

Putting the Brakes on Leakers with PCRI

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Inside This Story:

- Castings used in safety-critical applications require new approaches to assure defective components do not make it out of a metalcasting facility.
- Process compensated resonant inspection (PCRI) is one new non-destructive testing (NDT) method being utilized to assure quality.
- Detailed within is a NDT method that predicts the structural quality of a casting rather than simply scanning for indications of a defect.

A car's brakes arguably are the most critical system on the vehicle. The safety of drivers, passengers and pedestrians depend on every part of the system functioning properly. One failure can spell disaster.

Because of the safety-critical nature of the components, auto makers and their suppliers have to work to prevent defective parts from making their way into the assemblies. One critical part of the brake system is the master cylinder. If the cast aluminum component were to fail, it would open the gates for brake fluid to escape through the body of the casting, rendering the brakes useless. The component then would be considered a "leaker."

Millions of master cylinders are cast each year to meet the demands of the 15 million automobiles that are produced annually in the U.S. Even if a metalcasting facility were to achieve Six Sigma performance with respect to eliminating the problem, 3.4 leakers/million parts (50 leakers/yr.) would still be produced,

each of which represents a vehicle that requires rework at the assembly plant.

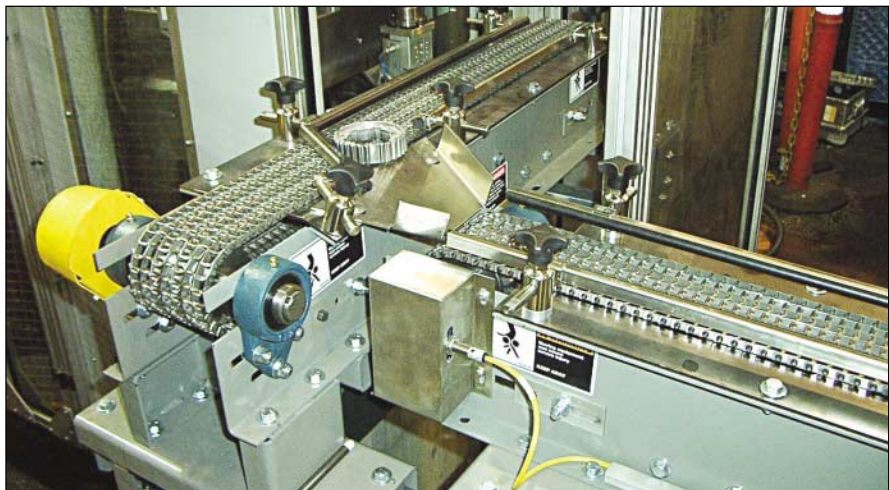
After assessing the scope of the problem, Delphi Corp., Dayton, Ohio, initiated a program to assure that the number of leakers delivered to its customers was as close to zero as possible. The firm incorporated an enhanced form of resonant inspection, process compensated resonant inspection (PCRI), to help solve its problem.

The process detects defects that significantly degrade the casting's structural integrity. This has proven more effective than scanning for indications of defects because the effect depends on a defect's size relative to the cross-sectional area. In other words, the presence of a defect may not necessarily affect the strength of the part.

This article details how Delphi used PCRI to drastically reduce the number of potential leaking castings received from its suppliers.

The Challenge

It was originally thought that leakers



PCRI scans castings by measuring the resonant frequencies because resonant frequencies are explicitly determined by the castings' stiffness and mass.

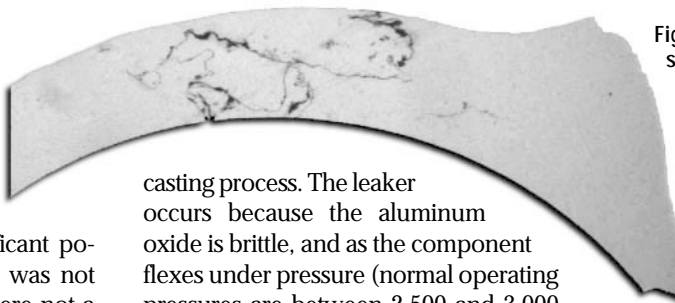
were caused by porosity defects that provided a leakage path through the body of the casting. Non-destructive testing (NDT) using both visual and x-ray inspection methods was implemented to identify and reject castings with significant porosity. The strategy, however, was not successful. The NDT results were not a reliable predictor of the hydraulic integrity of the castings, and the number of leakers detected did not decrease.

