NONDESTRUCTIVE EVALUATION OF HYBRID BEARING CERAMIC ROLLERS USING PROCESS COMPENSATED RESONANT TESTING (PCRT)

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ABSTRACT. We have used Process Compensated Resonant Testing (PCRT) for studying structural integrity and functional performance of ceramic balls used in various auxiliary power units (APUs), propulsion engines, and defense and space missiles. The results show that PCRT is successful in sorting acceptable parts from parts with defects such as micro-structural changes, C-cracks, and scuffs. However, PCRT suffers from limitations, generally not determining the type, size or location of the anomaly. The pursuit of improvements to PCRT is an on-going process.

Keywords: NDE, Process Compensated Resonant Testing, PCRT, Aerospace, Ceramic Balls, Cracks, C-Cracks, Scuffs, Whole Body Inspection.

INTRODUCTION

The current NDT methods (UT, ET, RT, PT, and MT) often provide partial inspection results and require additional inspections such as focused/directed when used to inspect aerospace parts that have diverse and complex shape and geometry. For example, emerging SONIC IR has been found suitable to detect tight cracks (under compressive stress state) when traditional PT, UT, and ET methods have limited success. Similarly, it is both time-consuming and cost-prohibitive to inspect ceramic balls using ultrasonic surface waves whereas use of an alternative emerging NDT method makes it possible to inspect each ceramic ball in less than one minute. Among the several emerging NDT technologies, namely SONIC IR, Flash Thermography, Laser Shearography, Phased Array, and Process Compensated Resonant Testing (PCRT), the latter has been reported an excellent alternative to inspect ceramic balls, gas turbine engine blades, and other ceramic parts that cannot be studied otherwise [1].

PCRT is comparatively a new approach in NDT and is based on Resonant Ultrasonic Spectroscopy (RUS). RUS was developed in the late 1980s at Los Alamos National Laboratories [2]. The underlying principal is based on the physics fundamental that any hard component will resonate at specific frequencies that are a function of mass, geometry, and material properties [1-4]. In RUS, any changes in a component during manufacturing processes cause noticeable changes in the specific resonances, i.e., resonant pattern [1-3]. The analysis of the resonant frequencies in a part has been used to detect major flaws in metal components for decades; however, this approach lacks resolution for detecting small defects and the onset of fatigue [1].

PCRT has been able to overcome the above shortcomings in RUS by combining RUS with a proprietary pattern recognition software and novel algorithms. These algorithms, called Sorting Modules, are developed to compensate for normal manufacturing variations, and the novel algorithm is used for monitoring structural changes in a part over its life. Sorting Modules and novel algorithms are the basis of a PCRT system, which is rapid, accurate, and operator independent.

PCRT is a fundamental shift in NDT philosophy and applications. In contrast with the current NDT methods that strive to highlight indications that could represent structural deficiency in a component, PCRT accurately measures the structural similarity of a component to known good parts. It is also able to measure the structural changes in a single part throughout its useful life. PCRT has been used on a wide range of materials, including steel, aluminum, composites, ceramics, and superalloys; it is not limited by the size and geometry of components.

The advantages of Ceramic Hybrid bearings have been studied and acknowledged for the last 30 years. However, the use of this bearing type in the production of turbine engines and auxiliary power units has not been widely adopted. The primary impediment to production applications has stemmed from the lack of a mature NDT method. As ceramics are non-conductive, the classical eddy current methods are ineffective. FPI and visual inspection are in current use, but these methods are slow, costly, and lack robustness. In this study, PCRT was used to study ceramic balls having surface reactions layers, scuffs, and C-cracks. Unlike any other NDT methods, PCRT cannot determine type, size, or location of a defect.

As of this date, Honeywell and Vibrant have inspected more than 1000 production 0.375 inch Silicon Nitride balls. The results from several studies (including SBIR phase I and II) show that PCRT is capable of sorting good balls from balls with known anomalies. PCRT has been implemented successfully for inspecting the production balls, though improving the detection capability of PCRT is an on-going pursuit. Since surface cracks are major concerns in ceramics, the current emphasis has been on generating and using high-frequency surface acoustic waves for detecting surface and subsurface cracks, along with low-frequency for inspecting chemical reactions layer, scuffs, and other manufacturing anomalies.

