PCRT RESONANCE SOLUTIONS

ADDITIVE MANUFACTURING

This paper describes ways to apply Vibrant Process Compensated Resonance Testing (PCRT) to parts produced by Additive Manufacturing Technologies.

INTRODUCTION

PCRT RESONANCE SOLUTIONS FOR ADDITIVE MANUFACTURING

Additive Manufacturing (AM) processes are being used increasingly to produce even critical components, and quality assurance tools have yet to catch up to the challenges posed by these manufacturing methods. We will present a variety of Resonance Solutions addressing these challenges and highlighting successful PCRT results.

- PCRT to Monitor Part/Process Consistency
- PCRT to Verify Critical Post-Processing Operations
- PCRT for Quality Assurance
- PCRT to Validate (Reverse Engineered) Models and Components

Vibrant's PCRT Resonance Solutions provide game-changing reliability improvements and impressive economic opportunities to the automotive, aerospace and power-generation industries. By inspecting with PCRT, in-service part failures can be nearly eliminated, while salvaging parts with remaining service life. PCRT supplements or can functionally replace legacy NDT methods, providing a more objective, environmentally-friendly, fully automate-able inspection.

ADDITIVE MANUFACTURING CHALLENGE	VIBRANT'S PCRT SOLUTION	EXAMPLE OF APPLIED SOLUTION
AM Parts vary Build-Build and System-System	Use PCRT to compare parts quantitatively, and confirm parts are within acceptable limits.	P&WC avoids process drift and monitors mold-mold casting variation via PCRT Process Monitoring.
AM parts have regions that cannot be inspected by traditional (visual, imaging) means	PCRT is a quantitative, whole-body inspection that monitors parts for structural integrity, consistency.	Delta TechOps screens blades for cracking, over-temperature, thin-wall, Inter Granular Attack (IGA) with a single PCRT measurement.
AM Powder production is still being refined and is inconsistent in quality	PCRT is sensitive to material properties and can quantitatively compare powder batches.	American Society for Testing and Materials (ASTM) working groups have validated that PCRT has extremely high sensitivity to AM mechanical properties.
As AM Processes are still maturing, process control is uncertain	Use PCRT to monitor consistency of parts produced. Compare to other manufacturing methods, compare as process improvements are devised.	Casting House returns parts to qualification range by monitoring PCRT metrics and adjusting process parameters.
Witness Coupons may not represent properties of every part	PCRT can inspect every part quickly (< 10 sec. per part), economically, and monitor for consistency.	When PCRT replaces sampling inspection methods with 100% inspection methods, reliability and yield both increase.
Critical post processing operations are expensive and can introduce errors and risk	PCRT measurements before and after critical processing operations can be used to verify that all parts receive uniform treatments, verify benefits.	OEM uses PCRT to verify induction hardening operations in 100% of components, replacing a destructive sampling method. PCRT evaluates the consistency of Hot Isostatic Parts (HIP) and Heat Treatment (HT) processes for AM parts.
Reverse-Engineered Part is only as accurate as the model	Use PCRT to validate models, and to compare legacy and reverse-engineered components, to improve model accuracy.	Measurements of many cast single crystal parts match models produced from their geometry and crystal orientation measurements. Some measured parts deviate significantly from these models, indicating 'hidden differences' or measurement error relating to part integrity.
Confident Inspection Methods (i.e. CT) are not Production-Friendly	PCRT can quickly and accurately detect parts with Lack of Fusion (LoF), deficient heat treat, or other defects, while providing process control feedback.	Computed Tomography (CT) and HiRes Digital Radiography (DR) do not have single layer resolution, especially in thicker walled AM components. PCRT is full body and can detect defective issues under the CT and DR resolution limitations.

A recent report by **AMERICA MAKES–** ***The National Additive Manufacturing Innovation Institute*–identified PCRT as one of only two methods that can screen geometrically complex parts with 100% coverage.**

Additive Manufacturing Technologies provide a wealth of advantages over traditional manufacturing methods. Structurally efficient geometries can be designed and created without the limitations of legacy casting, forging, and machining operations. Costly part tooling is eliminated, replaced by almost infinitely adjustable computer models. AM systems can be used to create a myriad of part designs with much shorter development times, and in locations currently inaccessible to legacy manufacturing systems. With these advantages however, comes uncertainty. AM technologies are still somewhat immature, and the process variation, potential manufacturing defects, and long-term stability and capability are poorly understood. With new geometries and multipart consolidations come new inspection challenges. Component regulators in safety-critical fields are unsure how to qualify these revolutionary components. Part producers struggle to produce supportive data packages that validate structural integrity. How can the AM community increase confidence in the manufacturing and inspection environment to allow us all to take advantage of this tremendous potential?

