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RESONANT INSPECTION AS AN AUTOMATED NDT METHOD FOR SINTER BRAZED POWDER METAL COMPONENTS

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ABSTRACT

With continued growth of powder metal components in the vehicle, particularly within the power train, the requirement for defect free manufacturing has driven suppliers to seek out cost effective methods of 100% inspection. To achieve zero defect ("Zero PPM") output cost-effectively, manufacturers are making the commitment to move to online, automated nondestructive testing (NDT) methods. This type of online inspection requires accuracy, reliability, and high throughput. Resonant Inspection is emerging as a very efficient method of structural defect discrimination and lends itself very well to 100% inspection of powder metal components. This paper will present the fundamental principles of the resonant acoustic method (RAM NDT), on a structural basis, followed with RAM NDT applied to a variety of sinter braze integrity inspection applications.

INTRODUCTION

Many industries, especially automotive, are rapidly converting from machined metal component parts to powder metal. Powder metallurgy, or PM, is the process of forming metal components by mixing elemental or metal alloy powders, die pressing at high force levels, and heating at temperatures just below the melting points of the particulate materials. This heating process, called sintering, takes place in a controlled-atmosphere furnace, and bonds the particulate materials metallurgically. Over recent years, the PM process has shown to be a superior technique for manufacturing high quality parts compared to forging or metal casting. Advantages include material utilization, shape complexity and dimensional control, all yielding lower costs and greater flexibility.

Due to the high expectations of both primary manufacturers and end consumers, shipping parts with defects cannot be tolerated, even when shipping in million piece quantities. With a growing requirement for zero defect output, manufacturers are implementing automated NDT methods such as the Resonant Acoustic Method for assuring reliable 100% inspection. Utilizing structural dynamics and statistical variation, RAM NDT provides mature, proven technology in a robust, economical, process-friendly manner.

COMPARISON OF RAM NDT WITH TRADITIONAL TECHNIQUES

RAM NDT is a volumetric resonant inspection technique that measures the structural integrity of each part to detect defects on a component level. This technique is easily automated to eliminate human errors with fast throughput, providing cost effective 100% inspection with minimal disruption to production. With a large number of successes on the production lines of powder metal and cast parts, RAM NDT is the simple and effective solution to manufacturers' zero PPM challenge.

Traditional NDT techniques, for example magnetic particle testing, focus on detecting and diagnosing defects. They use visual or imaging techniques that scan for indications of specific defects. For production line quality inspection, identifying the type of defect itself is secondary to identifying the defective parts. While diagnosing specific defects is applicable when evaluating and inspecting some systems, such as using ultrasonics to inspect gas pipelines, it is not appropriate for high volume 100% inspection of manufactured metal parts. For these production lines it is of primary importance to detect *if* a part is non-conforming rather than *why*. Therefore, an end-of-line “go/no go” objective inspection, such as by RAM NDT, is preferred here to a subjective diagnosis, perhaps useful in defect root cause analysis.

Resonant inspection (RI), the general classification of RAM NDT, measures the structural response of a part and evaluates it against the statistical variation from a control set of good parts to screen defects. Its volumetric approach tests the whole part, both for external and internal structural flaws or deviations, providing objective and quantitative results. This structural response is a unique and measurable signature, defined by a component’s mechanical resonances. These resonances are a function of part geometry and material properties and are the basis for RI techniques. By measuring the resonances of a part, one determines the structural characteristics of that part in a single test. Typical flaws and defects that can adverse affect the structural characteristics of a part are given in Table 1 for powdered metal, cast and forged applications. Many of the traditional NDT techniques can detect these flaws as well, but often only RI can detect all in a single test, throughout the entire part (including deep sub-surface defects), in an automated and objective fashion.

Table 1. Typical structural defects commonly detectable by resonant inspection technique for powder metal, cast and forged processes

Powder Metal	Cast	Forged
Cracks	Cracks	Cracks
Chips	Cold shuts	Double strikes
Voids	Nodularity	Porosity
Hardness	Porosity	Hardness
Inclusions	Hardness	Inclusions
Heat treatment	Inclusions	Heat treatment
Decarb	Heat treatment	Quenching
Oxides	Stresses	Laps
Contaminants	Contaminants	Contaminants
Missed ops	Missed ops	Missed ops

After defective parts have been sorted with RI, complimentary traditional NDT techniques may provide a means for subjective diagnosis on the smaller subset of “rejected” parts. This is useful for determining a defect’s root cause and ultimately improving the production processes. The ASME has published standards that detail each of the traditional NDT methodologies.