This led to extensive studies to understand the mechanics of the leak defect. These studies revealed that porosity is not the major cause of leakers. Instead, at least 90% of leakers appeared to be caused by aluminum oxide films entrapped or formed within the component during the gravity permanent mold

casting process. The leaker occurs because the aluminum oxide is brittle, and as the component flexes under pressure (normal operating pressures are between 2,500 and 3,000 psi), the oxide eventually ruptures, turning the oxide path into a leakage path (Fig. 1). Given the propensity of aluminum to form oxides, it is virtually impossible to cost-effectively control the permanent mold casting process well enough to completely eliminate the occasional leaker.

This oxide defect also explains the lack of success using visual and/or x-ray testing. Because the oxide does not

Fig. 1. Shown here is the polished surface of a master cylinder wall highlighting the oxide films that have created a leak path from the interior machined surface to the exterior surface of the casting.



break the surface of the casting, visual methods, such as fluorescent penetrant inspection (FPI), are not effective. X-ray inspection fails because most of the oxide film interfaces have an insufficient density gradient to materially affect x-ray transmission. An alternative NDT method that could detect the presence of these embedded oxide films was needed.

Resonant Inspection

Conventional NDT methods identify defective parts by scanning for indica-

Testing Safety-Critical Components with PCRI

When producing safety-critical cast metal components for the automotive industry, nothing should be left to chance. The consequences of shipping a defective casting are magnified when the component is directly responsible for ensuring automobiles are as safe as possible.

Yet, the non-destructive testing (NDT) performed on these components is typically the same as with any other casting. Citation Corp., Birmingham, Ala., knew that its Butler, Ind., facility (formerly called Bohn Aluminum), needed to have more reliable testing methods for the aluminum steering knuckles and control arms it produces via gravity permanent mold casting. The firm wanted to move away from the somewhat subjective testing of fluorescent penetrant inspection (FPI) and implement a more quantitative system.

In 2001, Citation installed process compensated resonant inspection (PCRI) with hopes that it would replace FPI.

"We were looking for the best way to make a more competitive product," said Chuck Leonard, technical director and division chief metallurgist at Citation Butler. "We wanted a less subjective method."

After training the system, Citation fully implemented PCRI as a part of its NDT process. For safety critical components, after solidification, a robot extracts the component and quenches it. The gating system and risers then are removed, and the robot presents it to a fixture where laser gauging is performed prior to being placed on an x-ray pallet. The casting then

goes through automatic defect recognition systems and is placed on a heat treat rack. Castings then are shipped off-site for heat treating. When they return, their mechanical properties are checked, and the components are sent to a post-heat treat inspection cell, which includes gauging, PCRI and visual white light inspections.

During the implementation process, Citation performed GR&R studies of 200 known good and bad castings. The results showed PCRI and white light inspection were 99.8% effective. In contrast, FPI and white light inspection were only 80% effective. In addition, the cost of PCRI was 33% of FPI.

Leonard said Citation now is studying the possibility of moving PCRI to the beginning of the inspection process and using it in place of x-ray testing.

"We have now walked away from FPI with a step down verification plan," he said. "We also noticed that PCRI could possibly replace x-ray, because in offline studies there seems to be a correlation between structural x-ray defects and what PCRI detects. We think it is possible to move it farther up in the process in place of x-ray." *MC*



At Citation, PCRI and white light inspection proved to be 99.8% effective. In contrast, FPI and white light inspection were only 80% effective. In addition, the cost of PCRI was 33% of FPI.