Vibrant's PCRT offers Resonance Solutions to a variety of AM challenges. PCRT can:

- Monitor component consistency to provide manufacturing process control data, correlating final component attributes to process parameters, material (powder) batches, and machine-to-machine variation. PCRT's precise, repeatable part-level data feed big data analytics, and combines with manufacturing and operational data to provide insight not available with other inspection methods.
- Monitor the consistency of critical processing operations such as hot isostatic pressing (HIP) and heat treatment (HT). These operations are critical to our confidence in these components. We need assurance that they affect all components similarly.
- Validate models and quantitatively compare legacy and reverse-engineered components. **Resonance is an integrity fingerprint to quantitatively verify you have built what you designed.**

Figure 1—**Photo of AM samples and PCRT fixture**

PCRT measurements involve low-energy swept-sine wave excitation of the part over a range of ultrasonic frequencies (generally 5kHz–500kHz). The measurement records the natural resonance frequencies of the component, which are determined by its geometry and material properties. Parts can be in any state of manufacture, but generally should be 'individual components' rather than assemblies or still on the build plate ***(Figure 1)***. Build supports should generally be removed or at a minimum, standardized. Measurements generally take on the order of seconds to a few minutes, depending on the analysis mode. Measurements and disposition can be completely automated ***(Figure 2)*** and require and produce no chemicals. Digital records of each test are stored by serial number (where available).

Figure 2—**Fully-Automated PCRT system. Handles higher volumes with less labor. Reduces risk of human factor inspection errors.**

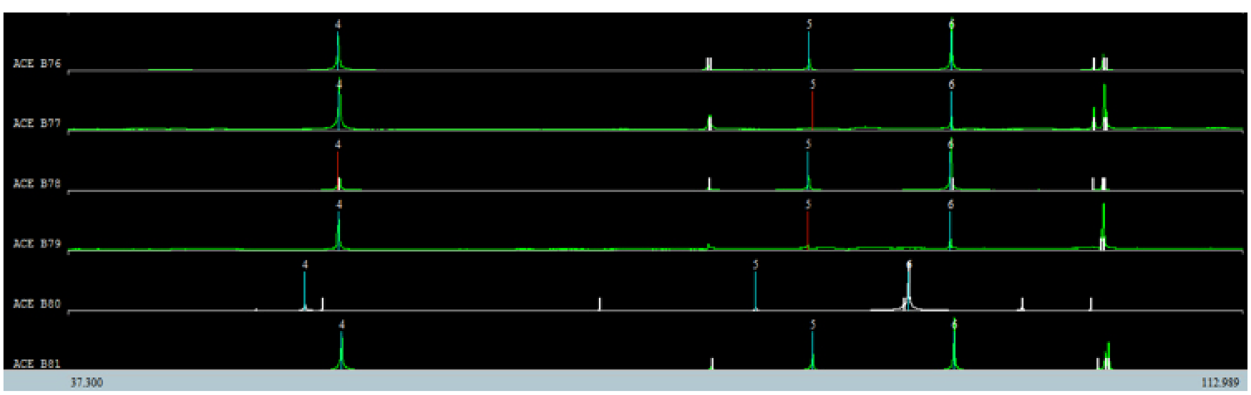


Figure 3— **Spectra for a selection of samples, recorded by serial number.**

PCRT FOR PROCESS CONTROL MONITORING

- Assure part consistency is as good as process sensors suggest
- Assure process does not drift over time
- Verify various machines produce common parts
- Monitor process capability

PCRT is most effectively applied to AM Process Control Monitoring in applications where multiple, ongoing builds produce parts in the many hundreds or thousands annually. PCRT measurements correlate to energy density and scanning speed settings, raw material properties and sourcing, build position, cooling rates and residual stress, and any potential process parameter affecting material state and mechanical properties. Resonances are measured for all parts being produced, metrics are calculated, and a confidence limit boundary is determined ***(Figure 4)***. This may coincide with qualification testing, Production Part Approval Process (PPAP), new equipment qualification, process capability studies, and/or vendor selection.

