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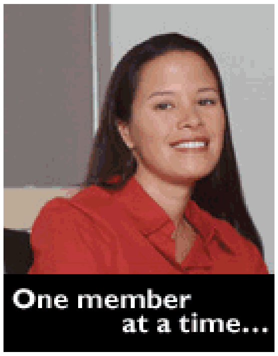

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Nondestructive Testing of Small Castings

by Godfrey Hands* and Robert H. Nath*

> It is easy to tell if a bell or a piece of quality crystal drinking glass is unacceptable by the sound it makes when caused to "ring." It is much more complicated to detect and measure the resonant sounds a manufactured component will make. If you can do that in a reproducible, known fashion and can compensate for acceptable production variations that interfere with it, you have a valuable nondestructive test! This article provides some of the basics for doing just that.
>
> *Frank Iddings*
> *Tutorial Projects Editor*

Figure 1-3
Figure 4-6

INTRODUCTION

A recent "Back to Basics" article by Stuart Kleven and Malcolm Blair (2003) discussed the use of ultrasonic and radiographic methods of nondestructive testing (NDT) on large castings. The techniques described in that paper are not, however, always the best NDT techniques for smaller castings. There is a vast amount of smaller castings, both ferrous and nonferrous, produced annually for the automotive industry (Figure 1). Many of these castings weigh between about 0.2 and 90 kg (0.5 and 200 lb) and are mass produced, with typical numbers of a product sometimes exceeding two million pieces per year. Many of these are for safety critical applications, such as suspension, steering or brakes, and need some form of NDT.

When testing mass produced castings, the manufacturer has to ensure that the price is competitive. In many cases, the customer will dictate the price, with an annual reduction in price, and it is up to the casting manufacturer to decide whether the company can remain in business at that price. If the company is unable to accept the price, then the automotive manufacturer will obtain these components where lower labor costs permit the castings to be supplied for a lower price. This means that manufacturing costs have to be minimal and expenditures on seemingly less important production overheads have to be carefully examined.

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In this paper, we will examine the different types of discontinuities that may occur in smaller castings and the NDT techniques that are needed to detect them. We will also look at a relatively new test technology that has become available in the last decade or so, which can potentially replace all of the conventional techniques with one very cost effective and rapid whole body test.

CONDITIONS AND TECHNIQUES

With any NDT technique, labor costs are a major concern for the manufacturer and any technique that can be at least partially automated will have a significant advantage over techniques unable to be automated, provided that the integrity is comparable. If we look at the characteristics of a casting, we see that it usually has a very complex shape. If it were a simple shape (for example, rotationally symmetrical), then automation would be simpler, but in that case, it may be better manufactured from bar stock and machining, and not need the NDT in the first place.

Radiography does lend itself to automation, but it carries a very high price tag compared to other techniques and, in addition to the limitations described in the earlier "Back to Basics" article, it is not easily able to detect discontinuities that lie very close to a significant section change, where radiographic density changes mask smaller discontinuities. In mass production applications, radiography may cost up to $1 per component; when the selling price is only $5 to $50, this is a significant increase in manufacturing costs.

Ideally, then, we need to find a cost effective and reliable NDT technique that can detect conditions that will have a detrimental effect on the structural integrity of castings. These conditions can be:

- gross porosity (shrink or large gas hole or blow hole)
- fine porosity (microshrink throughout casting or diffuse small gas bubbles)
- inclusions
- nodularity below specification (in ductile cast iron)
- cracks (including mechanical handling cracks, but more often shrink cooling related cracks)
- cold shuts, cold folds and "miss-runs"
- oxide layers (in light metal castings)
- wrong material chemistry or grain structure
- wrong (or missing) heat treatment
- interrupted or short pour
- wrong parts mixed in production.

Let's now look at conventional NDT techniques to detect the above conditions.

