Implementing PCRI, an Improved NDT Method for Structural Aluminum Castings

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ABSTRACT

Bringing a new NDT method into foundry production testing is never easy, but improving reliability of detection capabilities as well as cost reduction are compelling motivators. This paper discusses the process of cooperation between supplier and customers, by which a new NDT method, Process Compensated Resonant Inspection (PCRI), was implemented for two pairs of aluminum suspension castings–control arms and rear knuckles. The qualification of this method, including gauge R&R tests against current methods, is described, as well as the implementation plan after the testing change was approved by the customers. The results to date are presented, and the challenges yet to be met are described.

THE CHALLENGE

The casting industry faces two continuing, and to some degree conflicting challenges: 1) continuously improving customer quality performance, while 2) reducing costs. Successful casting suppliers have multi-faceted programs to address both of these challenges. Nondestructive testing is one approach to ensuring customer quality, but it tends to increase costs. In addition, recent research has shown that traditional manual inspection NDT methods have low capability of containing the types of defects that are most likely to cause field failures. Relying on human evaluation has inherent limitations in detecting certain types of anomalies impacting product performance.

One solution to this problem is improved NDT technology. However, manufacturing specifications historically tend to specify methods that do not always correlate to product performance, especially for structural components. Thus the specification may require 100% dye penetrant inspection (PT) and 100% X-ray inspection (RT) of all castings, in addition to requiring that the castings survive 5 million fatigue cycles at maximum road-load levels. So, before an improved NDT method can be deployed, it must be properly validated and verified prior to going into production.

As part of its Continuous Improvement Program, Citation's Butler Operations identified the Process Compensated Resonant Inspection method (PCRI) developed by Quasar International as offering the best opportunity to meet the enhanced quality/ reduced cost challenges. Citation recognized that an extensive engineering effort would be necessary to develop the comprehensive data required to validate and verify the NDT performance requirements; but with principal approval in hand, management decided to make the investment in order to realize the long-term benefits. Two pairs of castings (front control arms and rear knuckles) were identified and a formal project was launched to develop the NDT method through an extensive process validation.

APPLICATION

Citation-Butler produces a variety of permanent mold aluminum castings primarily for automotive applications. In 2002, two applications were identified as candidates for substituting PCRI for PT. These new programs were selected to replace PT for quality, productivity, and cost reasons. The OEM's were open to innovation due to the potential of having a more objective, quantitative and repeatable quality screen than the subjective PT method.

One application is the Control Arm shown in Fig. 1. It is an A356 permanent mold casting weighing approximately 15 lbs as cast. The other application is the rear knuckle, also an A356 casting, shown in Fig. 2. It weighs about 7 lbs. Both components are produced at a rate of approximately 700,000 pairs (left and right) per year.

Fig. 1. The cast aluminum front control arm used in the PCRI application.

Fig. 2. The cast aluminum rear knuckle used in the PCRI application.

The initial engineering specification called for 100% PT and 100% RT inspection of both parts. Previous to the validation of the PCRI system, 100% PT was performed by an outside supplier, while state of the art RT was performed on site. The cost of transportation and PT was about 4% of the cost of the parts. While there were no product performance or customer quality issues for either component, there was a general appreciation that PT is dependent on human evaluation and could not detect oxide inclusions, which are known to compromise the structural integrity of the part. PCRI on the other hand, had claimed to reliably detect the presence of structurally significant surface-breaking oxides as well as other defects such as cold shuts, cracks, hot tears, surface porosity, and surface breaking inclusions.

NDT METHODS – DYE PENETRANT (PT)

The typical surface integrity NDT method used for aluminum suspension parts, such as control arms and knuckles is PT. This project addressed substituting PCRI for PT. PT is a method of examining components to detect surface-breaking discontinuities, such as cold shuts, cracks, hot tears, and surface shrink. The technique is based on the ability of a liquid to be drawn into a "clean" surface-breaking discontinuity by capillary action.