METHOD AND MEASUREMENTS

The PCRT System must be configured for a given component prior to testing [5]. Typical configuration of a PCRT system is shown schematically in Figure 1. The details for the system configuration and measurements, including compensation for process variation and temperature changes, are described elsewhere [1,5]. The essential steps for developing PCRT methodology are shown in Figure 2. Figure 3 shows display of the inspection report results for a typical part.

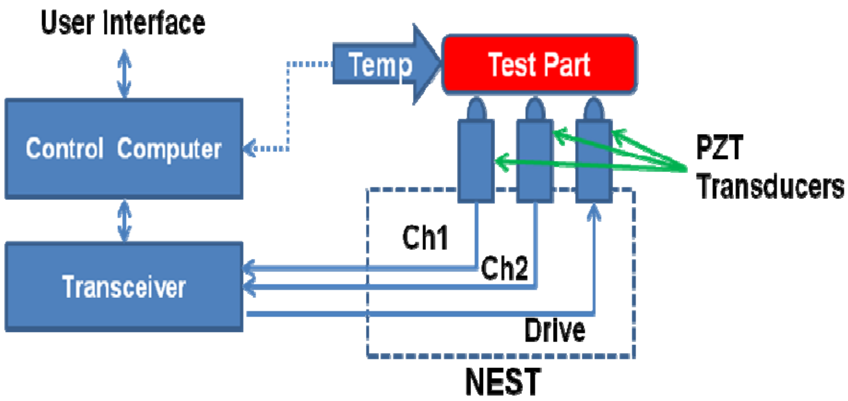

Figure 1. Typical PCRT System Schematic

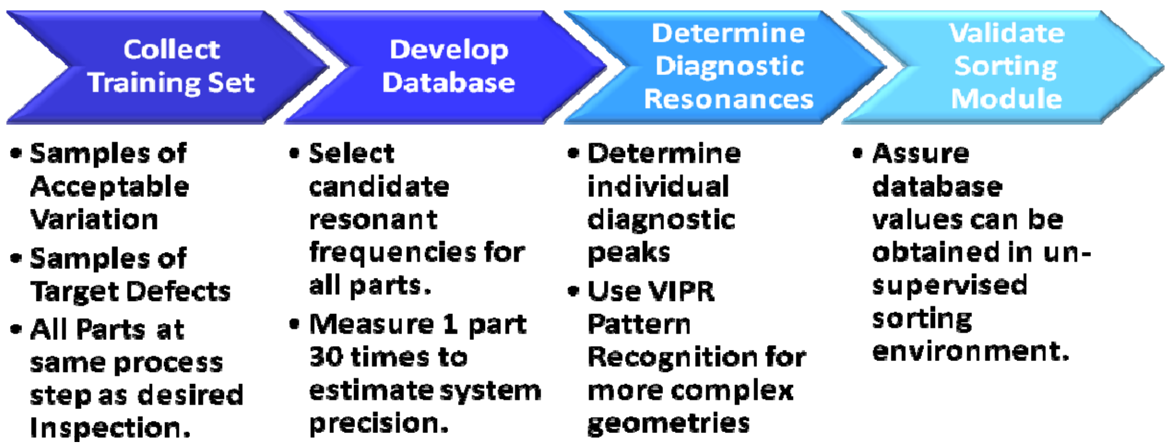

Figure 2. Typical Steps for Developing a PCRT System

PCRT System Configuration for Ceramic Balls

The setup for inspecting ceramic balls using PCRT is shown in Figure 4. Figure 5 shows the fixtures used in this study for studying ceramic balls. The use of a proper fixture significantly improves repeatability and reproducibility (Gage R & R) and Measurement System Evaluation (MSE) for the PCRT system [6].

