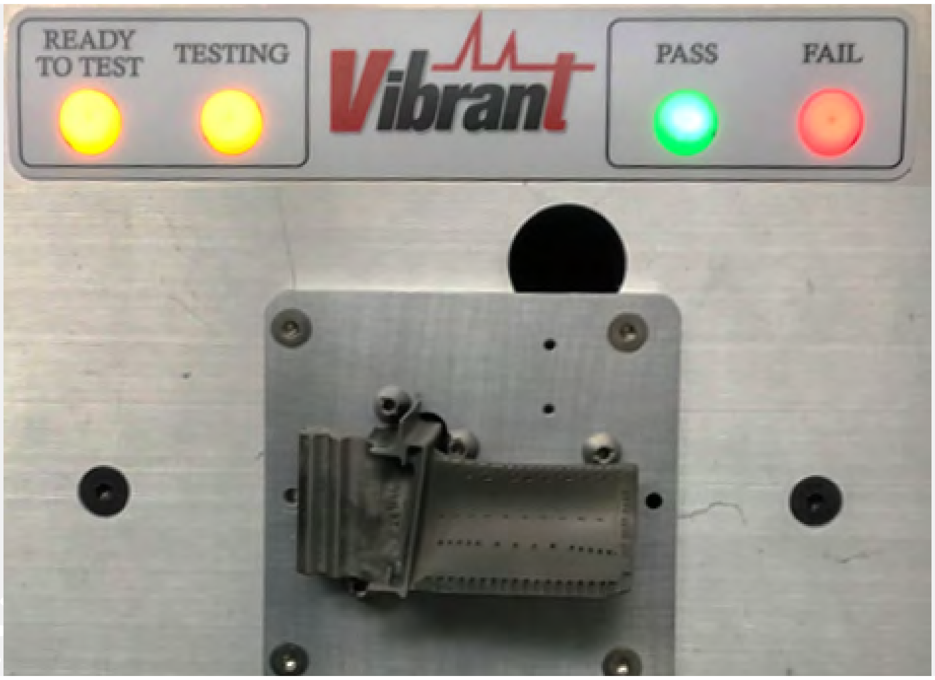
PCRT RESONANCE SOLUTIONS

SINGLE CRYSTAL (SX) ORIENTATION

This paper describes ways to apply Vibrant Process Compensated Resonance Testing (PCRT) to single crystal parts to verify grain orientation.



INTRODUCTION

PCRT RESONANCE SOLUTIONS FOR SINGLE CRYSTAL MATERIALS

Advances in superalloy casting over the last 50 years have provided the aerospace industry with significant improvements in engine efficiency, via increased operating temperatures, and decreased component weights. Component life is also improved through increased creep resistance and thermal fatigue life. Specifically, the development of single crystal casting techniques has improved creep-resistance, allowing higher temperature operations.

The optimal orientation of the single crystalline grain runs in the radial direction of the blade (root to tip). This orientation is monitored, generally for 100% of SX (Single Crystal) castings, using an x-ray diffraction method called Laue diffraction. While the Laue technique is the industry standard, it has sensitivities and subjectivity that can produce misleading results, and component failures from grain related issues still occur. Vibrant's PCRT technology can provide additional assurances that components have properly aligned single crystal grains.

Vibrant's PCRT offers Resonance Solutions to support quality control efforts in SX manufacturing by:

- Assuring that parts with outlying material properties are not accepted, even if single-point Laue measurements imply the grain angle is acceptable.
- Detecting secondary grains which significantly impact material properties.
- Providing quantitative feedback to compare a part to a qualification population.
- Aiding in the understanding of how grain angle control impacts effective material properties by correlation between population metrics and angle measures.
- Providing automate-able, objective inspection metrics that can be tracked as a process monitoring function, correlate to manufacturing process control variables, and compared against operating/performance data to aid in risk assessment and mitigation.