There are several variations of PT and several good suppliers of each, but the fundamental concept is common to them all. The component to be inspected is thoroughly cleaned to remove all traces of dirt and grease. The surface of the part is coated with a penetrant liquid in which a visible or fluorescent dye is dissolved or suspended. The penetrant is pulled into surface discontinuities by capillary action. After a waiting period to ensure the dye has penetrated into the narrowest cracks, the excess penetrant is rinsed from the surface of the sample. The part is air-dried and then, using ultraviolet light, the fluorescent dye indications are identified and located, thereby defining the possible discontinuity.

There are several drawbacks to depending on PT for reliable detection of defective parts.

- Defects that do not break the surface cannot be detected
- The correlation between the visible size of the indication and the degradation in performance is very poor.
- PT relies on human evaluation and is therefore dependent on the inspector’s observation and judgment.
- PT is labor intensive and expensive. Productivity is low.

NDT METHODS - PCRI

Resonant testing sorts parts by measuring their resonant frequencies, which are explicitly determined by the parts’ stiffness and mass. The presence of a structural defect reduces the stiffness of the part and therefore reduces the part’s resonant frequencies. The change in frequency is proportional to the change in stiffness, and so to the severity of the defect. This means that a part’s resonant frequency is theoretically a predictor of its structural integrity.

There is a practical obstacle to using resonances for NDT. Acceptable process variations also affect the resonant frequency, often to the extent that they mask the effect of even a very severe defect. This masking has caused previous attempts to use resonant testing to be ineffective for all except the most severe defects. The solution is to compensate for the acceptable process variations. PCRI measures several resonances for each part and uses a pattern recognition algorithm to ***compensate*** for the acceptable process variations reducing this masking difficulty.

The real test of the utility of any NDT method should be whether it correlates to the functional acceptability of the part being tested. Unfortunately, historically this is not the case in the casting industry. Depending on the function of the part, its acceptability is determined by its visual characteristics rather than its durability under a static load or fatigue cycles. So there is insignificant correlation between NDT categorization ratings and functional performance. A major benefit of PCRI is that the correlation between performance and measured characteristics is explicit and can be measured. Figure 3 shows the correlation between the Qscore, and accelerated fatigue cycles for a cast steering knuckle. (Qscore is the parameter computed by the PCRI compensation algorithm to accept or reject a part–a positive Qscore causes rejection.) As seen, the correlation is very good, but not perfect. In particular, there is one outlier part for which the Qscore would predict a much lower fatigue life. The imperfect correlation arises because some parts (such as the outlier) have significant anomalies in areas that are not particularly stressed in the fatigue test.