FUNDAMENTALS OF RAM NDT

All structures have mechanical resonances. A resonance occurs when a structure, due to its natural, structural properties, amplifies energy imparted to it at certain frequencies. The structure itself acts like a speaker, deforming in a certain, specific pattern and radiating acoustic energy. For example, tuning forks or bells will vibrate at very specific frequencies, their natural frequencies, for long periods of time with just a small tap. The sound that is made is directly due to these natural frequencies. In fact, any noise generated by a structure is done so by vibration, which is simply a pattern of summed sinusoidal deformations. The Resonant Acoustic Method of Nondestructive Testing (RAM NDT) utilizes this structural dynamic behavior to evaluate the integrity and consistency of parts.

For illustrative purposes, consider the single degree-of-freedom (SDOF) mass, spring, damper system model in Figure 1. It has one DOF because its state can be determined by one quantity (*x*), the displacement of the mass. The elements of this simplified model are the mass (*m*), stiffness (*k*) and damping (*c*). The energy imparted into the system by the excitation force (*f*) is stored in the system as kinetic energy of the mass and potential energy of the spring and is dissipated by the damping. The mathematical representation of the SDOF system, which is called its equations of motion, is given in Equation (1) below.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \tag{1}$$

The solution to the equation of motion produces an eigenvalue problem which yields the undamped natural frequency, see reference [1], as:

$$\text{⌖}_n = \sqrt{\frac{k}{m}} \tag{2}$$

Equation (2) reveals the natural frequencies, or resonances, of a system that are determined by its mass (i.e., volume and density) and stiffness (i.e., Young's modulus and cross-sectional geometry). While equation (2) holds only for an SDOF system, the underlying relationship of mass and stiffness can be generalized for more complex systems. That is, an increase in stiffness will increase the natural frequency and an increase in mass will decrease the natural frequency. For example, consider the strings on a guitar. The larger diameter strings (more mass) produce lower tones than the smaller strings (less mass). Also, a string has a higher pitch when tightened (increased stiffness) than when loosened (decreased stiffness). It is these fundamental properties of the resonances of a system that RAM NDT utilizes to evaluate the integrity and consistency of parts.

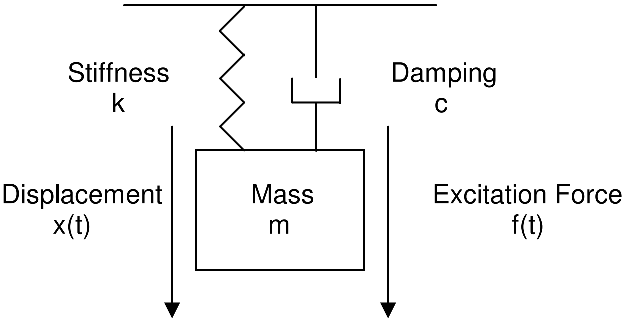
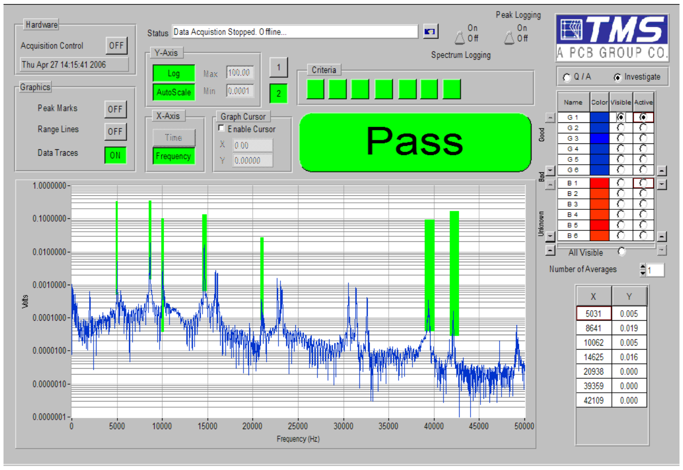