Selection of Sweep Sine Frequencies

An understanding of a part's dominant resonant peaks in relation to its mass and geometry is important for maximizing the usefulness of PCRT. Each component has a unique range of frequencies to be studied, with larger parts generally yielding lower frequency resonances than smaller parts [1-5]. Like other conventional ultrasound methods, detection improves with frequency [7]. For the ceramic balls, small surface defects are found with relatively high frequency surface acoustic mode resonances. Thus, it is important to include these factors in designing the experiments.

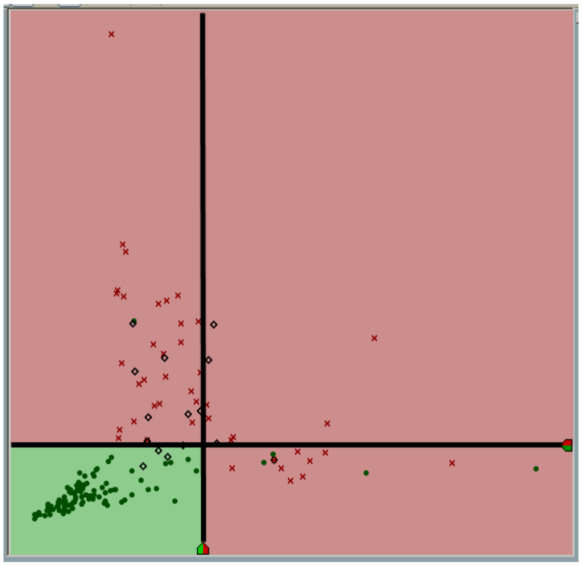

Figure 3 Graphical Representation of PCRT Inspection Report

Figure 4. Setup used in the PCRT study of ceramic balls.

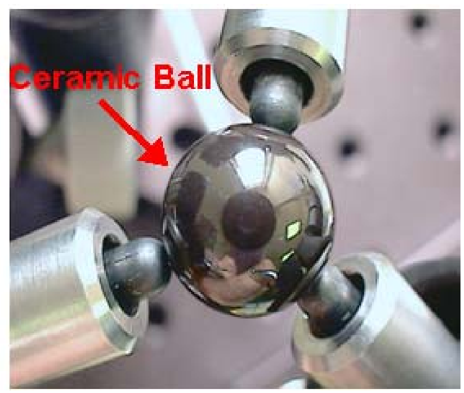

Figure 5. Nest Designs

RESULTS AND DISCUSSIONS

Samples with known anomalies such as reaction layers, scuffs, and C-cracks were used to study the effect of various anomalies (see Figures 6 through 8).

Results from early studies show that relatively low frequency resonances (first 10-15 modes) for the ceramic balls proved capable of detecting a number of whole body and surface anomalies including microstructure differences, surface chemistry/reaction layer defects, metallic inclusions, density variation, and heat treat variation.

Figure 6 shows some of the microstructure defects (also referred to as 'Reaction Layer Defects') in balls that had 'differences' visible even without a microscope. The effect of these reaction layers on the spectra was apparent (see Figure 9). The shift due to the 'clouding' type of defect marked "A" in Figure 6 was 0.7 percent (3-10 times the variation seen within a common population of balls). Similarly, the equatorial defect marked as B in Figure 6 caused almost a two percent shift (Figure 9).