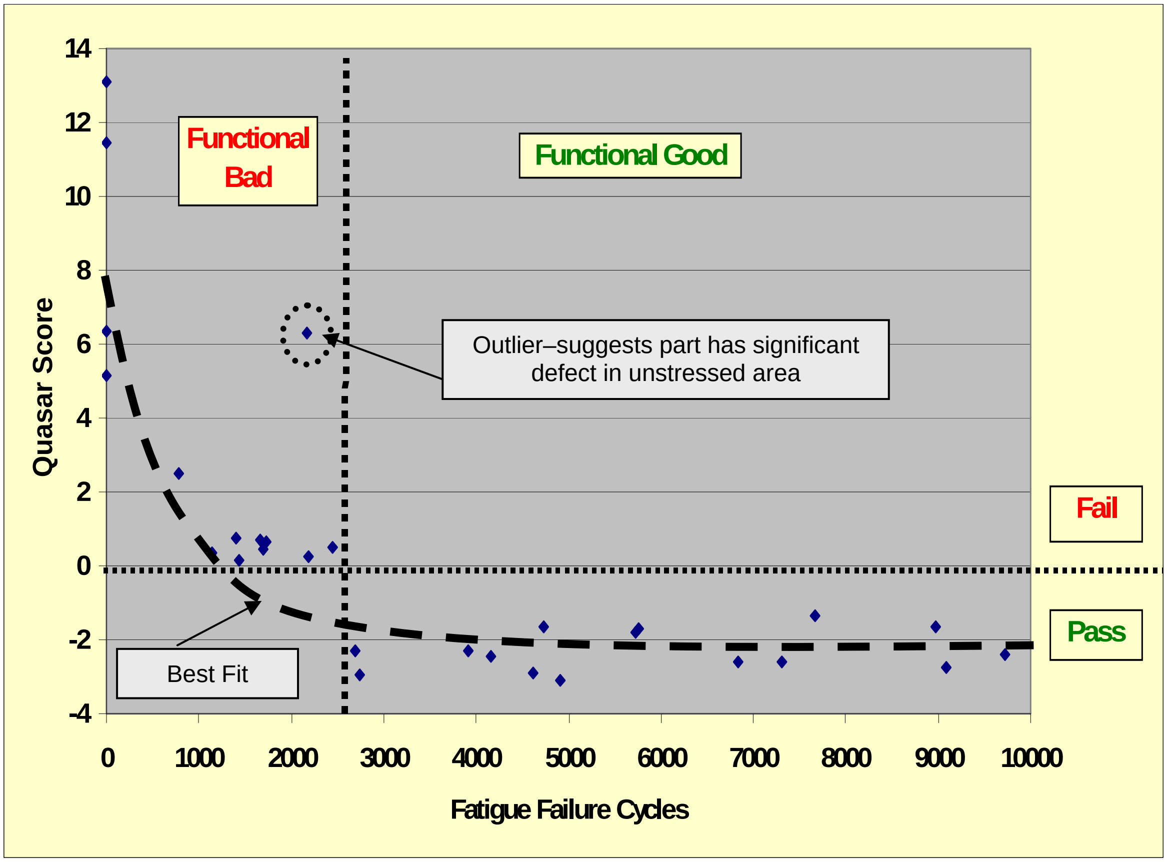


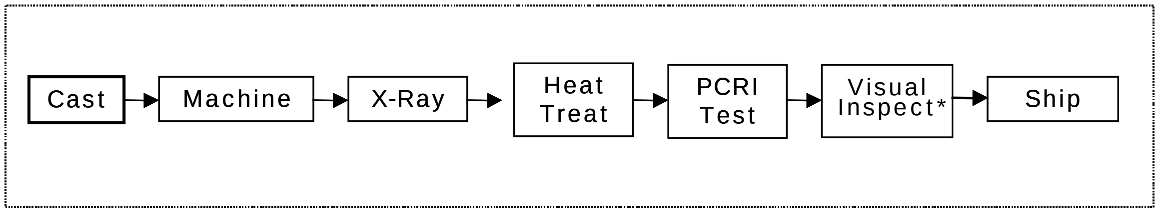
Fig. 3. The Quasar Score (Qscore) highly correlates to fatigue failure cycles.

As seen from this discussion, PCRI overcomes many of the PT limitations. It is a full body test that detects defects independent of their location. It is objective and it provides a quantitative result that is correlated to the part performance. Finally, the cost of the PCRI test is about 1/3 the cost of PT.

The most significant drawback to the PCRI method is that it is a "taught system," that is, PCRI differentiates between acceptable and defective parts based on the characteristics of the parts that it has been given as representative of these classes. This makes the proper classification of the "Training Set" of parts, the parts used to construct the reference database, a critical factor in its subsequent reliability in operation. PCRI also requires precise placement of the parts on the test station tooling, which emphasizes the importance of close co-ordination of the material handing design and programming with respect to the PCRI test station fixturing. Finally, PCRI requires that a qualified system manager, a senior technician or engineer comfortable with general computer applications as well as the PCRI configuration and maintenance, be assigned to monitor the test operation on an on-going basis in order to modify the Sorting Module as process changes occur.

SYSTEM TEST CONFIGURATIONS

The systems were procured and installed during 2002 and 2003. An engineering tradeoff was made to determine where to locate the PCRI system in the manufacturing flow. One approach was to locate the system as early in the process as possible to minimize the investment in parts that will eventually be scrapped. The other approach was to locate the system at the end of the process to minimize the process variation and capture the essential elements of the fully processed component that the PCRI must compensate, thereby improving defect detection sensitivity and product discrimination. Experience had shown that the latter approach produces better results, so the decision was to maximize the effectiveness of the system by locating the systems after heat treat. The process flow is shown in Fig. 4.



