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CORRELATION OF QUASAR RESONANT INSPECTION MEASUREMENTS WITH YIELD FORCE IN POWDER METAL PARTS

Robert Nath, James Schwarz, M. Kimber Johnson,
James Long, and Jay Saxton

Quasar International, Inc.
5550 Midway Park Place
Albuquerque, New Mexico 87109
Telephone: 505.247.9660 email: info@quasarintl.com

ABSTRACT

The purpose of Nondestructive Test (NDT) is to identify and reject defective parts, that is, parts that would fail prematurely in service. To reliably meet this purpose any NDT test's resulting measurement must be closely correlated to some property that predicts performance. Generally, a structural part is considered to have failed when it yields or breaks, so Yield Force is the appropriate measurement (usually normalized to Yield Strength for material mechanical properties measurements) for this class of parts. Therefore, the necessary test of the validity of any NDT method on structural parts is an experiment demonstrating that the results of the test are strongly and positively correlated with the tested part's actual Yield Force. This paper describes an experiment conducted on Powder Metal (PM) parts that were intentionally cut to reduce the cross-sectional area of the part, and then tested individually using the Quasar resonance NDT method. The parts were then mechanically tested to failure and the Yield Force (force required to cause the part to fail mechanically) measured for each. A high correlation was observed between the predicted and the measured structural qualities of the parts, and an equation was developed to predict Yield Force from the Vibrational Pattern Recognition (VIPR) score. (The VIPR software is a proprietary pattern recognition program developed to separate structurally defective parts from good, normally varying production parts.) The result validates this NDT method as a predictor of in-service performance of PM parts.

INTRODUCTION

Powder Metal parts manufactured for automotive applications demand high levels of structural integrity to eliminate costly field failures. Here "structural integrity" is defined as the ability of the parts to perform as designed and not fail in assembly or in subsequent vehicle service. Where effective manufacturing process controls are in place, low prevalence of defects is expected at the outset. But even in a well controlled high volume production process, a 100% inspection regimen is required to detect and discard those few statistically inevitable defective parts in order to achieve the near zero parts per million defects demanded by the application.

The nature of the PM process requires that the NDT method used must be capable of reliably classifying parts at production test rates, and that the results of the NDT tests have a high correlation with the actual performance of the part in service. Generally, a reasonable proxy for structural integrity of PM parts is Yield Force. The part chosen for this series of experiments was a flange that is stressed when bolted in place. The most frequent failure mode for this part is yielding or breaking during assembly when the attachment bolts are torqued.

The nature and source of the failure mode, notably fatigue failure, warrants some consideration. We do not make the global assertion here that an NDT method that correlates with Yield Force *always* provides a correlation with performance in the vehicle. This depends on the function of the part and the design factors (previously called safety factors) used. We can observe that many PM part designs have a large design factor that prevents a part from being stressed even close to the Yield point in normal operation, and thus a condition is not created in the crack, inclusion or other stress riser that grows into a more serious discontinuity causing eventual failure.

What is the significance if a Yield Force test for PM parts with small but visible surface cracks results in a failure force that is within normal variation of the failure force of parts with no visible cracks? We recognize the differences in failure modes from fatigue and those failures more related to fracture toughness and we do not assert that the Yield Force is always highly correlated with fatigue life. There is no simple answer to the question posed above, but our sense of the overall data, e.g., fatigue curves and proprietary fatigue tests reviewed by the authors, suggest the relatively greater importance of fracture toughness, rather than fatigue resistance, in the performance of PM parts in most vehicle applications. The test results reported in this paper are, therefore, highly applicable to PM parts' structural integrity during installation and operation.

TEST DESIGN

In order to assess the correlation of the subject NDT method to Yield Force, a test was designed in which a set of nominally good parts would be selected and a sub-set of these parts cut to varying degrees to simulate cracks. Then, all parts would be tested by resonance-based NDT and the measurements recorded. The parts would then be individually destructively tested while measuring the Yield Force for each. Then the NDT test measurements' numerical values and the Yield Force values would be compared. High correlation between the NDT measurements and the Yield Force would confirm the validity of the NDT method, while a low correlation would indicate that the NDT was not predictive, and therefore not effective.

Theory suggests that the Yield Force should follow a quadratic relationship with respect to the cut depth:

$$\mathbf{F \propto 1/d^2}$$

where F is the Yield Force and d is the depth.

This occurs because the bending strength depends on the moment of inertia about the neutral axis, which is proportional to the square of the depth (thickness). Therefore, we would expect to see this quadratic relationship between the cut depth and the Yield Force measurements experimentally verified. In addition, for a valid NDT method, we would expect to see this same quadratic relationship between the quantitative NDT measurement and the Yield Force.

