46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-7038

VALIDATION OF MODEL-TRAINED PROCESS COMPENSATED RESONANCE TESTING INSPECTION FOR CREEP DEFORMATION – A MODEL-ASSISTED PROBABILITY OF DETECTION STUDY

Eric Biedermann[1], **Leanne Jauriqui, Julieanne Heffernan, Alexander Mayes**
Vibrant Corporation
Albuquerque, NM

John C. Aldrin
Computational Tools, Inc.
Gurnee, IL

Siamack Mazdiyasni
Air Force Research Laboratory
Dayton, OH

ABSTRACT

A model-assisted probability of detection (MAPOD) validation of Process Compensated Resonance Testing (PCRT) inspection for creep deformation is presented. The PCRT inspection was trained entirely with resonance data from PCRT forward models that predicted the effect of creep deformation on resonance frequencies. The MAPOD validation was conducted with a combination of physical validation specimens and modeled specimens. The modeled specimens included simulations of the effects of uncertainty inherent in the measurement of physical samples. The results validated PCRT forward modeling accuracy for creep deformation, and accurate PCRT classification of acceptable and unacceptable levels of creep.

Keywords: Process Compensated Resonance Testing, Probability of Detection, creep deformation, modeling

NOMENCLATURE

Φ	standard normal cumulative density function
$a_{90/95}$	POD reliable detection level
f, g	linear algebraic functions
p	probability of detection
X	matrix of controlling variables
y	signal response

1. INTRODUCTION

Process Compensated Resonance Testing (PCRT) is a nondestructive evaluation method that measures and analyzes the resonance frequencies of a component for material state characterization and defect detection. Historically, PCRT has required a statistically significant training set of components with material state variations of interest to establish an operational inspection. The development of PCRT modeling tools offers a path to overcoming those data-driven limitations. Recent work [1][2] has demonstrated the use of modeled resonance spectra for training PCRT inspections to detect creep deformation and crystallographic orientation variation in nickel-base superalloys. This paper describes a model-assisted probability of detection (MAPOD) study performed to validate a model-trained PCRT inspection for creep deformation.

2. MATERIALS AND METHODS

The subject material for this study was a single crystal (SX) variant of Mar-M-247, a nickel-base superalloy. Raw castings were purchased from an aerospace propulsion casting vendor and then machined into dogbones compliant with ASTM E139-11 (2018): Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials.

2.1 Process Compensated Resonance Testing for Creep Deformation

The methods for modeling the resonance effects of creep deformation have been described in [1] and [2]. A Monte Carlo population of modeled dogbone specimens with acceptable variations in geometric dimensions, bulk material properties, crystallographic orientation and acceptable/unacceptable levels of creep deformation was generated with the finite element method (FEM). The resonance spectra from the Monte Carlo populations were imported into the Vibrant PCRT software and analyzed with the Vibrational Pattern Recognition (VIPR) machine learning tools. VIPR identified resonance modes of vibration that were diagnostic for creep deformation. Pass/Fail statistical scoring criteria for the resonance frequencies were established using the Mahalanobis-Taguchi System (MTS). The diagnostic modes and MTS scoring were configured into a PCRT Sorting Module that was validated with the MAPOD analysis.

2.2 Model-Assisted Probability of Detection Analysis

For the studies performed in this work, a variety of both physical samples and modeled samples were utilized to more

---

[1] Contact author: ebiedermann@vibrantndt.com

fully represent potential sample variation without incurring excessive sample expense. Multiple inspectors performed the inspection seven times. A single test system was used because PCRT testing fixtures are generally customized to the specific part geometry, so fixturing is not often an inspection variable. Sample classification was unknown to the inspectors at the time of the testing, and inspectors were all similarly instructed as to how to perform the inspection.

Probability of Detection calculations were performed in accordance with MIL-HDBK-1823A [3], using the mh1823 POD software developed and distributed by Chuck Annis [4]. Both hit/miss and signal response analyses were performed. The PCRT Sorting Modules used for the POD studies inspected each sample, and provided both a Pass/Fail result, and MTS scoring metrics, which were used for the Signal Response analysis.

Measurement uncertainty was inherent in the repeat measurements of the physical samples, which were tested many times each. This measurement uncertainty was also passed to the modeled POD samples in the following way. Repeat measurements of the physical samples across the various operators were compared, and for each part/peak combination, the difference from the average was calculated. These differences were then used to calculate a standard deviation of measurement error for each of the resonances used in the sorting module. This standard deviation was used, in Monte Carlo style, to add measurement error 'noise' to the model frequency predictions. In all, seven different 'noisy' versions of each modeled point were included in the POD study. Noise was applied randomly, and independently, to each frequency, following a normal distribution.