* Required to detect non-structural cosmetic surface anomalies.

Fig. 4. The production process flow diagram for the PCRI application.

The PCRI installation was customized to the size of the part and material handling considerations. The control arm installation is shown in Fig. 5.

Fig. 5. The front control arm is shown under test on the PCRI test fixture.

Mirror image configurations are used for the right and left arms. The test process is fully automated with no operator intervention required. In each case a robot unloads the control arm from a heat treat rack and places it on the PCRI test station. The test station contains tooling that precisely locates the part with respect to the transducers. This precise location is critical since the relationship between the part and the transducers has a small, but significant effect on the resonant frequency. The PCRI system measures several (typically 8) resonant frequencies and uses the computer algorithm to make the pass/fail decision. The robot then loads the passed parts onto a conveyor where it proceeds to visual inspection and shipping. Failed parts are placed into a reclaim bin. The throughput is about 132 control arm pairs per hour.

Fig. 6. A rear knuckle is shown being loaded onto the PCRI test fixture.

The knuckle installation is shown in Fig. 6. It uses a work cell approach where the PCRI test is combined with a Brinell hardness test. Parts are loaded into the cell and a carousel moves them to the Brinell test and then on to the PCRI test station. The test station is a "dual nest" configuration, which uses a single electronics package to alternately test left and right knuckles. Both knuckles are loaded and unloaded simultaneously. The throughput is again about 132 pairs per hour.

LESSONS LEARNED IN THE STARTUP PROCESS

When the systems were installed, the control arms and knuckles represented the largest parts being tested with PCRI. Therefore, the first step was an experimental effort to optimize the integration of the automation with the PCRI system. Challenges arose with both applications. For the control arm, the challenge was placing the parts precisely enough so that they settled properly into the tooling, minimizing measurement variations. Several modifications to the tooling were required and the robot programming was refined several times before a satisfactory integration was achieved.

The first step in validating the PCRI systems was development of the pass/fail algorithm. The critical issue was identification of truly "good" and "bad" parts to train the pattern recognition program. As indicated above, the PT rejects parts based on "indications" and these rejects are frequently not structurally defective. On the other hand, PCRI rejects parts that have structural degradation, whether or not there is any visible or X-ray indication. An extensive engineering effort was required to properly classify the training parts. Eventually, it was recognized that the agreement between PT and PCRI was never going to be perfect (indeed, the lack of confidence in PT was a major driver in choosing PCRI). Figure 7 shows the 3-step process used to resolve differences between PCRI and PT. Parts rejected by PCRI were then inspected using PT. If the two methods both rejected the parts, they were scrapped. If PT passed a part, it was identified for detailed engineering evaluation to determine whether it was good or bad. If the part was good, it was recognized as a new process variation that had not been captured in the Training Set. In that case, it was added to the Training Set and the PCRI sort was revised accordingly. This 3-step process was actively iterated for over a year, until all process variations were represented in the Training Set.