Gross Porosity

This problem can have a significant effect on safety critical parts, especially for suspension and steering components. It can be located almost anywhere in the part, but generally will be limited to a few locations. Ultrasonic or radiographic techniques can frequently detect these, but because of the complexity of many of the castings, automation will be costly, complex and not always 100% effective.

Fine Porosity

This tends to be located globally throughout the component and may be too fine to detect with radiographic or ultrasonic techniques. This type of porosity can be gas porosity or shrink porosity. The condition may be sufficiently severe to cause a reduction in tensile strength of 10% or more, while remaining undetectable by conventional NDT methods.

Inclusions

Inclusions can range from fine isolated inclusions to gross ones and may have a significant effect on the structural integrity of the component. They may be randomly located in the casting or may tend to be located in specific locations. Ultrasound and radiography can sometimes detect these, depending on the chemistry of the inclusions, but some types are almost undetectable.

Nodularity

This can be a critical condition in ductile cast iron. It tends to be a global characteristic, but may vary locally within a complex casting. Conventionally, ultrasound velocity techniques are used to detect this condition and can measure the degree of nodularity within the path of the sound beam. High carbides increase the velocity reading and the presence of carbides can mask a low nodularity condition when only measuring ultrasonic velocity.

Cracks

These are fortunately infrequent, but can occur at almost any surface (and in some cases subsurface) location. They can have a significant effect on the structural integrity of a component, in severe cases causing a catastrophic failure the first time that the vehicle is driven. In less serious cases, it can cause a catastrophic failure when the component is severely loaded (for instance, when the vehicle mounts the curb or when the antilock brake system is activated in emergency braking).

Magnetic particle, penetrant and ultrasonic techniques are frequently employed to detect these cracks, but, due to the complexity of the component, they normally have to be applied manually to be effective and manual techniques tend not to be 100% reliable in detecting rarely appearing conditions.

Cold Shuts

Cold shuts are a condition that can sometimes occur in castings and which have a very significant effect on the structural integrity. The severity is determined by the size and location, but can be even more detrimental to the structural performance than cracks. They are frequently located below the surface, with occasional components having shuts severe enough to extend to the surface of the component.

Cold shuts form when the flowing material starts to cool, either by touching part of the die or because the casting time is too slow. Frequently, this presents a smooth, tight interface surface, making it very difficult to detect with ultrasonic methods.

Radiographic techniques must be aligned exactly to the cold shut for it to be detectable and so are infrequently used. Ultrasound is frequently employed to detect this condition, but with the limitation mentioned above of poor detection unless sound beam alignment is optimal.

Oxide or Foil Layers

This is a very serious problem that can occur in a light metal casting. When a part is cast, a small amount of the molten metal may solidify in the "gate" or the passage to the gate, or may fall into the cavity from the parting line of the cavity. This may be very thin. When the next component is manufactured, the thin foil or film from the last component is carried into the die or mold with the new molten metal. Because this film has cooled, it will have an oxide film on the surface which will not melt, even though the small amount of metal beneath it may have remelted. An oxide film inclusion is more often the result of a cold shut or a cold fold during casting.

This foil or film will have a (relatively) large surface area and can lodge in the new casting at a random location and orientation. It can have a very significant effect on the structural integrity of the new part, depending on size and orientation.

Because of the random orientation and location of this type of problem, it will be almost impossible to (economically) detect with radiographic techniques and very difficult to detect with ultrasonics.

Wrong Material Grade

Use of a wrong material grade may have a significant effect on the component. A component may be of a type of material that is intended for hardening, to give a wear resistance to the surface, but use of a wrong material grade may mean that the surface does not become hard after hardening. Alternatively, a subsequent processing or heat treatment may leave the component with a totally unacceptable microstructure and a significantly compromised structural integrity.

Conventionally, eddy current techniques are used to check for this condition on the finished component, but sample (spectral) chemical analysis can be applied to the cast material to check for this condition. This is not a condition that needs 100% testing, unless a significant number of wrong components have been mixed with good components.