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

SINGLE CRYSTAL ORIENTATION

CRYSTAL ORIENTATION CONTROL

Much of the SX casting process focuses on maintaining proper alignment of the crystal through highly controlled cooling. The impacts of this control are critical. If the primary crystal orientation angle, θ (***Figure 1***), varies 15° off the radial axis of the blade, the effective modulus in that critical direction (which needs to withstand centrifugal forces on the blade) can change by 5%. If that angle is allowed to vary 20°, the change in material properties is more than 20%. In general, less focus is placed on controlling the other angles of alignment between the crystal and the blade, but variation in these also changes the overall material properties of the blade. If blades are produced with all angles near the upper specification limits, the material properties can be quite different from blades with lower angles.

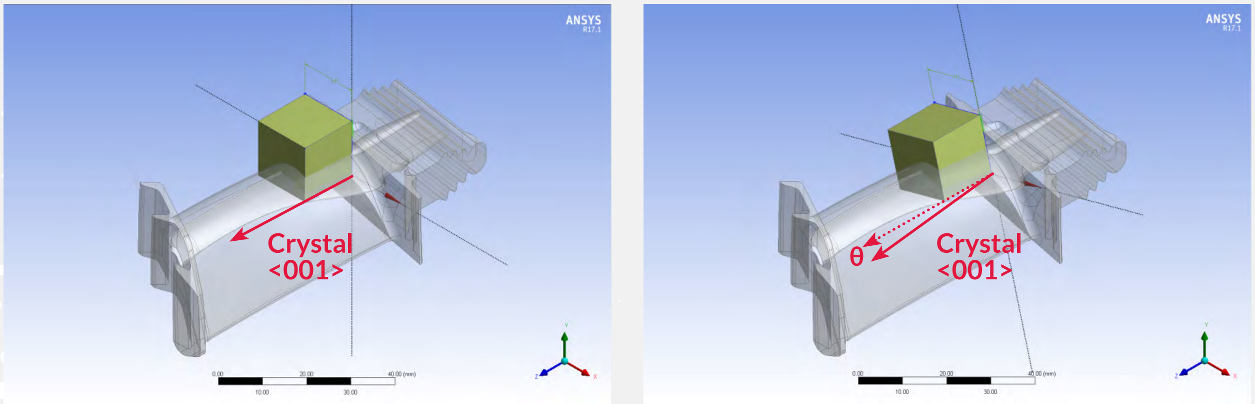


Figure 1—**Illustration of primary crystal orientation variation, θ, for a turbine blade.**

PROCESS COMPENSATED RESONANCE TESTING

PCRT is a whole-body resonance inspection method. Component resonances reflect the effective material properties of the whole part, and allow a very precise comparison of individual parts to known and predicted responses, as well as assuring that populations are consistent. Finite Element modeling of SX components highlights the changes in material properties as the crystal orientation is varied, and demonstrates how the component resonances will reflect the difference. PCRT measures many of these resonances to enable fine comparisons between properties of different parts.

Figure 2 shows a modeled population of blades where the primary crystal orientation, θ, is varied. The black series represents the effective modulus of the crystal itself. The modeled population includes variations that specifically affect this (density, Ex, Ey, Ez, etc…), as well as dimensional variation.

The red series represents the effective modulus of the ***blade***, in the radial direction, which varies because of the way the crystal is oriented. This is the effective property that determines how the blade performs in service. As the angle increases, the change is exponential in nature—larger angles make much greater changes to the material properties.