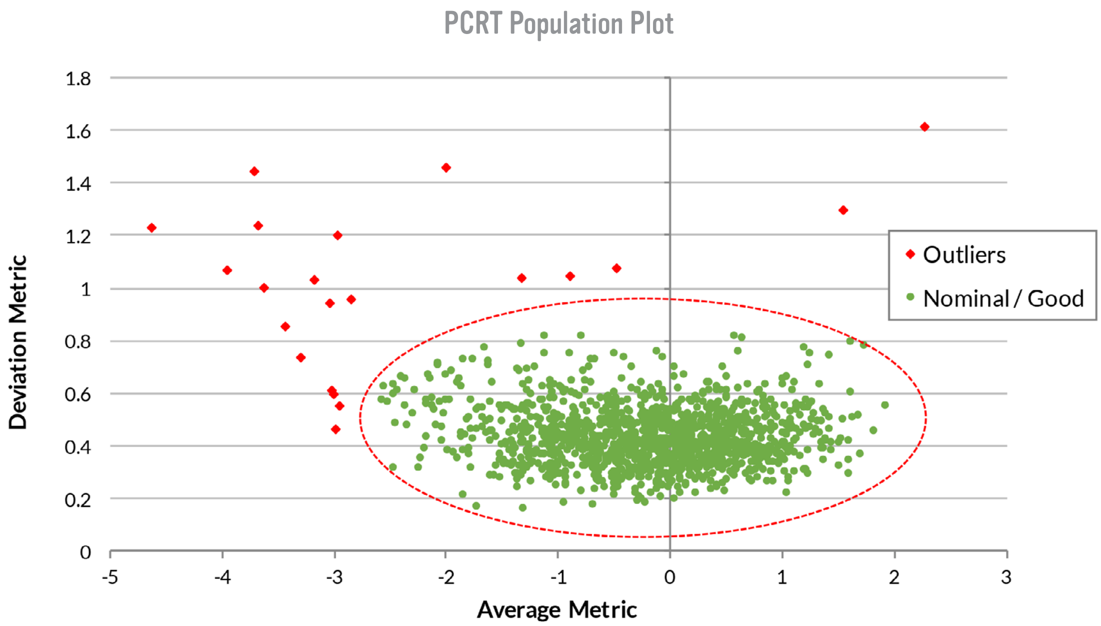


Figure 4**—PCRT Plot showing population distribution, highlighting 6-sigma outliers.**

PCRT can be used to monitor 100% of parts produced and aid other inspection methods in detection of defective components.

Future parts are compared to the acceptable/expected reference boundary, and discrepant parts can be scrapped or may be subject to further inspection. Such approaches are successfully used in casting operations to verify process consistency, approve planned process improvements and rate changes, and to reduce the need for periodic supplier monitoring.

PCRT can be used to monitor 100% of parts produced and aid other inspection methods in detection of defective components. In studies with the University of Sheffield, two print batches of nominal parts were produced. The first set showed consistent resonance measures for all parts. The second set included at least two statistically outlying parts, which were later found to be cracked. Many months later, a third batch of parts were produced, to similar specifications. This entire batch showed a significant change to resonance measurements. Whether due to machine-machine variation, or drift in control parameters over time, this demonstrates that PCRT Process Monitoring detects process drift.