Although theoretically preferred, naturally occurring cracks cannot be used for this type of controlled experiment for practical reasons. First, it is impossible to precisely and accurately assess or measure a natural crack's depth, length, width, area, etc. But more significantly, crack indication dimensions do not necessarily reflect the degree of structural weakening actually suffered by the part. Previous studies by the authors using Process Compensated Resonant Inspection have shown the ability to correlate resonance measurements with the measured breaking force on P/M pulse timing rings, but these cracks were made by stressing normal green compacts in various controlled displacements. The rings were then sintered. No crack "size" measurements were possible. A naturally occurring crack's root cause is often some process failure that creates localized density or material differences. The crack is often only direct visual evidence of that localized stressed volume. That is, the crack indication is the effect, not the cause of the weakness. On the other hand, cutting to remove a known amount of material and decrease the intact thickness of a part provides the basis for controlled and repeatable failure data. The cut does not, however, reproduce the larger volume of stress-induced metallurgical weakness that occur naturally in defective parts, so it has to be much larger than the equivalent natural crack.

It should be noted that it is essential that the resonant analysis technique used to correlate with the extent of local damage compensate for production variation, which can mask the differences caused by the sawing and overwhelm the differences in any given single resonance. The VIPR (Vibrational Pattern Recognition) program accomplishes this by using multiple diagnostic resonances to determine resonance patterns that can differentiate between production variation and defects.

PROCEDURE

Figure 1. Typical production Resonant Inspection system.

A representative group of 23 pre-inspected powder metal flanges were randomly selected to perform this experiment. The samples were taken from a wide range of powder batches and sintering batches, thus assuring normal production variation in the sample set. Three sets of 5 flanges each were then degraded by sawing them partially through in fixed depth increments for each set using a horizontal band saw. Eight baseline parts were left completely intact to provide the "good" parts needed to derive the VIPR pattern.

All resonance data were taken using a Quasar QRI-2000 desktop Resonant Inspection system (Figure 1 shows a typical production test system of this type). The system mechanically resonates a part using piezoelectric transducers over a given frequency range. Two other transducers measure the part's mechanical resonances within this range. These data are input into the VIPR software as