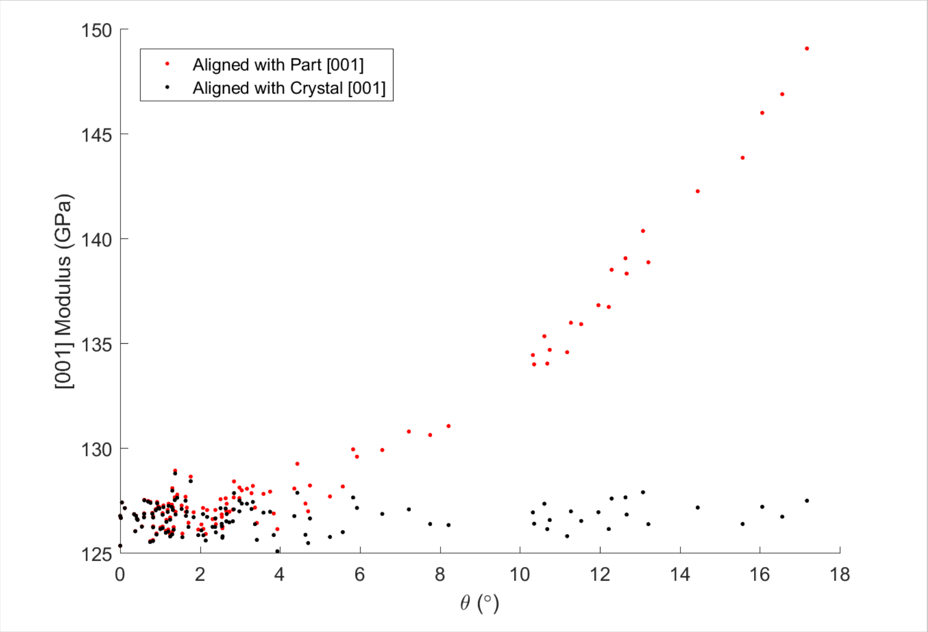


***Figure 2*—Modeled change in effective modulus in the radial direction for an SX blade, with varied primary crystal orientation angle, θ.**

Higher theta values cause significant changes to directional material properties.

Figure 3 shows how the changes in material properties manifest in the resonance spectra. Some variation in frequency is seen due to ‘other factors’ varied in the models, but clear trends are evident with increasing θ. PCRT measurements of these frequencies are used to infer material property values, and compare properties of parts within a population.

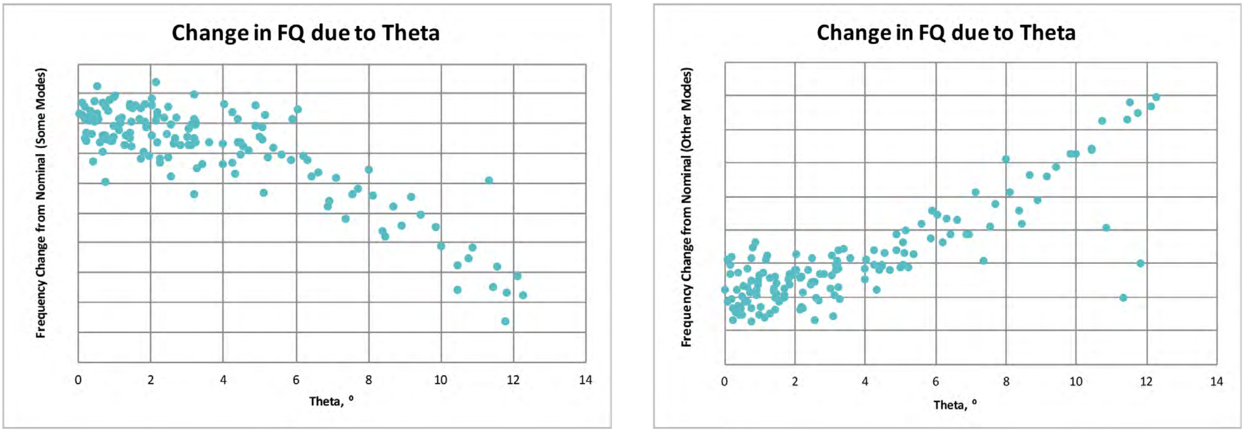
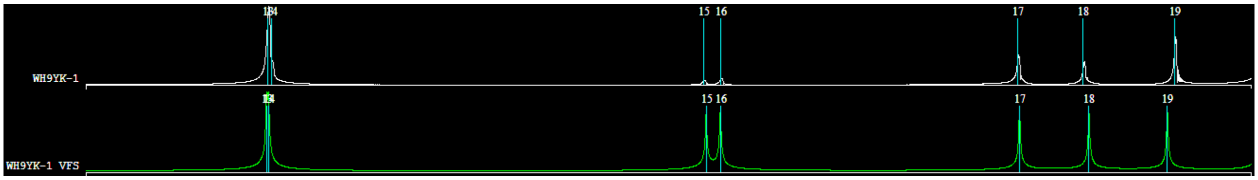