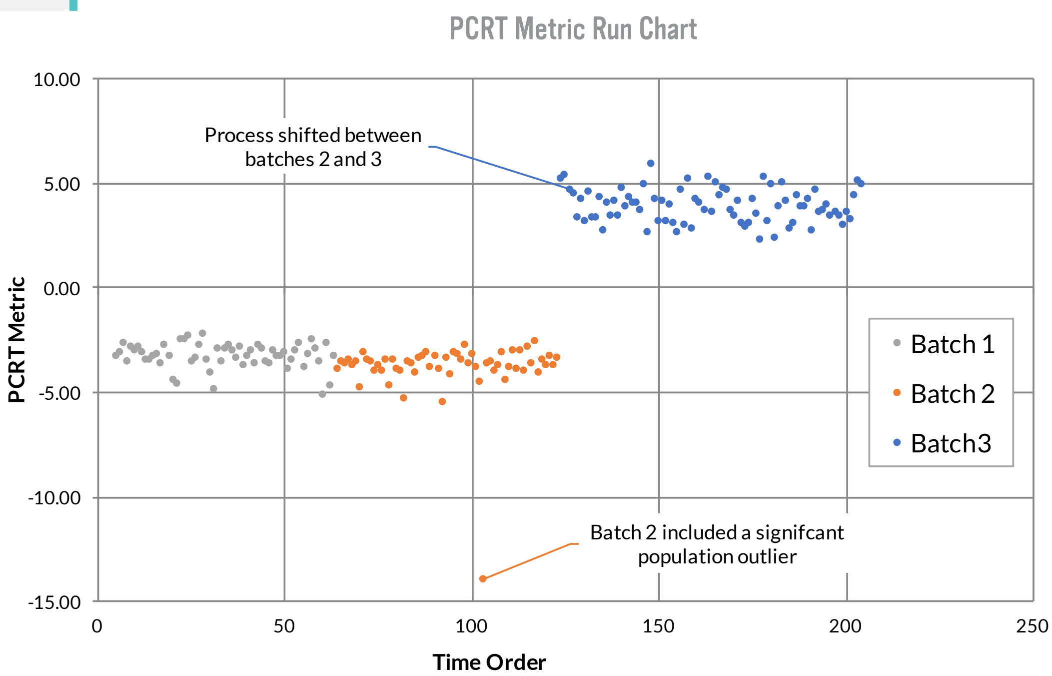


Figure 5—**Run Chart of PCRT Metric for multiple batches of AM components. PCRT identifies individual outlying parts, and process shifts and drifts.**

PCRT TO VERIFY CRITICAL PROCESSING OPERATIONS

- Assure that changes due to critical processes, such as Heat Treat or HIP, are consistent from part to part and batch to batch.
- Identify parts for further evaluation

Evaluation of a PCRT metric over time has enabled both casting supplier and customer to have confidence that parts produced today, and accepted by the PCRT inspection, match parts produced in the qualification study even many years previous ***(Figure 6)***. Examination and monitoring of the trends and values on the run chart enable increased process control, by correlating changes to process variables.

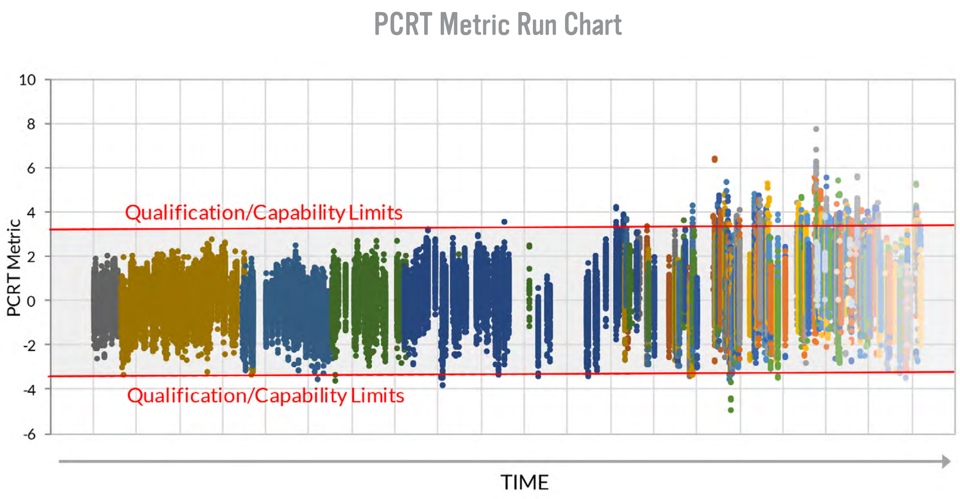


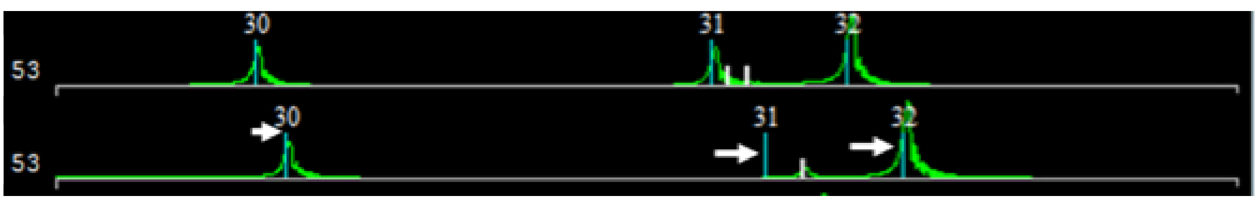
Figure 6**—Run Chart of PCRT Metric for as-cast turbine blades over time. Inspection limits guarantee that blades accepted match characteristics of the initial qualification parts.**

Resonance is an integrity fingerprint to quantitatively verify that you have built what you designed and intended.