Figure 1. Single Degree of Freedom (SDOF) discrete parameter model

The natural frequencies are global properties of a given structure and the presence of structural defects causes shifts in these resonances. For example, a crack will change the stiffness in the region near the crack and a variation in density or the presence of porosity will change the mass. A crack defect typically reduces the stiffness in the material, thus decreasing the natural frequency. Similarly, porosity in a cast part reduces mass, thus increasing the natural frequency. These shifts are measurable if the defect is structurally significant with respect to the either the size or location of the flaw within a specific resonance mode shape. With some defects, a shift in resonant frequency can also be noticed audibly, such as a cracked bell that does not ring true.

The Resonant Acoustic Method technique performs resonant inspection by impacting a part and "listening" to its acoustic spectral signature with a microphone. The controlled impact provides broadband input energy to excite the part and the microphone allows for a non-contact measurement of the part's structural response. The part's mechanical resonances amplify the broadband input energy at its specific natural frequencies, indicated as peaks in the frequency spectrum and measured by the microphone above the background noise in the test environment. "Good" parts (structurally sound) have consistent spectral signatures (i.e. the mechanical resonances are the same among part samples) while "bad" parts are different. Deviations in peak frequencies or amplitudes constitute a structurally significant difference that provides a quantitative and objective part rejection. An example of a typical spectrum from 0 to 50 kHz is given in Figure 2.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○ Q / A ● Investigate

Number of Averages 1

Name	Color	Visible	Active
G 1	🟦	●	●
G 2	🟦	○	○
G 3	🟦	○	○
G 4	🟦	○	○
G 5	🟦	○	○
G 6	🟦	○	○
B 1	🟥	○	○
B 2	🟥	○	○
B 3	🟥	○	○
B 4	🟥	○	○
B 5	🟥	○	○
B 6	🟥	○	○

All Visible ○

X	Y
5031	0.005
8641	0.019
10062	0.005
14625	0.016
20938	0.000
39359	0.000
42109	0.000

Figure 2. Typical acoustic signature, power spectrum to 50 kHz, for a powder metal part, shown as processed by NDT-RAM with criteria ranges (indicated with green "boxes") at seven natural resonant frequencies.

Gross defects can often be distinguished directly by the human ear, for example, a "thud" instead of a "ping", but human hearing is subjective and limited to approximately 20 kHz maximum. By analyzing data beyond 20 kHz, to upwards of 50 kHz, much smaller defects can be detected, even across production lots given reasonable process control. Typically, these defects cause frequency shifts as shown in Figure 3. These shifts are a function of how the specific defect affects the mechanical resonance, which is dependent upon the specific defect location with respect to the deformation pattern of the resonance. Fortunately, mechanical resonances are global properties of a structure, and generally a defect will alter at least one resonant frequency. For this reason, it is good practice to set up multiple criteria ranges for analysis.

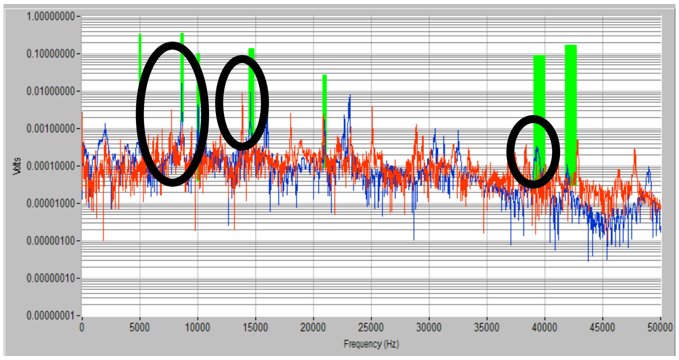

Figure 3. Data marked by black circles, show frequency shifts due to structural defect in a part. Note that resonant frequencies in red (defective part) are shifted down in frequency from those in blue (good part). This is typical with a crack defect present in the part.

SINTER BRAZE INTEGRITY APPLICATION CASE STUDY

Conventional PM, sometimes referred to as press-and-sinter, yields parts formed by compacting the metal powder in a single direction. The die forms the compacted shape, referred to as a green part. This shape is limited to definition in the compacting direction so that the green part can be removed from the die without damage.