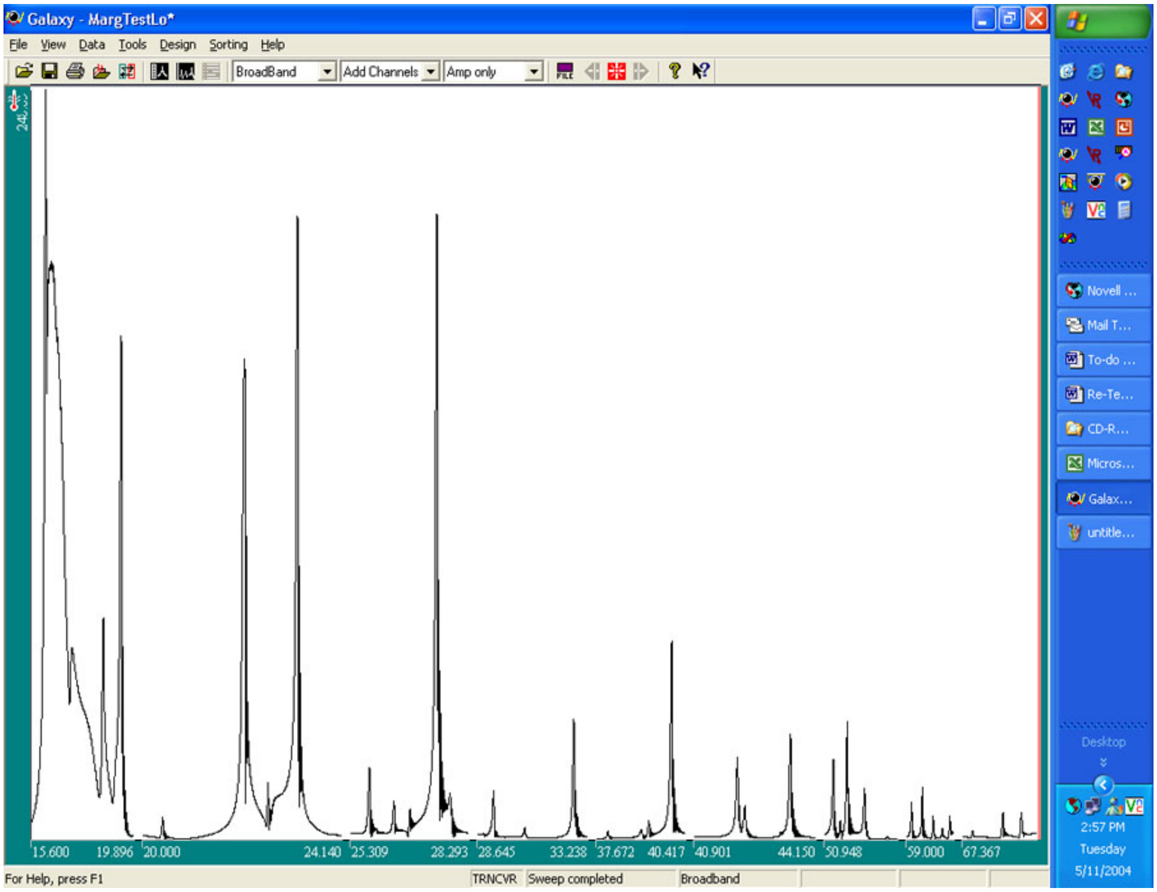

Figure 2. **A broadband resonance spectrum from which VIPR selects diagnostic resonances for pattern recognition scoring.**

either "good" or "bad" part data. VIPR then selects the best resonant pattern to separate the good from the bad parts, and scores each bad part as to degree of deviation from the good. Figure 2 shows the "Broadband" display of resonances from which VIPR selects certain diagnostic resonances to create pattern recognition scores.

Figures 3 and 4 show sample PM clamp flanges cut to the various depths. The cut is not perfectly horizontal across the flange since a pivoting horizontal band saw was used, but the amount of material removed was the same for each flange in a given group. The saw cut depth was limited with gauge blocks so that each series of cuts was to the same depth.

Figure 3. **Three different cut depths used in the measurements increasing from left to right.**

Before each clamp flange was stressed, its resonant frequencies were measured over a broad range and VIPR was used to determine a sorting pattern between the uncut (good) and cut (bad) clamp flanges using multiple resonances.

Figure 5 shows a clamp flange still in the fixture. The vertical cross bar at the end of the hydraulic cylinder spanned the flange and rested on the mounting boss (far right as shown in Figure 4). Force was increasingly applied until the boss either bent with no increase in force up to 20° (analogous to ultimate tensile strength) or until the flange fractured. The force and corresponding VIPR scores were recorded for each flange.

Figure 4. The same parts as shown in Figure 3, but stacked to show the relative depths.

RESULTS

The results of these tests, shown in Figures 6 and 7, confirm two important relationships.

1) An almost perfect correlation exists between the VIPR score and the actual yield/breaking strength of the material (see Figure 6).

2) Both the VIPR score and the measured Yield Force versus cut depth followed the theoretical (quadratic) prediction (see Figure 7).

Figure 5. Test fixture for measuring Yield Force (bent clamp flange shown).

The essentially perfect correlation between the predicted and the destructively measured parameters shown in Figure 6, means that the VIPR score is predictive of the Yield Force. For this fixturing, the relationship derived can be expressed as:

$$\mathbf{YF = -6.58V + 424.4}$$

Where YF is the Yield Force and V is the VIPR score. The ability to predict the failure force is the objective of any NDT measurement and Yielding is considered failure for this flange.

Note that the calculated Pearson correlation of 99.8% is exceptionally high, further validating the Resonant Pattern method for detecting significant structural defects. Also note that the difference between the first and second cut VIPR scores is separable within the error bounds, even though the difference in the Yield Force is not significantly different as demonstrated by the overlapping error bars (approximately 6% different). (Yield Force error was set at ± one half the maximum deviation of the Yield Strength for a given cut depth set and the VIPR score error is similarly ± one half of the maximum deviation of each of the parts in the part set.) This is a clear demonstration that the VIPR score provides a direct measure of structural strength.