Wrong or Missing Heat Treatment

This is a condition that should be controlled by process control, but even in the best of factories, mistakes can occur. The consequences of missed or incorrect heat treatment will be very significant to the life of the component. Conventionally, eddy current techniques (usually encircling coil) are used to detect this condition.

Interrupted Pour

This condition can sometimes occur and has a similar effect to a cold shut. Detection is similar to that for cold shuts.

Mixed Components

A small number of components from a previous batch can sometimes get mixed in with a new production batch. The components may be for different customers, manufactured to different specifications or have slightly different dimensions. These may not be detected until the component comes to be installed on the vehicle or is subsequently machined. Visual and optical testing can usually detect this condition, but specialized equipment may be necessary.

CONVENTIONAL NDT LIMITATIONS

We have now seen that with conventional NDT techniques, in order to ensure that only 100% acceptable components are supplied to customers, we need to employ several different techniques. These tests are very likely to increase the manufacturing costs beyond an acceptable level; in some cases, testing costs will exceed manufacturing costs. In addition, a 100% guarantee of supplying problem free components is almost impossible to achieve. Most manufacturers rely on process control and hope that their products do not contain significant discontinuities which will compromise the structural integrity of the components.

There is, however, a relatively new NDT technique that can detect all of the above conditions in one simple test. In addition, the test is a "whole body" test, detecting problems in all locations and orientations which have a detrimental effect on the structural integrity of the component. This technique is resonant testing.

RESONANT TESTING

Resonant testing has been available for many years. In fact, it is probably one of the earliest NDT techniques ever used (after visual testing). However, conventional resonant testing has a drawback. It is affected by piece to piece and batch to batch variations to such a degree that only severe problems are detectable.

An American company has recently developed patented techniques to compensate for these variations. The technology allows a single process to test cast components (as well as forged, machined or powder metal, and ceramic components) at typical production speeds, thereby making it ideal for 100% testing in manufacturing.

Background

Resonant testing has been available for many years in simple formats and in the latter quarter of the last century in more complex formats. Initially, it was applied by tapping the component, listening by ear to the "ring," then making a subjective judgment based on the perceived sound and memory of what good and bad components sounded like. It worked well for detecting the gross conditions that were of interest at that time.

The technique became more complex, becoming capable of detecting smaller discontinuities by applying a microphone or accelerometer to pick up the sound, which was then analyzed by performing a fast Fourier transform to produce the sound's spectrum. This had the advantage of taking some of the subjectivity out of the test and also enabled one to analyze more than one of the resonances. The sensitivity, however, was limited to detectable differences between unacceptable and acceptable components.

Resonance is affected by two factors: dimensions and material properties. The dimensional effect can be clearly demonstrated by looking at and listening to bells of different sizes. The larger bells will resonate at lower frequencies than the smaller bells. The material property effect can be demonstrated by manufacturing two bells to identical dimensions, but from different materials. These will ring at significantly different frequencies.

A component's resonance due to material properties (or stiffness) is in turn affected by numerous factors, including temperature, nodularity (for cast iron), the elastic properties of the material and any discontinuities within it.

For all components, elastic properties change with temperature. This change in elastic properties will in turn change the resonance of a component. For ferrous components, resonance changes by approximately 0.015% per kelvin (0.008% per degree farenheit) around the temperature range normally encountered in production. This effect is almost doubled for aluminum components.

Discontinuities will also reduce the stiffness of the components. A typical discontinuity will change one or more of the resonances of a component by 0.1 to 1%, while very large and gross discontinuities will change it by greater amounts (typically up to 10%). The graph in Figure 2 shows the effect on one resonance of introducing a small and then a larger discontinuity into a good component, showing the shift of frequency to lower levels.

Changes in the yield strength for ferrous components have been correlated with changes in resonant frequencies (Figure 3). Two researchers (Kovacs, 1977; Emerson, 1974) carried out this work and, while their results do not agree completely, their work shows the effect and suggests that a change in yield strength of about 5% correlates to a change in resonant frequency of about 1%.