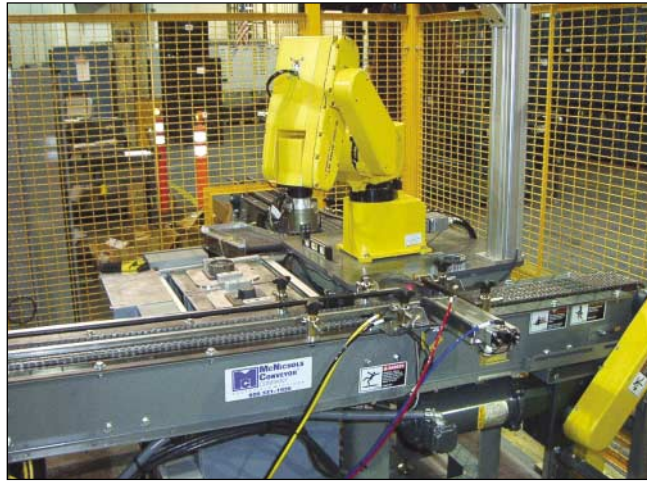


tions of a defect. The assumption is that the presence and size of the indication correlate with the presence and severity of the internal defect. The problem with this assumption is some defective castings show no indications, causing false accepts, while other operationally acceptable castings show cosmetic indications, causing false rejects. The key to predicting in-service performance is implementing a test based on the structural integrity of the entire casting rather than the presence of an indication in a particular area.

Resonant inspection (RI) does not scan castings for an indication of a defect. Instead, it sorts by measuring the components' resonant frequencies, because resonant frequencies are explicitly determined by the castings' stiffness and mass. The mass vibrates up and down at its resonant frequency, which is proportional to the stiffness (i.e., elastic constants from which material properties are derived) divided by the mass (i.e., dimensions in conjunction with density). Every casting has an infinite number of resonances, each determined by a specific combination of material properties and dimensions.

The frequency of each resonance is determined by the same parameters that determine a defective casting: the elastic constants (stiffness); dimensions; and density. Other NDT techniques measure parameters that are irrelevant to component defectiveness. For example, eddy current measures electrical impedance, which may change in the presence of a defect, but impedance itself has no relevance to the casting's function. Similarly, FPI visually surveys the surface of a casting for physical discontinuities, which do not always correlate to the presence of significant structural degradation.

The presence of an oxide film (or other defect, such as porosity or cracks) reduces the stiffness of the cast component and therefore reduces its resonant frequencies. The change in frequency is proportional



PCRI scans castings for localized, metallurgical and mechanical defects that will degrade the castings' structural integrity.

to the change in stiffness, which is proportional to the severity of the defect. This means that a component's resonant frequency is a predictor of its structural quality.

Good vs. Bad

There is a significant obstacle to using resonances for NDT, however. Changes in stiffness that shift the resonances also can be caused by acceptable process variations, sometimes to the extent that they mask the effect of a severe oxide film. Figure 2 is a histogram comparing a diagnostic frequency for a sample of 200 good and bad (defective) master cylinders.

Most of the defective castings in this sample set were caused by oxides that were created intentionally by adding foil to the melt, but the set also includes samples of normal production defects, such as porosity and cracks. The good component frequencies vary because the dimensions vary over time as the process changes. The variation in the set of good parts is relatively small because the process is in control. As a

set, the defective components have a lower average frequency and a broader distribution because they represent an out-of-control process state.

The average bad part frequency is lower because of the reduced stiffness, but a few bad castings have higher frequencies because the defect (a large shrink porosity) reduced the component's mass. The result of this overlap in the distributions of good vs. bad frequencies is that the simple resonance measurement is not a reliable basis for sorting.

The solution to this dilemma is PCRI. The method measures

several resonances for each part and uses a pattern recognition algorithm to compensate for the acceptable variations. This computation is made using the Mahalanobis Taguchi System (MTS), one of a class of Taguchi methods frequently applied to the design of robust systems. MTS is used to describe good parts in terms of the measured distributions of a set of resonant frequencies. The MTS computation then is augmented with another more powerful (but less general) mathematical tool called a linear or quadratic discriminator. This discriminator is used to differentiate between the general class of good parts and one or more specific classes of defective components.