Figure 3**—Plots showing how the resonance frequencies of a component change with varied θ. Not all mode shapes change in the same manner, but many modes follow similar trends.**

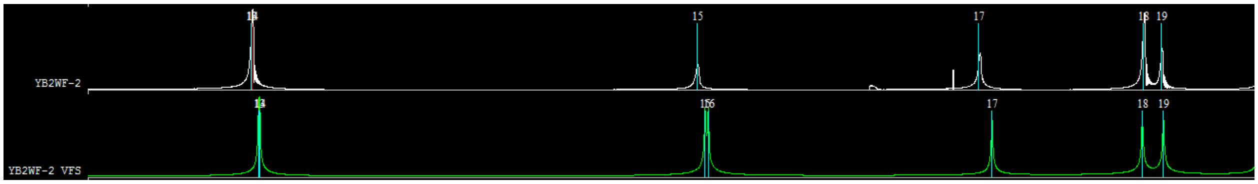
COMPARISON TO LAUE MEASUREMENT

Vibrant obtained a variety of cylindrical SX castings, for which the supplier provided Laue measurements for each rod. Each rod was machined into 2 dogbone samples, presumed to have material properties influenced by the primary angle, as measured by Laue. Additionally, Finite Element digital twin model instances of each dogbone were created with the Laue angles, and modal analyses were performed on these to predict resonance frequencies for each sample. The vast majority of samples showed excellent match between these modeled resonance frequencies and those measured with the PCRT system for the samples. However, some samples did not match well at all.

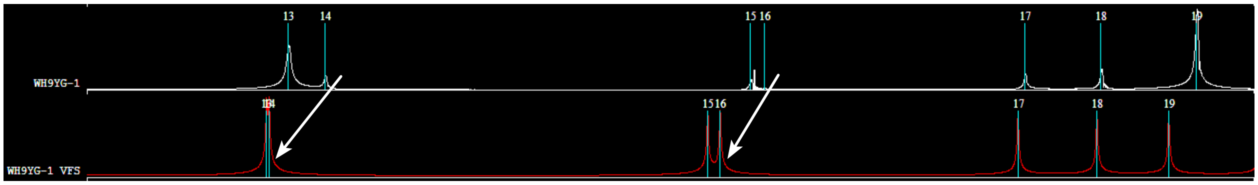
Sample WH9YM-1: Good Match (white = measured, green = modeled)



Sample YB2YF-2: Fair Match



Sample **WH9YG-1**: Poor Match (white = measured, red = modeled)



Sample **YB2WN-1**: Poor Match

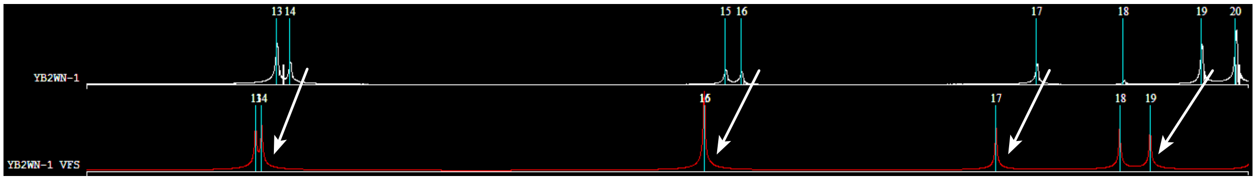


Figure 4—**Comparisons of modeled and measured spectra for sample components. Models are based on crystal orientation from initial Laue measurements, which appear misrepresentative for some samples.**

Laue measurements are subject to sources of error that PCRT inspection can overcome. Because Laue measurements are made at a single point on the surface, they might not be representative of the 'whole body'. Additionally the part is typically constrained in a specific fixture, and geometrical variation in the part might 'mis-align' the part axis with the measurement plane axis, skewing the measurement. If the part includes secondary grains, a single point measurement can also contribute uncertainty to the material properties inferred. The measurement cannot tell which grain was measured, which grain has a larger volume, what the effect of the grain boundary will be on the part strength, etc. While SX component inspectors rely on additional visual/reflectivity inspections to look for other sources of problems, PCRT inspections will provide insight into a variety of conditions (off-angles, recrystallization, multiple grains) in a single evaluation.