When a reduction in yield strength of a component of greater than 5% is not permissible, then we need to ensure that piece to piece and batch to batch variation of resonant frequencies between components do not have greater effects than one half of this (0.5%).

Typical piece to piece and batch to batch frequency variations in manufactured components is on the order of 1 to 5% depending on the manufacturing process, so it is obvious that we need to compensate for these variations in order to achieve a useful test sensitivity.

In Figure 4, we see what happens when we introduce small and larger discontinuities into similar components sourced from different production batches. The effect of batch to batch variation on the resonant frequency is significantly greater than the effect of the discontinuities on the frequency.

If we are able to compensate for these piece to piece and batch to batch variations as well as temperature variations, we are then able to achieve acceptable test sensitivity. The American company has achieved the ability to compensate for the temperature and variations in components to make the resonance technique feasible.

Compensation

Figure 5 depicts a simple example which is occasionally possible. Here, we see two consecutive resonances from some good and bad components. It is plain that the "distance" between these resonances is greater for good components than for bad ones. By measuring the lower of these two frequencies, then looking a set distance higher in frequency in a window for a second resonance, we will have a resonance in that window for good components and not for ones exhibiting problems.

In this example, the window should be 400 Hz wide and start 2.6 kHz above the frequency of the first peak. We can also generate a higher sensitivity test by developing a better mathematical relationship between these resonances. For example, here f_d = (0.3 x f_1) + (304 930 ±60 Hz) will provide a 120 Hz wide window, thereby providing a higher sensitivity (narrower "accept" window).

By using statistical pattern recognition techniques, we can develop even better tests. Taguchi (1994) writes that measurement of a parameter from good components will produce results which in general are grouped together. Parts with discontinuities will produce measurements that tend to be slightly different. If we can surround the measured value from good parts with an ellipse, then bad parts will tend to fall outside of this ellipse.

Mahalanobis (1936) further developed Taguchi's theories into usable mathematical formats and these techniques have been applied by the developing company as in the following example. In Figure 6, we see the effect of plotting two frequencies against each other for good and bad components. The good components are represented by diamonds and the bad ones by squares. The mathematically developed ellipse (Mahalanobis-Taguchi system) is able to contain all of the good parts and reject the majority of the problematic ones. By removing a separate two dimensional shape or curve from the ellipse (a mathematically developed bias), we are able to reject the remaining bad parts.

Figure 6 is an example shown in two dimensions. It is possible to imagine one with three frequencies plotted together in a three dimensional plot, with an American or rugby football shape, containing all the good component responses and a three dimensional bias rejecting the remaining bad parts.

It is possible to work in more than three dimensions (in fact, work is typically done in five to seven or more dimensions by correlating five to seven or more resonances together mathematically), but we can no longer visualize this. These techniques allow us to work with optimal test sensitivity and we are generally able to detect all true problems while not encountering significant numbers of false rejects. The process is computer controlled, with the accept/reject decision programmed into the system, thereby removing any degree of subjectivity from the test.

A typical component in mass production will require between five to seven resonances to correctly test. This will then entail a typical testing time of about 3 to 5 s, making the technology suitable for 100% testing of mass produced components.

With full automation, typical throughputs of between 250 000 and 2.5 million parts per year are regularly achieved. Resonant testing costs are typically only a small fraction of the cost of testing the component with only one of the normally applied test techniques and there is the added advantage of detecting all of the desired unacceptable conditions in the one test. Temperature compensation algorithms have also been developed, making it possible to compensate very accurately for component temperature variations also.

CONCLUSION

The resonant testing technique described in this paper is now a very reliable way of guaranteeing the fitness for purpose of smaller castings for the automotive industry. It is a technique that can be applied to 100% of production and, because it can be automated, will also provide substantial cost savings.

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