The pattern predicts the frequency of a target resonance for each casting. The difference between the predicted and measured frequency for a component is its predictor error. Good parts have a small error; bad parts have a larger error. Figure 3 shows a calculated Accept Window based on the relatively small error computed for the good parts. Castings with errors outside the Accept Window are rejected.

The predictor error readily discriminates between the good and bad parts despite the overlap in the raw frequency measurements. A visual presentation of the technique is shown in Fig. 4, which displays the measured and predicted frequencies for each of the castings in the sample.

The first step in implementing PCRI is "train-

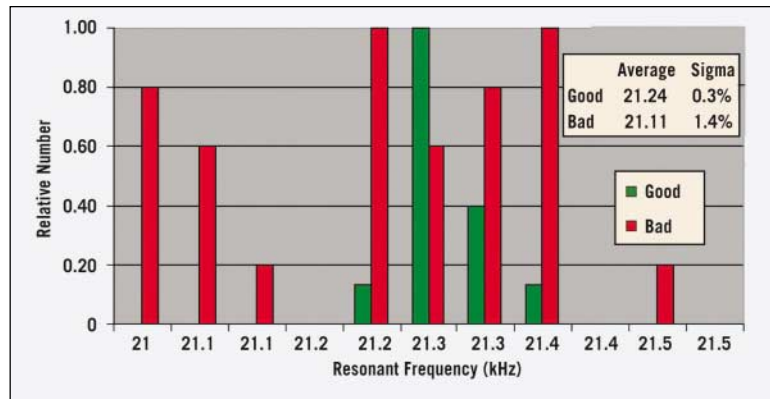


Fig. 2. Shown are the resonant frequencies of good and bad master cylinders.

ing” the system by using a qualified sample of good castings that characterize the allowable range of process variation. The system is only as good as it is taught to be, so the accurate characterization of the parts in the training set is critical. Even when the oxides are introduced intentionally, the oxide foil occasionally floats out of the component, so the part is not actually defective. Similarly, a casting that is good according to conventional NDT actually may have an undetectable oxide. There is no certain method for assuring that the casting is truly good or defective until it is machined and leak tested.

Once trained, PCRI is taught to reject castings with significant structural defects. In aluminum applications, this includes:

- localized defects—including shrink porosity, cold shuts, hot tears, inclusions, foil, cracks and runout;

- metallurgical defects—including wrong alloys, gas porosity, nodularity, hardness, carbides and other microstructure variances;
- mechanical defects—including incorrect dimensions or missed operations.

Standard of Performance

RI detects defects that significantly degrade the casting’s structural integrity, while other conventional NDT methods detect defects based on indications. This invariably leads to conflicting inspection

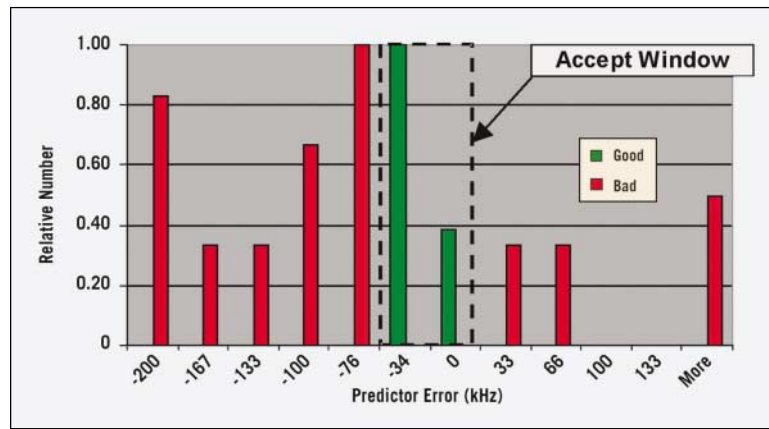


Fig. 3. Shown in this histogram is the predictor error for good and bad castings.

results and uncertainty as to which is the real NDT standard. In resolving this conflict, it is important to recognize that the effect of a defect on a casting’s stiffness and yield strength depends on the defect’s size relative to the cross-sectional area. This means that the presence of a defect, whether made evident by an indication or not, may not be correlated to the strength of the part.