PCRT data collected after the initial build step can then be used as a reference to verify proper application of post-processing treatments. AM processes often include stress-relief HT and HIP operations. While these are often batch operations, they are not always perfectly consistent. Location within a furnace, atmosphere, inert gas circulation, power interruption and varied cooling profiles can all lead to variations in material properties within a batch of parts. Qualification runs often include small batch sizes which may not completely represent the range of potential variation, or stress throughput conditions. PCRT monitoring provides quantitative feedback on the consistency of these operations, in terms of the change affected in the parts, and helps to identify components which may need further evaluation, or to expand qualification testing.

In these applications, parts are measured before and after the critical operations, with data tracked by part serial number ***(Figure 7)***.

Part 53: Pre-HIP vs. Post-HIP



Part 55: Pre-HIP vs. Post-HIP

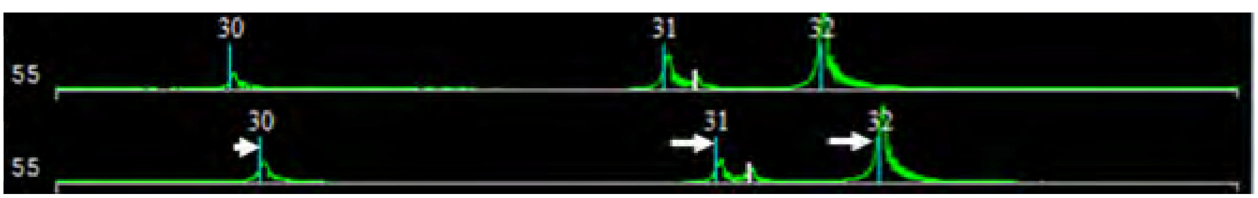


Figure 7—**Resonance Spectra for parts before and after HIP. Change in resonance provides valuable process control feedback.**

Resonances change with changing stress state and/or cracking.

Data from a study with the University of Sheffield shows how samples changed when a stress-relief heat treatment was not immediately available as planned ***(Figure 8)***. As the parts waited, the stress relieved naturally, leading to cracking in many of the components. It is not clear whether only a portion of the parts had significant residual stress, or whether it was only relieved in a portion of the waiting parts. It is clear that the resonances changed as a result of the stress state and/or part integrity, and that the cracked components show significantly different resonance measures than un-cracked components.

Part Z10: Intact vs. Intact After Delay

Part Z13: Intact vs. Cracked After Delay

Part Z22: Intact vs. Cracked After Delay

Figure 8**—Spectra view of Batch 3 parts before (green) and after delay (red, white).**

HIP increases the density of AM components. This change is detectable with PCRT measures ***(Figure 9)***. Parts can be measured before and after the HIP operation, to assure that each part is treated consistently. This change can be monitored to assure that parts are responding as expected to the HIP treatment, and to identify any parts that are not treated properly. ***Figure 10*** shows how parts with (intentional) LoF porosity change **more** during HIP than parts with higher starting density. Monitoring this change can identify *unintentional* LoF samples for further evaluation.