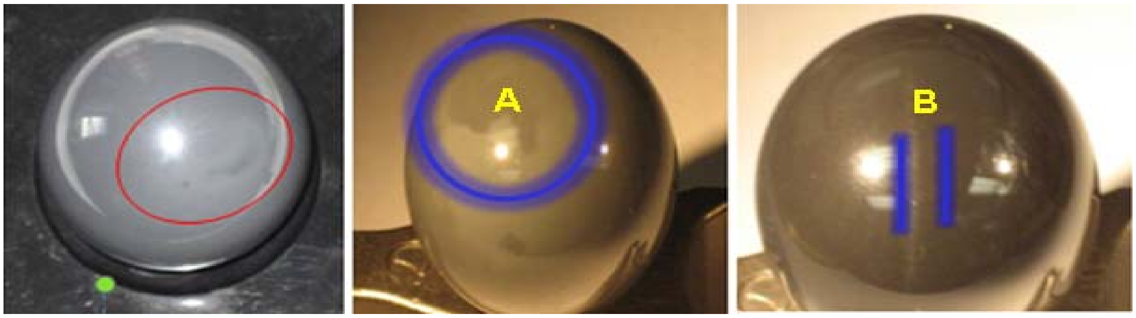

Figure 6. "Reaction Layer" Defects

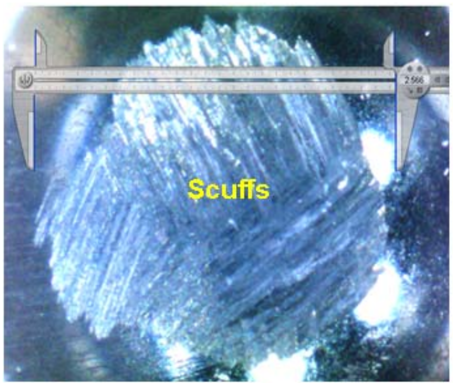

Figure 7. Scuffs on Ceramic Ball

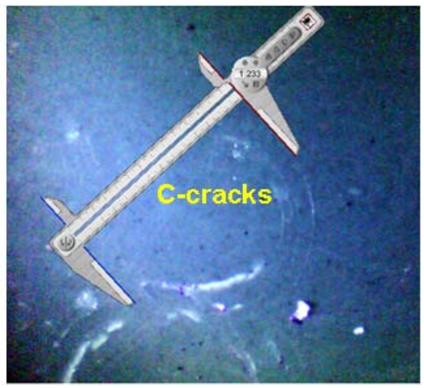

Figure 8. C-cracks on Ceramic Ball

In addition, low-frequency resonances also were found capable of detecting significant surface scuffs and gouges (Figure 7); though the scuffs caused significant split in frequency instead of frequency shift (Figures 10, 11). For repeated measurements, it was found that PCRT sorting methods could reliably detect a scuff or gouge representing about a 0.02 percent volume effect, and/or about a one percent effect on the surface area. Figure 11 further shows that the magnitude of frequency split increased linearly with the scuffed area when this area increased from 0.007 square inch to approximately 0.023 square inch. This is in agreement with results reported earlier and also with internal works within Honeywell [6].

Surface C-cracks

C-cracks are often present in ceramics due to ball-to-ball contact during manufacturing. In order to study the use of PCRT for detecting surface cracks in ceramic balls, C-cracks were produced in 1.125 inch ball (Figure 8). Both low-frequency (0.520 MHz) and high-frequency (2.15 MHz) modes were used to study the comparative detection capability of PCRT in 1.125 inch balls. The results from this study show that high-frequency 2.15 MHz was more effective than the low-frequency 0.520 MHz in detecting surface C-cracks (Figure 12). This finding is in agreement with the conventional ultrasound wherein detectability improved with increase in frequency and vice-versa [7].