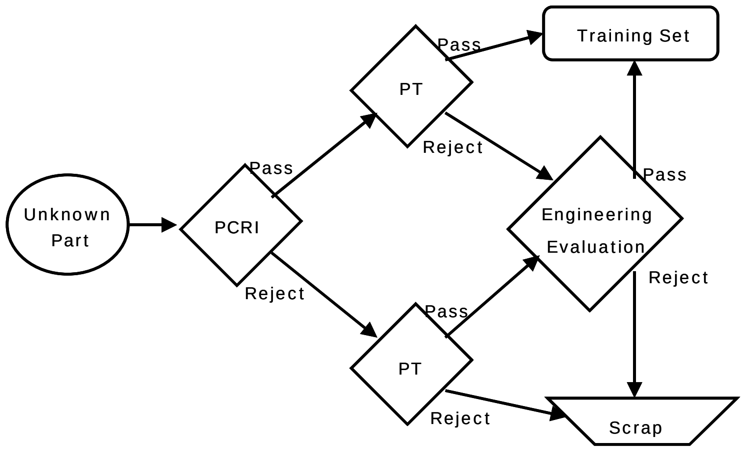
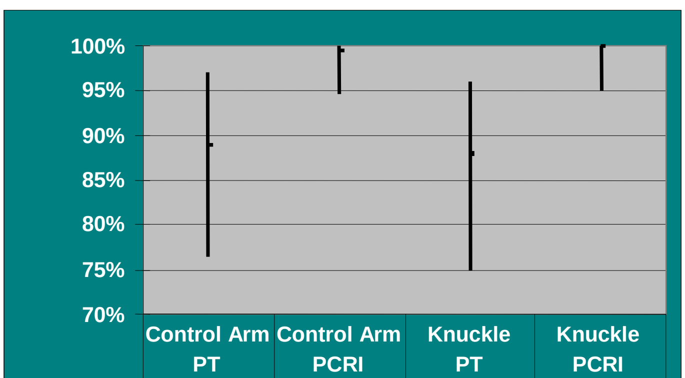


Fig. 7. This training process flow was used for resolving classification conflicts between PCRI and PT.

The most important lesson learned was that PCRI is not a "plug and play" replacement for NDT and specifically PT. It requires careful data acquisition and analysis combined with informed engineering judgment to drive the development of both the hardware and software.

EVALUATION OF RESULTS

Once the fixturing placement issues were resolved and the Sorting Module developed, the process validation to replace PT could commence. The basis for this approval was a formal Attribute GR&R (Gauge Reliability and Repeatability) experiment follow by a validation period in which a minimum of 5000 piece evaluation were concurrently tested with both PT and PCRI, with no false accepts by PCRI. The GR&R test consisted of testing 100 pairs of parts using 2 operators 3 times each. Separate tests were performed for both left and right hand versions of both the control arm and the knuckle. The results for both applications are shown in Fig. 8. The vertical axis is the percentage of correct classifications for each method during the GR&R. The vertical lines provide the upper and lower 95% confidence interval for each NDT method and part type, which is tabulated below the graphic. As seen, in both cases the PCRI test was significantly superior to PT.



	Control Arm PT	Control Arm PCRI	Knuckle PT	Knuckle PCRI
Lower 95%	77%	95%	75%	95%
Upper 95%	97%	100%	96%	100%
Proportion	89%	99%	88%	100%

Fig. 8. This was the GR&R comparison results for PCRI versus PT for the control arm and knuckle parts.

The part classification process (see Fig. 7) was expanded into an overall validation procedure as shown in Fig. 9. The validation test required successful sorting of 5,000 pairs for both the control arms and the knuckles. The dotted line feedback was added to require restarting the count for additional confidence.