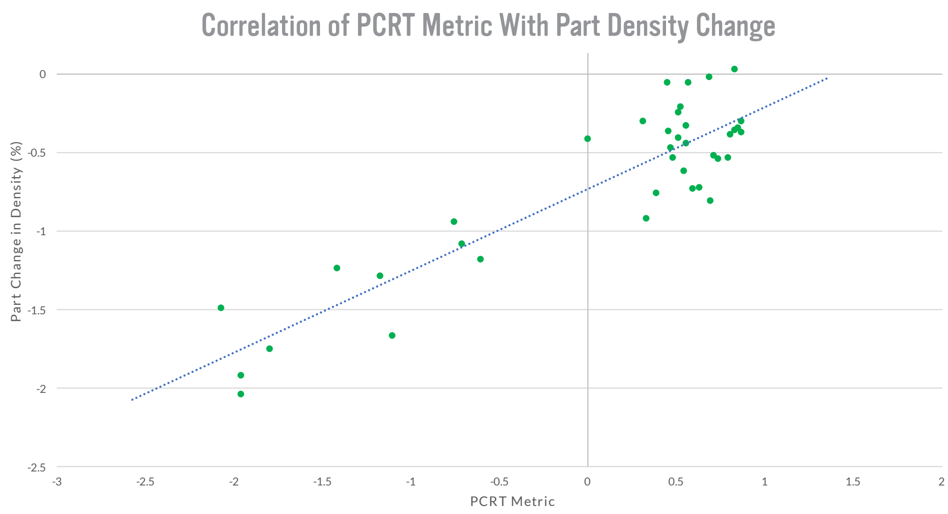


Figure 9**—Correlation of PCRT Metric with change in part density.**

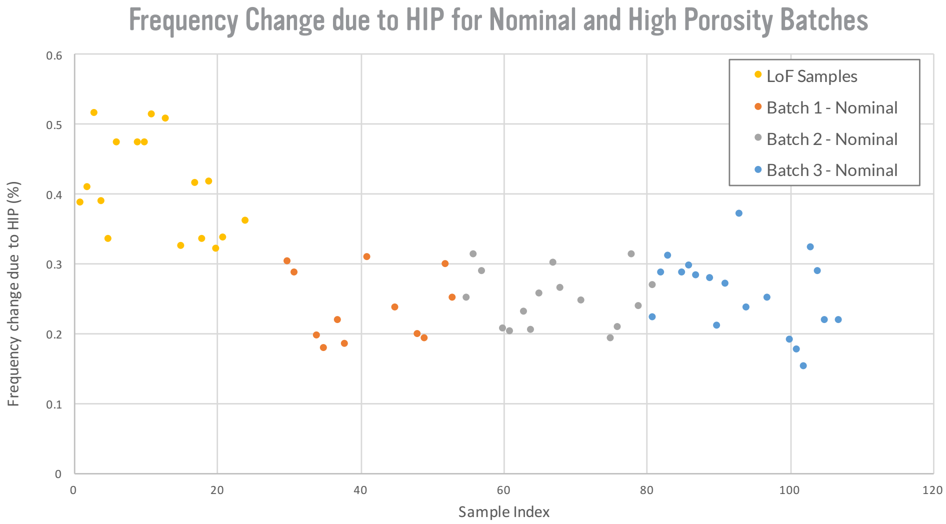


Figure 10**—Monitoring the change in resonance due to HIP over time/batches. One batch of LoF samples is included to demonstrate that those parts change more than parts that did not have that original porosity.**

PCRT FOR QUALITY ASSURANCE

- **Quickly pass parts that are free of defects, with nominal properties**
- **Identify parts with characteristics inconsistent with good population, or consistent with trained defect samples, for further inspection**

The methods discussed to this point focus on consistency of the manufacturing process, the value of having quantifiable data on 100% of the parts produced, and evaluating change in parts due to similar treatments. PCRT measures can also be used to target detection of specific defects, with some caveats. Resonance is a whole-body inspection method, and part resonances are sensitive to the condition of the whole part. PCRT cannot generally detect anomalies in one area of a component while accepting a similar anomaly in a different location. PCRT defect targets must be structural, rather than cosmetic. The defect must adversely affect the performance or material properties of the part.

PCRT Targeted Defect Applications may be trained with built samples of target defects or with carefully modeled samples of defects. PCRT cannot generally be used yet to locate, size or characterize defects, although PCRT measures will report which samples are most different from the nominal reference set. PCRT can be used to immediately segregate parts as non-conforming or to set aside for more costly, time-consuming NDT methods, such as computed tomography (CT). In AM parts, PCRT has been used to detect unacceptable levels of porosity, cracking, lack of fusion, and sub-optimal heat treatment. In many cases, the metallurgical changes are detectable only with PCRT and are completely invisible to DR and CT.

Vibrant has also detected samples with retained powder, parts with non-conforming heat treatment, and samples made from recycled powder.