For the hit/miss analysis, many common link function models were considered, including the probit, or inverse normal function, and logit, or log-odds function. The mh1823 POD software presents results for the various models to aid in selection of the best model. The hit/miss results shown here used the probit model [4]:

$$f(X) = g(y) = \Phi^{-1}(p) \tag{1}$$

For the signal response analysis, the mh1823 POD software evaluates both linear and log-based relationships between the signal and the defect size. For the creep sort results evaluated here, the signal (MTS Score) correlated linearly to the % creep damage experienced by the samples.

3. RESULTS AND DISCUSSION

A PCRT Sorting Module was trained with modeled data for the dogbone specimens to sort creep deformed components from nominal variations seen in acceptable samples. The acceptability criteria for geometric variation was based on the machining drawing provided by the specimen vendor and measurements of some physical specimens. The acceptability threshold for crystallographic orientation was based on casting process controls. The creep deformation acceptability threshold was set to 2%, with training set specimens having 2% or greater creep deformation classified as unacceptable. The overall as-received length variation in the population was ±1.6%. To avoid confounding this normal length variation with creep deformation in the sorting results, specimens with creep deformation in the 1%-2% range were excluded from the training set. Specimens with creep strains less than or equal to 1% were classified as acceptable.

The VIPR pattern recognition algorithms generated multiple candidate solutions. A solution using four diagnostic resonance modes was selected for its high sorting accuracy. A VIPR plot with the Sorting Module Pass/Fail results is shown in Figure 1. This Sorting Module was used to test physical samples of both creep deformed and undeformed dogbones. The test time was around four seconds per dogbone. Test results for the measured parts showed an excellent match to the modeled sample predictions. The Sorting Module successfully rejected 100% of the unacceptable parts (with creep > 2%). The Sorting Module rejected a significant fraction of borderline parts (1 < creep < 2%). One sample with 0% creep was rejected.

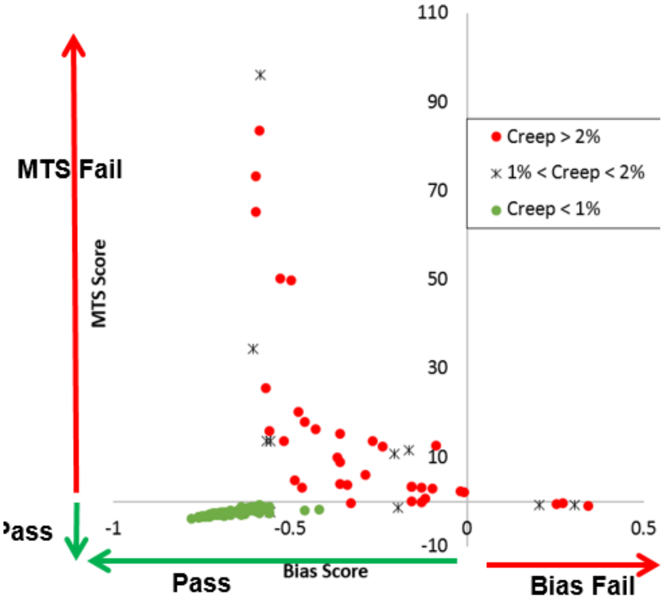

FIGURE 1: PCRT SORTING MODULE RESULTS FOR CREEP DEFORMATION

Figure 2 shows a hit/miss POD curve for this data set using the probit model, or inverse normal function (which had marginally the lowest deviation), with the defect size (expressed in % creep, gauge section) on a cartesian scale. The $a_{90/95}$ level, or reliable detection level, was computed at 2.9% creep. Additionally, a false call rate was calculated from 114 samples with creep ≤ 1 %. For this Sorting Module, the false call rate (likelihood of rejecting a sample that does not have creep) was 2.6%. This result applies to both the hit/miss and signal response analyses.