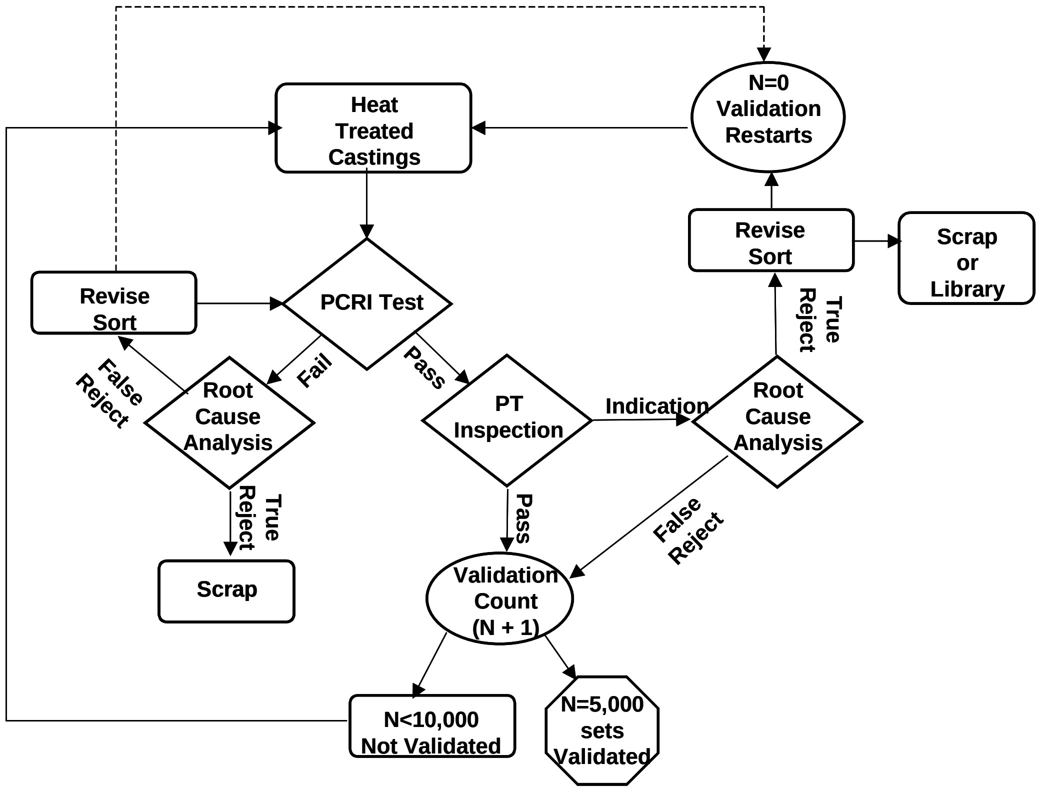
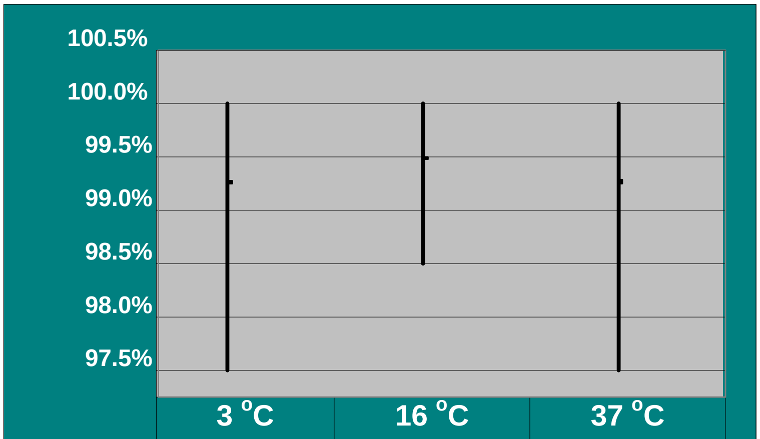


Fig. 9. This model shows the process flow for validation of the PCRI test.

Finally, GR & R tests were performed to identify any possible degradation in the PCRI performance as a function of part temperature (as resonant frequency varies with part temperature, so the temperature of each part must be measured to reference the temperature to a predetermined compensation baseline). These results are summarized in Fig. 10. While there is a slight degradation in theoretical performance as the temperature varies from the baseline at which the thermocouple is calibrated; it did not affect the sorting performance of the system. The low confidence bound is primarily due to a smaller sample set at 16 degrees C.



	3 °C	16 °C	37 °C
Lower 95%	97.5%	98.5%	97.5%
Upper 95%	100%	100%	100%
Proportion	99.3%	99.5%	99.3%

Fig. 10. The degradation of performance as a function of part temperature is nominal.

SUMMARY

The implementation of PCRI was successfully approved for production in 2004. As shown in Fig. 8, the PCRI system demonstrated a reliability of greater than 99% versus approximately 89% for PT. This means in 1000 trials, it is probable that 110 parts would be misclassified with PT, and in 1000 trials, only 10 parts would be misclassified with PCRI. Further, experience has shown that the probability of a PT false accept is independent of the severity of the defect, while PCRI reliability increases with the severity of the defect. Another benefit is a 75% reduction in NDT cost. The cost of the PT is approximately 4% of the product price while the PCRI cost is approximately 1% of the product cost.

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