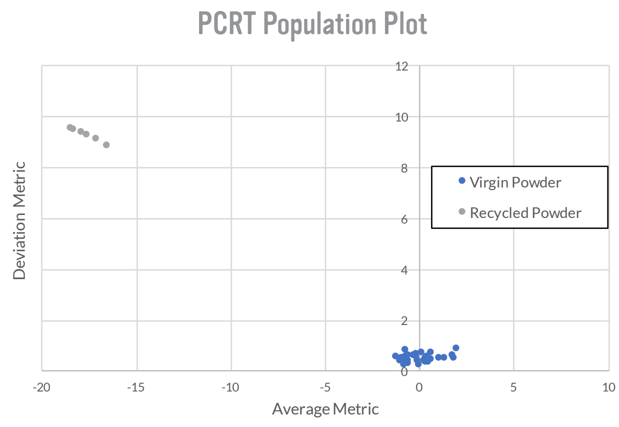


Figure 11—**Population Characterization plot comparing virgin and recycled powder populations in AlSi10Mg specimens.**

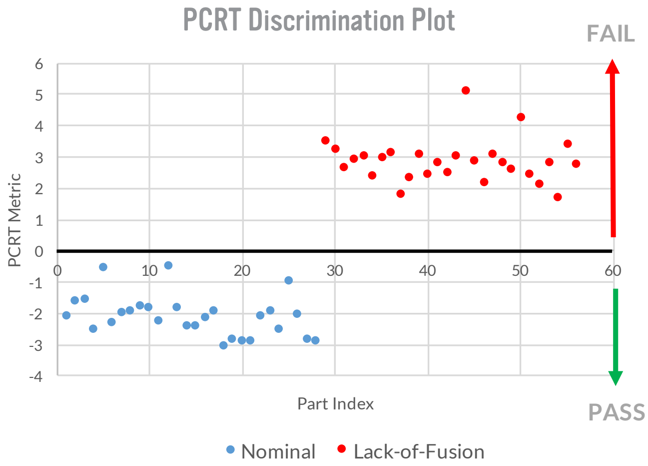


Figure 12—**PCRT sorting results for nominal vs. LoF dogbones.**

Vibrant and Incodema3D studied the effects of powder variation in AlSi10Mg components. Incodema3D produced a population of 30 specimens with virgin powder and 6 specimens with recycled powder. The build and post-processing parameters for the two samples were identical. ***Figure 11*** shows that the variation between the two populations was significant. The lower PCRT 'average metric' values for the recycled powder indicate significantly lower Young's Modulus values for parts made with recycled feedstock, consistent with customer expectations. The significantly higher 'deviation metric' values for the recycled powder indicate that the difference is not only to the Modulus, but to other material properties or states as well. Material variations can be targeted to reject non-compliant components in a PASS/FAIL NDE scenario.

Vibrant studied lack of fusion (LoF) porosity in the gauge section of Ti-64 dogbones made by CalRAM, Inc. CalRAM produced two sets of dogbones: one with nominal build processing and one processed to intentionally create an area of LoF porosity in the gauge section. Mechanical testing confirmed that the LoF parts failed at lower stress levels than the nominal parts. A Targeted Defect Detection sort was developed to demonstrate PASS/FAIL sorting for the defective LoF condition. ***Figure 12*** shows how the Targeted Defect PCRT Metric can separate the nominal from LoF samples. PCRT can be used to target LoF conditions that lead to structural degradation in AM components.

Vibrant has also detected samples with retained powder, parts with non-conforming heat treatment and samples made from recycled powder. Note that PCRT results do not indicate a type or location of defect, but provide quality assurance that all parts are conforming to the nominal specification.

PCRT TO VALIDATE (REVERSE ENGINEERED) MODELS AND COMPONENTS

• Verify that models accurately reflect legacy part
• Verify built part matches model/legacy part

AM processes often use 'witness coupons' to verify material properties of a particular build. While this process can verify the properties of the witness coupon itself, it cannot verify the properties of the engineering components. PCRT can be used to non-destructively evaluate both the witness coupons and engineering components. For the witness coupons, a PCRT metric will correlate to destructive test results. Repeated comparisons of the PCRT metrics for witness coupons to engineering components may lead to a reduced reliance on the destructive testing, as all built components can be quantitatively evaluated with PCRT.