Sinter brazing is a common joining process used by powdered metal part manufacturers that allows them to produce more complicated parts while still using conventional PM. The technique involves assembling multiple powder metal parts prior to sintering, adding a braze compound and sintering at temperatures above the melting point of the brazing alloy. When processed properly, sinter brazing is very cost effective and produces a very strong joint, see reference [2]. Several examples of brazed powder metal parts are shown in Figure 4 below.

Figure 4. Examples of sinter brazed powder metal parts, with braze plug locations marked by red circles.

Certain defects are common among sinter brazed powder metal parts. These include sub-component misalignment during initial assembly and incomplete braze material infiltration. Inadequate infiltration is typically caused by using an improper braze alloy or damaged braze pellets, for example, a slug with 50% of its material chipped away. Another likely root cause of poor sinter brazing is missing the braze pellet altogether. Other common process variances that can lead to inadequate braze joints include improper furnace settings and dewpoint. Several examples of these defects are shown in Figures 5 and 6 below.

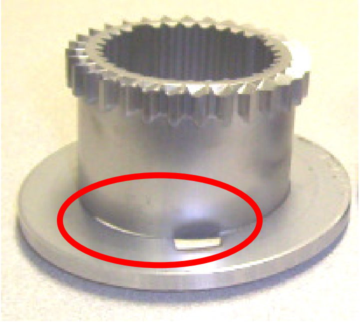

Figure 5. Gross misalignment defect (indicated by gap within red circle) common with sinter brazed powdered metal parts.

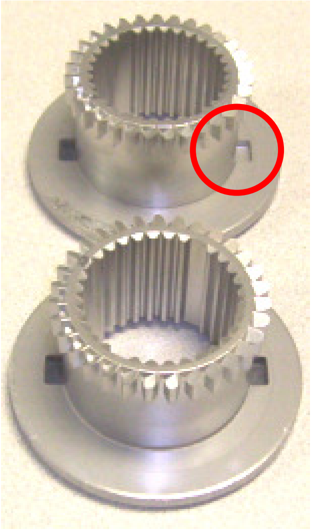

Figure 6. Missed braze pellet defect (indicated by the lack of darker discoloration within red circle) common with sinter brazed powdered metal parts

RAM NDT has repeatedly proven to be effective for inspecting the structural integrity of sinter braze joints. In one such application, presented previously by Byrd and Walker of GKN Sinter Metals, see reference [3], the structural integrity of brazing a powder metal carrier gear assembly is tested using RAM NDT while correlating the results with destructive testing. Criteria templates with several critical resonant frequencies were established from a baseline set of parts. This initial set of parts was inspected with visual examination and microstructural analysis, and included acceptable production process variations in density, lot-to-lot powder, dimensions and sintering effectiveness. Additionally, certain defects were induced during manufacturing which are representative of real world quality issues. These include:

1. Carrier assemblies were sintered with either one, two or three of the required four brazing pellets omitted. Without a braze pellet inserted during the manufacturing process, one or more of the braze joints will not braze during sintering.
2. Carrier assemblies were sintered with misalignment at the sinter braze joint, reducing the surface area of the effective braze. Typically, this defect occurs due to improper assembly of sub-components or vibration within the sintering furnace.
3. Carrier assemblies were sintered using an insufficient amount of brazing material. The surface area of the braze joint determines the mass required for the braze pellet. Braze pellets can crack and chip, significantly reducing the mass of the pellet, leaving an inadequate braze.
4. Carrier assemblies were poorly sintered at reduced temperatures, contributing to ineffective brazing. Although these brazes typically flow over the joints' entire surface area, the braze penetration, and thus strength, is poor.

RAM NDT was used to test the resonant frequencies of the carrier assemblies. A destructive tensile test was also completed to evaluate braze joint integrity and strength. Figures 7 and 8 show typical frequency shifts at two of the critical resonant frequencies. Figure 9 shows a diagram of the tensile test on the carrier assembly. In this test, the separation force was measured for a variety of groups of parts, with the induced defects including misalignment, omitted braze pellets, small braze pellets and poor sinter. The results are given in Table 3 below.

