of third stage E-Class blades in the new and service-run conditions. The service-run components formed distinct clusters corresponding to the SN prefixes. Both of these clusters were the same design and were exposed to the same run conditions. The clustering was attributed to residual variations in the manufacturing process.

6 Upcoming Work

The application of PCRT methods to IGT blades shows a lot of promise. Here we present some early experiences and preliminary results. Work is on-going in multiple areas. These include drawing quantitative relationships between resonance and microstructural changes from heat treatment variations, crystallographic orientations, and various degradation mechanisms. Upcoming work will also include the monitoring and qualification of repair/rejuvenation processes, addressing the underlying causes of outlying behavior, and detecting specific defects.

A long-term goal of this work is to build a fleetwide database of IGT component records. This is a necessary step given that IGT service intervals generally last for several years (or longer), most components will see multiple service intervals, and processes can drift or change over time. Records in the database can be used to track changes in a given part through its lifecycle, evaluate the quality of repair, or help move into a condition-based maintenance regime. The database can also be used to track and compare changes in a given blade design either through intentional modifications in design or through drifting processes.

SUMMARY AND CONCLUSIONS

PCRT has been shown here to be sensitive to metallurgical deficiencies through a combination of case studies from aerospace and power generation. While PCRT applications for IGT blades are still in the nascent stages, the initial results from IGTs have uncovered interesting deviations and shown the same type of sensitivities as those demonstrated in aerospace.

This paper presented the detection and characterization of crystal misorientation in single crystal dogbones and modeled aerospace turbine blades in addition to suspected cases in IGT's. Metallurgical aspects such changes in phase volume fraction and varying levels of precipitation were examined for both aerospace and IGT blades. The influences of process variations and degradation differences on the resonance signature were also explored. In addition to metallurgical defects, the use of PCRT to detect specific defects and unspecified defects leading to outlying behavior was presented and discussed.

PCRT has demonstrated its effectiveness as an NDE tool for OEM's and end users alike. PCRT is a fast, accurate, efficient, and inexpensive means of evaluating the material state of a component individually and in the context of the entire population of components. PCRT provides the end user with a noninvasive method of verifying the quality, conformance, and consistency of received components.

Follow-up characterization is needed to provide more comprehensive training data for PCRT inspections and to validate those inspections. A barrier to characterization is the cost and availability of components. Modeling and simulation can mitigate this by studying of the effect of defects and process variations. PCRT simulations can also produce model-trained PCRT inspections, reducing the need for physical component populations.

ACKNOWLEDGEMENTS

The authors thank Julieanne Heffernan and Leanne Jauriqui for their assistance in gathering the information presented in the aerospace case studies.

REFERENCES

[1] Campbell, F. C., *Elements of Metallurgy and Engineering Alloys*, ASM International, Materials Park, OH, 2008.

[2] Smallman, R. E., Ngan, A. H. W., *Physical Metallurgy and Advanced Materials*, Butterworth-Heinemann, Burlington, MA, 2007.

[3] Migliori, A., Sarrao, J., Visscher, M. W., Bell, T., Lei, M., Fisk, Z., and Leisure, R., "Resonant ultrasound spectroscopy techniques for measurement of the elastic moduli of solids," Physica B, 183, 1–24 (1993).

[4] *ASM Handbook, Volume 17: Nondestructive Evaluation of Materials*, Eds. Ahmed, A., Bond, L., ASM International, Materials Park, OH, 2018.

[5] Krautkramer, J., Krautkramer, H., *Ultrasonic Testing of Materials*, Springer-Verlag, New York, NY, 2002.

[6] ASTM E2001, *Standard Guide for Resonant Ultrasound Spectroscopy for Defect Detection in Both Metallic and Non-metallic Parts*, ASTM International, West Conshohocken, PA, 2018.

[7] Piotrowski, D., Hunter, L., and Sloan, T., "Process Compensated Resonance Testing JT8D-219 1st Stage Blades," ATA NDT Forum 2008, (September 24, 2008). [http://www.vibrantndt.co.uk/files/2008_ATA_NDT_Forum-PCRT_of_JT8D-T1_Blades.pdf].

[8] Piotrowski, D., Weaver, G., "Enhancing Reliability with Process Compensated Resonance Testing (PCRT) at Delta TechOps," *2016 airlines for America NDT Forum*, 2016.

[9] Craig, D. M., "NDT Technology Readiness: A P&WC Case Study," *2016 Airlines for America NDT Forum*, 2016.

[10] Federal Aviation Administration, Atlanta Aircraft Certification Office (2010). A/W File No.: G2010-07 5087.

[11] Fabris, N., Lopez, R. D., *Materials and Processes for NDT Technology*, ASNT Inc., Columbus, OH, 2016.

[12] ASTM E2534, *Standard Practice for Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts*, ASTM International, West Conshohocken, PA, 2015.

[13] ASTM E3081, *Standard Practice for Outlier Screening Using Process Compensated Resonance Testing via Swept Sine Input for Metallic and Non-*

Metallic Parts, ASTM International, West Conshohocken, PA, 2016.

[14] ASTM E3213, *Standard Practice for Part-To-Itself Examination Using Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts*, ASTM International, West Conshohocken, PA, 2019.

[15] Mayes, A., Heffernan, J., Jauriqui, L., Livings, R., Biedermann, E., Aldrin, J., Goodlet, B., Mazdiyasni, S., "Process Compensated Resonance Testing (PCRT) Inversion for Material Characterization and Digital Twin Calibration," *45th Review of Progress in Quantitative Nondestructive Evaluation*, Eds. Bond, L., Holland, S., Laflamme, S., paper 020019, 2019.

[16] J. Heffernan, L. Jauriqui, E. Biedermann, A. Mayes, R. Livings, B. Goodlet, and S. Mazdiyasni, "Process compensated resonance testing models for quantification of creep damage in single crystal nickel-based superalloys," Materials Evaluation, 75, n 7, pp. 941-952, 2017.

[17] Heffernan, J., Biedermann, E., Mayes, A., Livings, R., Jauriqui, L., Mazdiyasni, S., "Validation of process compensated resonance testing (PCRT) sorting modules trained with modeled data," 45th Review of Progress in Quantitative Nondestructive Evaluation, Eds. Bond, L., Holland, S., Laflamme, S., paper 020020, 2019.

[18] Livings, R., Mayes, A., Biedermann, E., Heffernan, J., Jauriqui, L., Mazdiyasni, S., "Detection of microtexture regions in titanium turbine engine disks using process compensated resonance testing: A modeling study," 45th Review of Progress in Quantitative Nondestructive Evaluation, Eds. Bond, L., Holland, S., Laflamme, S., paper 020022, 2019.

[19] Maddams, W. F., "The Scope and Limitations of Curve Fitting,", *Applied Spectroscopy*, Vol. 34 (3), pp. 245-267, 1980.

[20] Taguchi, G., Jugulum, R., *The Mahalanobis-Taguchi Strategy*, John Wiley & Sons, New York, NY, 2002.

[21] Smart, H. D. M., *A Study of Directionally Solidified Rene 80 Subjected to Short-term Overtemperature*, MS Thesis, University of Manitoba, Canada, 2017.

[22] Rettberg, L. H., Tsunakane, M., Pollock, T. M., "Rejuvenation of Nickel-based Superalloys GTD444(DS) and René N5(SX)," *Superalloys 2012*, Eds. Huron, E. S., Reed, R. C., Hardy, M. C., Mills, M. J., Montero, R. E., Portella, P. D., Telesman, J., pp. 341-349, 2012.