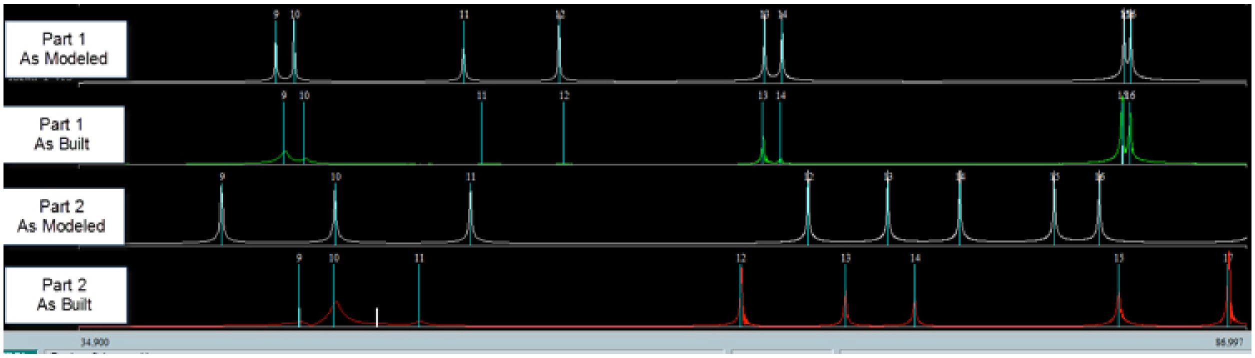


***Figure 13*—Comparison of resonance spectra 'as modeled' and 'as built' for 2 samples. Part 1 is much more representative of the modeled properties and dimensions than Part 2.**

PCRT benefits are obvious to high volume applications, where it is often applied to components in the automotive and aerospace industries. AM has additional, unique advantages in producing low volumes (no expensive tooling charges), the prospect of reverse engineering legacy components for which no supply is currently available, and the ability to buildreplacement parts in environments where spare supply may be limited. In these applications, the need is to confirm that the modeled component has been built properly, or that the replacement part adequately matches the legacy or sample component. PCRT measures can be compared to modeled resonance predictions, to confirm that the built component matches the model ***(Figure 13)***. The model will assume/specify material properties, and the PCRT measures will confirm that the built component has properties consistent with those model inputs. If available, the legacy component's PCRT measures can be compared with the newly built component, to assure that the model and re-buildwere accurate. Examination of differences can be used to improve the model, ensuring modeled performance predictions and assumptions are most accurate.

CONCLUSION

Vibrant's PCRT Resonance Solutions have long-proven success for large-scale cast, forged and machined applications in the aerospace and automotive industries.

These solutions can also provide the data needed to prove confidence in AM components as well. Emerging PCRT studies of AM parts show detection of porosity-related defects, powder supply variation, process variation, retained powder and correlation to performance testing. PCRT assures part quality at every state, from verifying that the part built is the part designed, to tracking the consistency of each and every part produced. PCRT is production-line ready, capable of testing parts in seconds, integrated with parts-handling automation, and providing Pass/Fail results without highly trained inspectors.

Contact Vibrant to discuss opportunities for PCRT in your business!

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Additional Reading & Resources

"America Makes: National AM Innovation Institute (NAMII) – Project 1: Non-destructive Evaluation (NDE) of Complex Metallic AM (AM) Structures," June 2014 Interim Report. AFRL-RX-WP-TR-2014-0162.

"Process Compensated Resonant Testing in Manufacturing Process Control," Material Evaluation, 63 736-739, (July 2005). Todorov, E., Spencer, R., Gleeson, S., Jamshidinia, M., Kelly, S., (June 2014). J. Schwarz, J. Saxton, and L. Jauriqui.

"Process Compensated Resonance Testing JT8D-219 1st Stage Blades," ATA NDT Forum 2008, (September 24, 2008). D. Piotrowski, L. Hunter, and T. Sloan.

"Delta TechOps Reduces Engine Inspection Costs by Nearly $2m Annually," Vibrant Corporation and Delta TechOps. (April 2014).

"Enhancing Reliability with Process Compensated Resonance Testing at Delta TechOps," ATA NDT Forum 2016, (September 28, 2016). D. Piotrowski, G. Weaver.

PCRT Standards & Approvals

ASTM E2001-13 Standard Guide for Resonant Ultrasound Spectroscopy - outlines capabilities and applications of several resonant inspection methods

ASTM Standard Practice E2534-15 – Describes auditable method for application of PCRT Targeted Defect Detection inspection

ASTM Standard Practice E3081-16 – Describes auditable method for application of PCRT Outlier Screening inspection

Federal Aviation Administration Approved – Since July of 2010 for the detection of micro-structural changes indicating over-temp of turbine blades (JT8D-219 HPT)

AS9100D & ISO9001:2015 – Certificate #10928 issued by PRI Registrar