A portion of the dogbones from ***Figure 4*** were sent to be re-inspected by Laue diffraction. This time, both ends of the samples were evaluated, to verify consistency in the whole-body material properties (***Table 1***).

	θ ORIENTATION ANGLE		
PART	ORIGINAL CAST BAR LAUE	RE-LAUE SIDE A	RE-LAUE SIDE B
WH9YG-1	8.7°	13.3°	14.1°
YB2WN-1	6.6°	7.7°	14.1°
YB2YF-2	0.9°	0.5°	0.6°

***Table 1*—Laue results from reinspection of dogbone samples.**

In the case of sample **WH9YG-1**, re-measurements from both ends were reasonably consistent, and were consistent with the PCRT whole-body orientation prediction, which was almost 5° higher than the original Laue measurement. The reason for the original erroneous measurement is not obvious, but could be related to etch quality, part fixturing or human factors. For sample **YB2WN-1**, which had poor model-measure match, the re-measurements showed significantly different values for each end, confirming at least 2 grains. This secondary grain was not identified by the initial Laue single point measure, nor was a secondary grain reported by a visual inspection. Sample YB2YF-2 was sent for re-Laue to verify that a sample that had a good model-measure match could have the original measurement confirmed. The repeat measurements from both ends were consistent, and within measurement error of the original.

> PCRT population monitoring techniques can be used to segregate parts that fall outside of a qualified range, to help identify potential sources of error from the initial Laue evaluation.

PCRT FOR QUALITY CONTROL OF SX CASTINGS

In ***Figure 5***, a population of sample components were modeled, varying base material properties (Modulus, Poisson's Ratio, Anisotropy Ratio), sample dimensions and crystal orientation. The PCRT Population Characterization Plot aggregates resonance frequency data to highlight parts that are significantly different from the bulk of the population. This analysis shows that the parts with primary angle θ below 8 are fairly consistent, falling in a dense, overlapping cluster. As θ increases further, the parts become less like the rest of the population. This is due to the changing effective material properties.

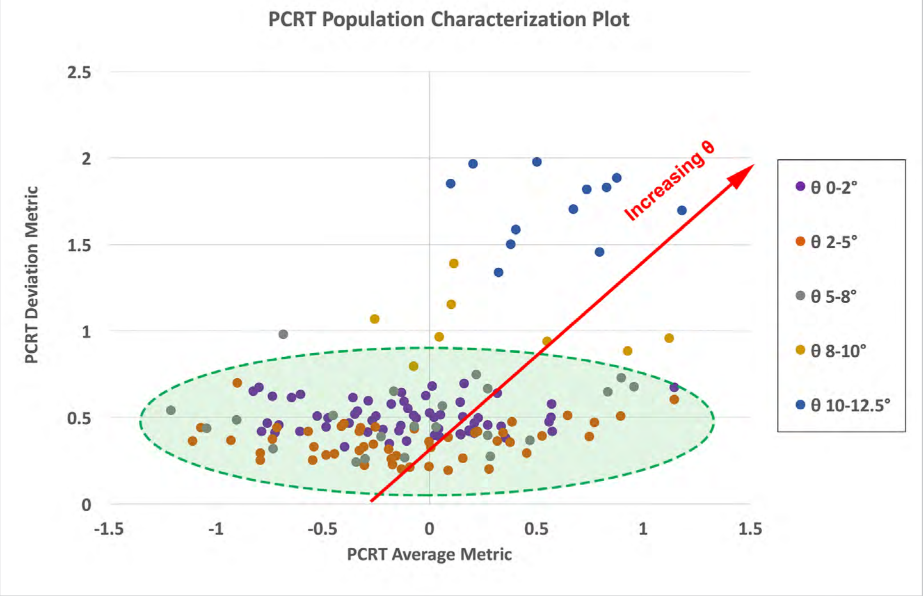


Figure 5—**PCRT Population Characterization Plot demonstrating how parts with increasing θ are outlying from the nominal population.**

PCRT can be used to 100% inspect SX castings, to provide a pass/fail result based on a trained theta specification (trained with modeled and/or measured samples). Sorting Boundaries might be based on population distribution and consistency, and look like the dotted line in ***Figure 5***, or might be optimized to correspond to a specific measured theta, as demonstrated in ***Figure 6***, which sets an acceptability limit at 10°, representing a well-controlled casting process. PCRT sorts are custom-configured to each customer's specific sorting goals, so the theta limits can be varied from these examples. PCRT analyses may also be configured to estimate the effective crystal orientation, based on PCRT data.