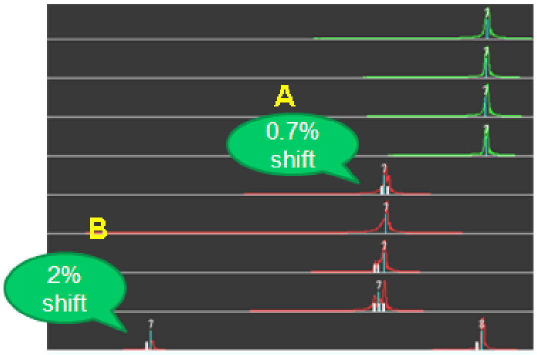

Figure 9. Frequency as a result of reaction layers

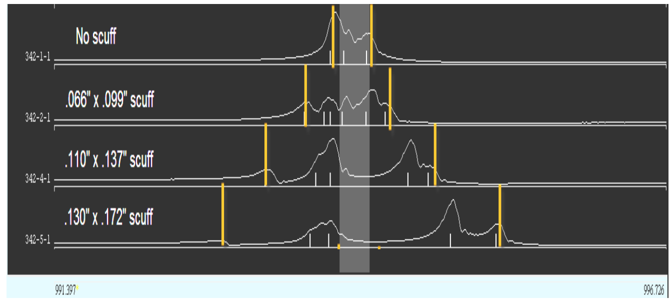

Figure 10. Split size vs. scuffed area

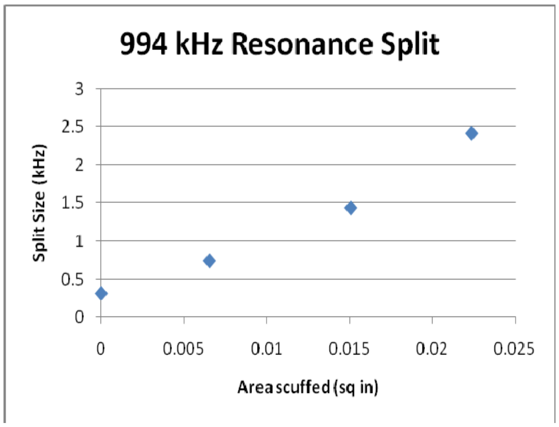

Figure 11. Graphical presentation for split size vs. scuffed area

A similar trend was also observed wherein high-frequency (8.025 MHz) was found more suited than the low-frequency in detecting C-cracks in half-inch ceramic balls (Figure 13). Five resonances were evaluated, from 3500 kHz to 8175 kHz. The right screen in Figure 13 shows that 8.025 MHz was able to show some additional peaks after the half-inch ball was impacted. This warrants the need to extend the frequency range to higher than 10 MHz for detecting small cracks. This is a goal of current and future works.

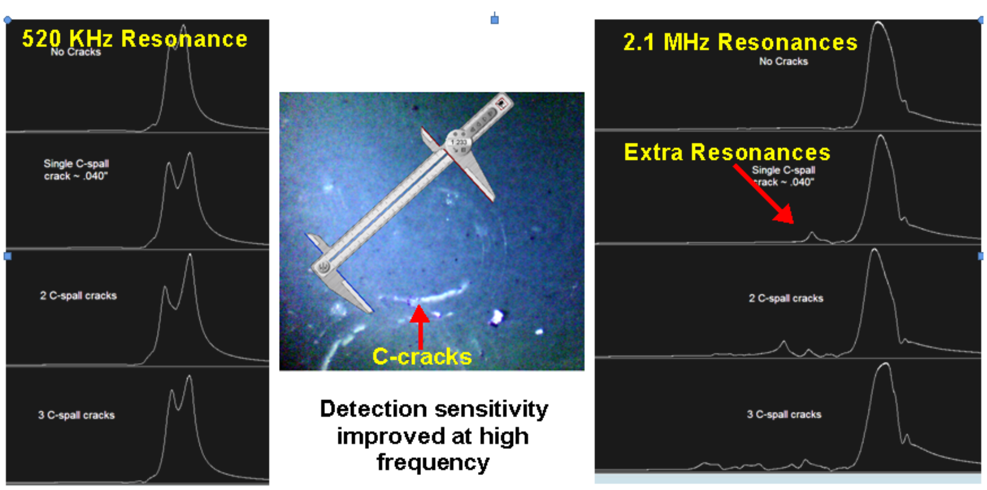

Figure 12. Demonstrating the enhanced detection sensitivity at high frequency 2.1 MHz