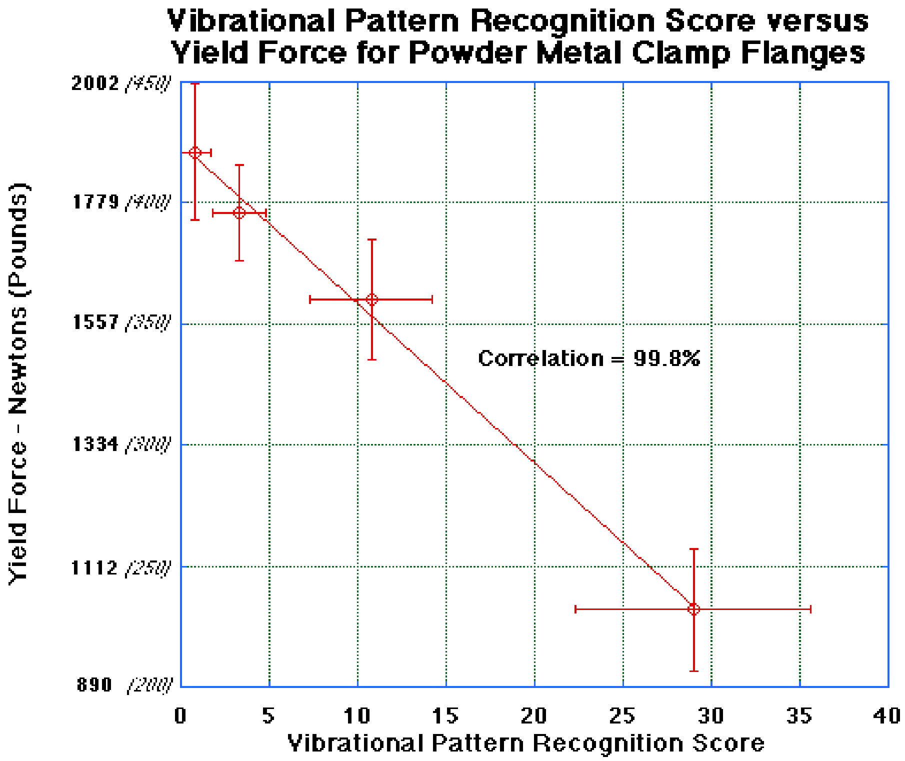

Figure 6. **A nearly perfect correlation between the Quasar score and Yield Force.**

Figure 7 shows the Yield Force and the VIPR scores as a function of the cut depth. Note, once again, the nearly perfect quadratic curve fit correlations, as predicted by theory. This again demonstrates that the VIPR results correlate well to actual part strength. The theoretical prediction is demonstrated experimentally, and the fundamental physical relationship between the VIPR scores and actual structural condition is confirmed.

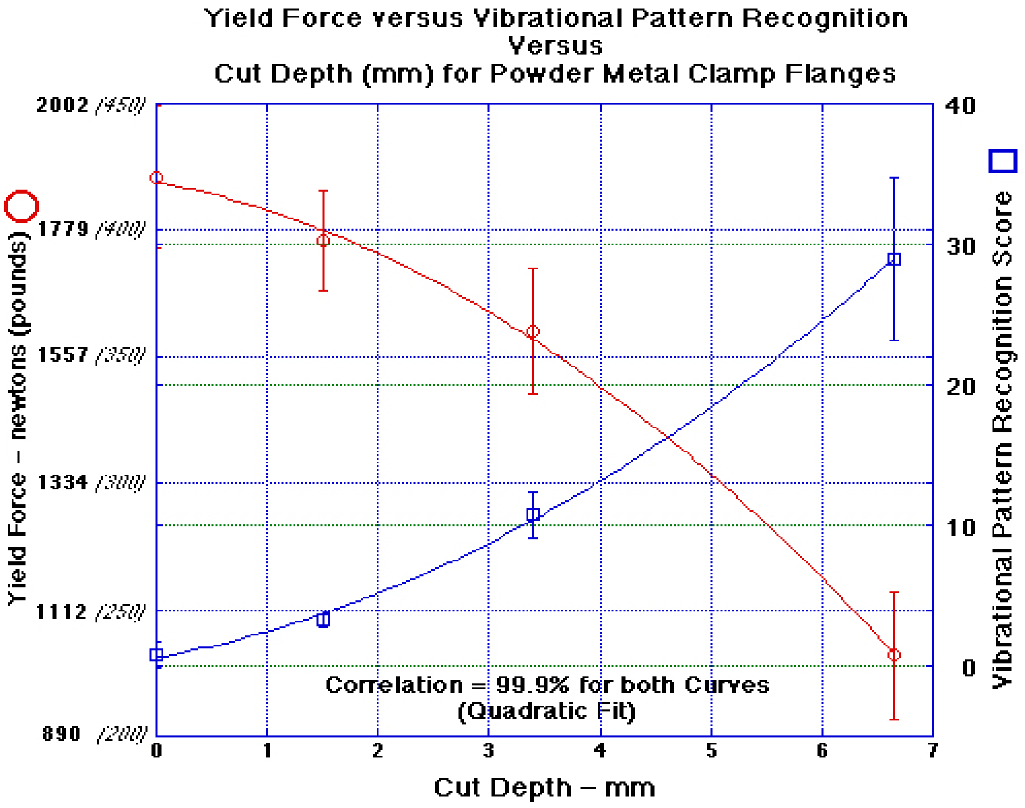

Figure 7. **An overlay of Yield Force and Quasar score versus cut depth showing the high correlation used to associate Quasar scores with the real physics of determining part strength.**

CONCLUSION

The VIPR scores reliably predict structural performance of Powder Metal parts in service. These scores correlate almost perfectly for both measured and theoretical Yield Force predictions for actual automotive powder metal parts. This shows that the VIPR scores a direct predictor of failure level. This, combined with the VIPR score's ability to separate small differences in parts' strength within margins narrower than acceptable manufacturing differences, makes it ideal for detecting structural flaws that can lead to catastrophic failure in low cycle automotive parts.