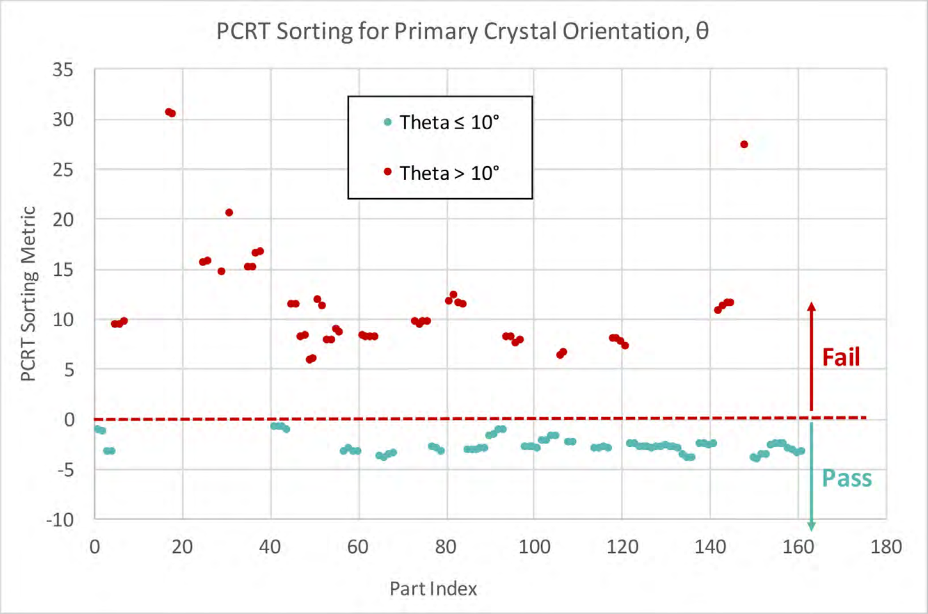


Figure 6—**PCRT Sorting Plot. Sort trained to reject primary crystal orientation angle, θ, greater than 10°.**

> **PCRT can be used to 100% inspect SX castings, to provide a pass/fail result based on a trained theta specification.**

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 be used to support monitoring of SX crystal orientation, to identify parts that are currently misinterpreted through Laue inspection, accurately evaluating the whole-body material properties and segregating risky secondary grains. PCRT's quantitative output can also be used to aid Process Control and Monitoring efforts, and to combine with other big data sources for expanded performance analytics.

Contact Vibrant to discuss opportunities for PCRT in your business!

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Additional Reading & Resources

***"Process Compensated Resonance Testing Modeling for Damage Evolution and Uncertainty Quantification"**, QNDE 2016, E. Biedermann, J. Heffernan, A. Mayes, et al.*

***"PCRT Inversion for Material Characterization and Digital Twin Calibration"**, QNDE 2018. A. Mayes, J. Heffernan, L. Jauriqui, et al.*

***"Validation of Process Compensated Resonance Testing (PCRT) Sorting Modules Trained with Modeled Data"**, QNDE 2018. J. Heffernan, A. Mayes, R. Livings, et al.*

***"Evaluation of PWA1483 for Large single crystal IGT Blade Applications"**, Superalloys 2000. D.M. Shah, A. Cetel*

***"Determination of the crystallographic orientation of a single crystal using resonant ultrasound spectroscopy"** Rev. Sci. Instrum, 65 (6), June 1994. J.L. Sarrao, S.R.Chen, W.M. Visscher, Ming Kei, U.F. Kocks, A. Migliori.*

***"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**—out-lines 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*