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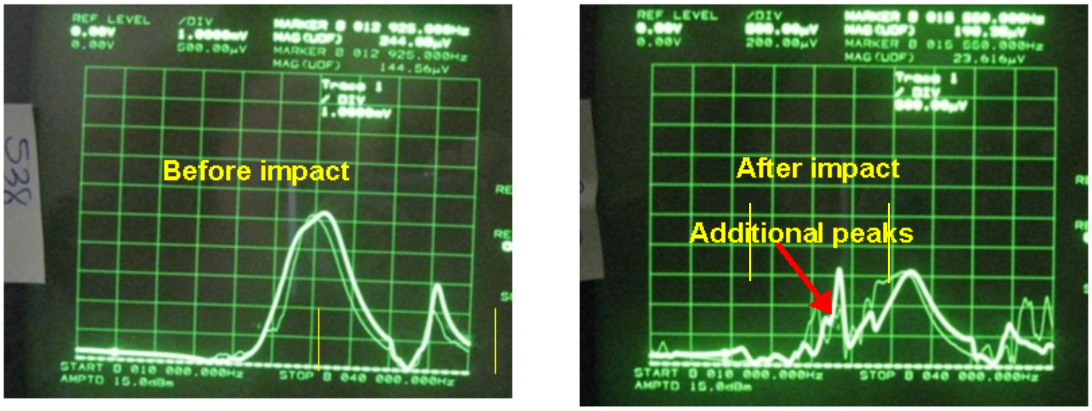

Figure 13. Before (left) and After (right) resonance at 8.025 MHz for half-inch balls with C-spalls (from impact with half-inch ball)

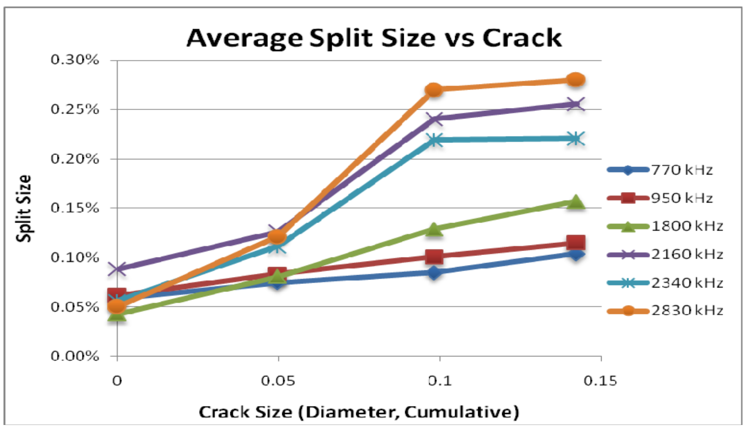

Figure 14. Correlation between split and crack size for 1.125 inch ceramic ball.

These data were further plotted (see Figure 14) using normalized split size resolution (normalized split size, i.e., percentage of the ratio of split to resonant peak) versus C-crack size. Figure 14 shows that the normalized split resolution increased with frequency, in particular when detecting C-crack size smaller than 0.050 inch. For example, for a PCRT system to have discernible resolution, resonance frequency should be equal to or higher than 2.16 MHz for 1.125 inch ball. Alternatively, split size percentage should be higher than the system precision, which is close to 0.07 - 0.08 percent.

SUMMARY AND CONCLUSIONS

A growing need for the use of modern NDT in aerospace has led Honeywell and Vibrant to enhance Process Compensated Resonance Testing. The results from this study show that:

1. The PCRT technology offers both volumetric and surface inspections at low-frequency and high-frequency, respectively.

2. The current PCRT system is capable of sorting ceramic balls with reaction layers, scuffs, and C-cracks from good balls.
3. This study further demonstrates that high-frequency resonances provide better detection capability for detecting surface C-cracks than the low-frequency resonances.
4. An improved C-crack detectability at high-frequency is attributed to small wavelength; similar to observed in conventional surface acoustic waves (SAWs).
5. This study also demonstrates that in general small-sized components require higher-frequency sweeping sine waves than the large-sized parts and vice-versa.
6. PCRT can be used for process control such as batch-to-batch variations as well as recording the digital signature in a part over its entire life.
7. Application of PCRT is not limited to a particular material type and can be used for any size and geometry, although it has some limitations. For example, it cannot specify the type and location of a defect in a part.

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