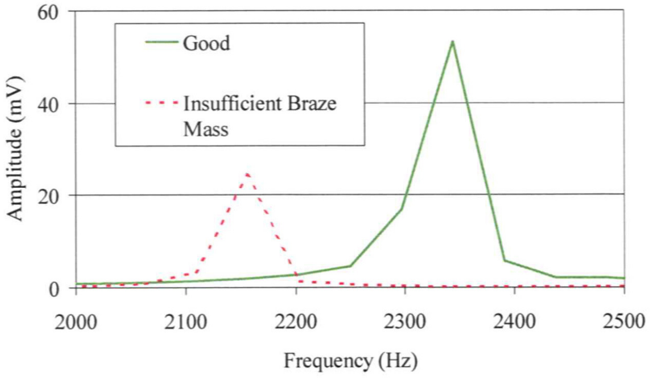

Figure 7. Resonant frequency shift due to insufficient braze mass (i.e. chipped pellet), ~7.5% from approximately 2325 Hz down to 2150 Hz.

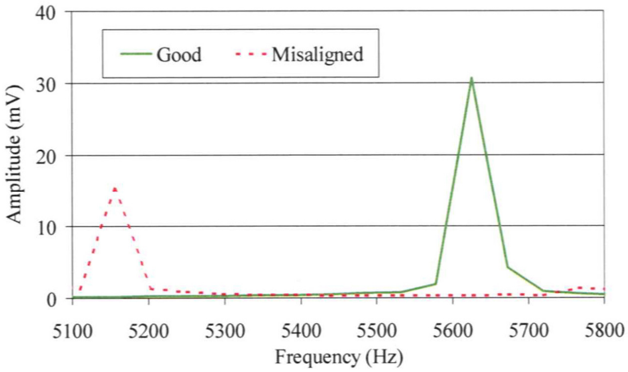

Figure 8. Resonant frequency shift due to sub-component misalignment, ~9% from approximately 5625 Hz down to 5150 Hz.

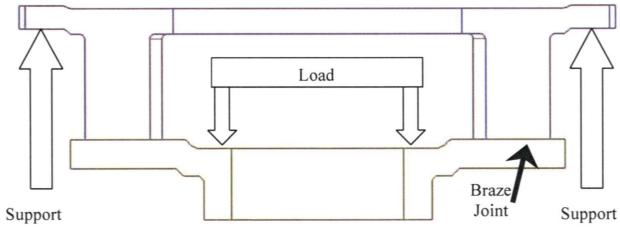

Figure 9. Schematic of sinter braze carrier assembly tensile test used to gather data presented in Table 3.

Table 3. Correlation of known induced defect to separation force data on a powder metal carrier gear assembly, compiled by Byrd and Walker

Part Characterization Induced Defect	Separation Force, lbs (N)
Good parts	26,118 (116,180)
(1) Missing braze pellet	13,360 (59,430)
(2) Missing braze pellets	8,121 (36,124)
(3) Missing braze pellets	4,288 (19,074)
Misaligned sub-components	8,129 (36,160)
Small braze pellet	8,812 (39,198)
Poor sinter	5,995 (26,670)

CONCLUSION

Within each of these groups of parts, certain resonant frequencies shifted to allow accurate and reliable 100% inspection. Typically, these frequency shifts were on the order of 6% - 10% as compared to resonant frequency shifts due to acceptable process variation less than 1%. As a result, it was concluded that RAM NDT can easily and reliably detect poor sinter braze joints and is a far superior technique than subjective visual inspection.

REFERENCES

[1] Ewins, D.J. Modal Testing: Theory and Practice. Research Studies Press Ltd, 1984.

[2] Byrd, K. “Joining Technologies for Powder Metallurgy Planetary Carriers”, *Power Transmission Components Advances in High Performance Powder Metallurgy Applications,* edited by W.D. Badger and H.I. Sanderow, MPIF, Princeton, NJ, 2001, pp. 118-119.

[3] Byrd, K et al. “Testing Sinter Braze Integrity Using Acoustical Resonant Frequency Analysis”, PM2TEC 2003, Las Vegas.