For example, a 0.079-in. (2-mm) defect in a 0.79 sq.-in. (20 sq.-mm) area is more significant than the same defect in a 3.94 sq.-in. (100 sq.-mm) area. This can lead to the rejection of a casting by other NDT methods, while PCRI accepts the component. Although the defect may be visible to other NDT inspections, it is not structurally significant.

Resolution of this conflict is achieved by performing a destructive structural test, in a manner consistent with the component’s intended use, to validate the casting classification. If the part is defective, the PCRI system is doing what it was trained to do. If it is not defective, the part that was incorrectly classified is representative of a defect type and must be added to the training set.

Problem Solved

For the last year, Delphi has required that its suppliers test all master cylinders using PCRI. To date, more than 10 million master cylinder castings have been tested, and the leaker rate has been reduced from a mean of 5.5/month to less than 0.5/month when the full capability was implemented (Fig. 5). This represents a reduction from 9/million parts to 0.7/million parts, helping Delphi effectively put the brakes on leakers. *MC*

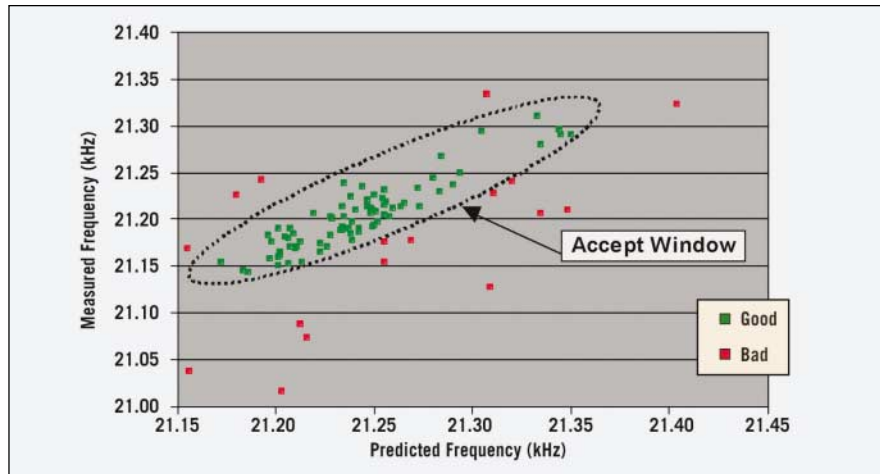


Fig. 4. The accept window shows the predicted and measured resonant frequencies of the cast components.

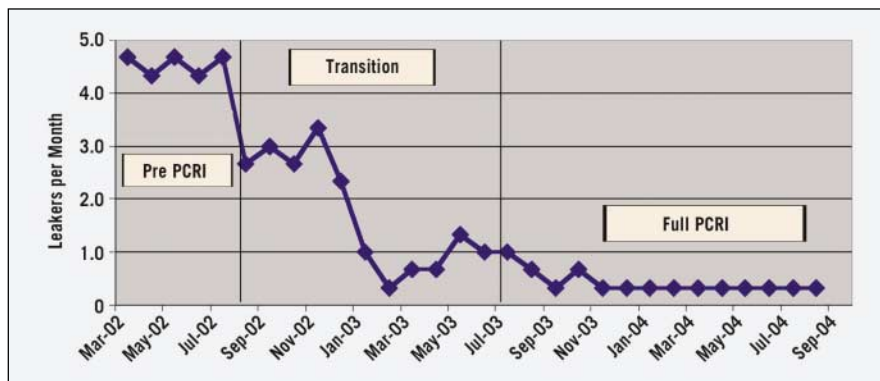


Fig. 5. After implementing PCRI, Delphi Corp. drastically reduced the number of leakers it received from its suppliers.

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For More Information

Visit www.moderncasting.com to view, “NDE Methods to Detect Oxides in Aluminum Cast Components,” J. Slater, L. Wang, R. Ludwig and D. Apelian, 2005 AFS Transactions, Paper 05-076.

“New Approach in Non-Destructive Evaluation Techniques for Automotive Castings,” T. Prucha and R. Nath, Proceedings from the 2003 SAE World Congress, Paper 2003-01-0436.