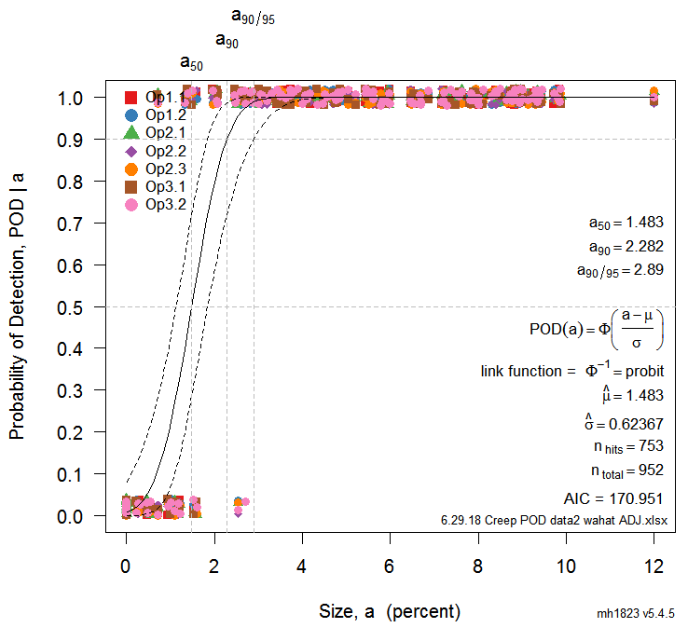

FIGURE 2: HIT/MISS POD CURVE BASED ON PROBIT [4] MODEL

The signal response analysis showed a strong linear trend between the signal response (PCRT MTS score) and the defect size (creep, in %). VIPR's MTS limit, or the $\hat{a}_{threshold}$ value, was 4.394. The $a_{90/95}$ value for the signal response POD was fit at 2.2% creep (Figure 3). The confidence bounds on the signal response POD curve were tighter than those on the hit/miss curve, as is typically expected.

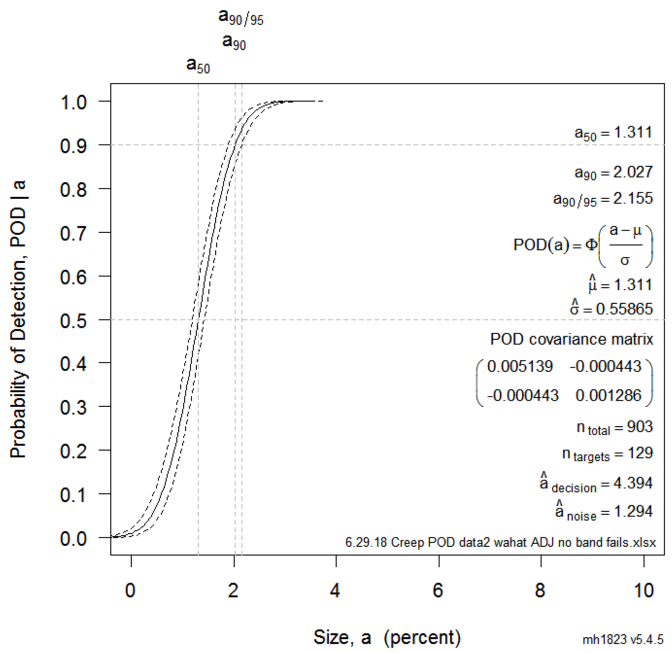

FIGURE 3: SIGNAL RESPONSE POD CURVE, BASED ON LINEAR â vs a [4] MODEL

The PCRT Sorting Module and POD for detecting creep deformation demonstrated excellent results. The $a_{90/95}$ levels of 2.9% for hit/miss and 2.2% for signal response were close to the original target threshold value of 2.0%, and false call rate of 2.6% was considered acceptable.

4. CONCLUSION

The results of the MAPOD validation demonstrated the accuracy of PCRT forward modeling of the effects of creep deformation on resonance frequencies. Furthermore, the accuracy of PCRT inspections based solely on modeled data was also demonstrated. The reliable detection levels for hit/miss and signal response POD were very close to the target value of 2.0%, and the false call rate was found to be acceptable. The MAPOD process established for PCRT inspections may be applied to a wide range of applications. A model-assisted approach that accurately simulates material states of interest and accounts for physical measurement variation significantly reduces the cost of PCRT inspection validation.

ACKNOWLEDGEMENTS

The authors are grateful to Eric Lindgren of AFRL/RXCA for his review, feedback and guidance. The authors also wish to acknowledge Chuck Annis and Floyd Spencer for their substantial contributions to the field of POD analysis. This work was supported by AFRL/RX contract FA8650-15-C-5208. This abstract has been cleared for public release under case number 88ABW-2019-1560.

REFERENCES

[1] Heffernan, J., Jauriqui, L., Biedermann, E., Mayes, A., Livings, R., Goodlet, B., and Mazdiyasni, S., "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).

[2] Heffernan, J., Biedermann, E., Mayes, A., Livings, R., Jauriqui, L., Goodlet, B., Aldrin, J.C., Mazdiyasni, S., "Detection and Quantification of Creep Strain Using Process Compensated Resonance Testing (PCRT) Sorting Modules Trained with Modeled Resonance Spectra*," 44th Annual Review of Progress in QNDE, AIP Conf. Proc*., (2018).

[3] U.S. Department of Defense, MIL-HDBK-1823A, *Nondestructive Evaluation System Reliability Assessment*, 30 April 1999

[4] Annis, C., "*Statistical best-practices for building Probability of Detection (POD) models*" R package mh1823, version 5.4.5, http://StatisticalEngineering.com/mh1823/, 2018.