Shot Peening Ductile Iron

P1528

Shot peening provides a useful tool to arrest stress corrosion cracking in ductile iron, provide beneficial compressive stresses and improve casting appearance.

Mark Lawerenz
Milwaukee Div/Metal Improvement Co
Milwaukee, WI

Shot peening is a production process too often confused and used synonymously with shot blasting. They are not the same nor are the benefits of each interchangeable.

In the foundry industry, shot blasting is used to clean castings and remove scale; shot peening is a much more controlled process used primarily to:

- combat fatigue problems;
- prevent stress corrosion cracking;
- assist in form or shape correction;
- provide a uniform texture.

In the peening of ductile iron and austempered ductile iron (ADI), there is the added benefit of the material responding favorably to work hardening.

The first three above rely on the beneficial compressive stresses induced by peening, while the fourth item is used only for the uniform appearance produced by the strict control of shot.

The Theory

To understand why shot peening is an effective tool in fatigue-related problems, a primary consideration for ADI, it is necessary to understand shot peening theory.

It is known that fatigue failures consist of three events:

- the initiation of a crack at a surface that has either residual tensile stresses (possibly produced by machining operations), or applied tensile stresses (as in external forces produced by gear tooth loading);
- crack propagation or movement through a member (as in a gear tooth);
- eventual fracture of the member due to insufficient cross section of the member, making it unable to carry the applied loads.

Based on the crack propagation theory, a crack will not propagate into a metal layer that has compressive stress.

Peening Effect on Fatigue

Shot peening is defined as the bombardment of a surface with small spherical media (or shot) to produce a thin layer of high magnitude, residual compressive stress. Eliminating crack propagation can arrest a fatigue crack.

In Fig. 1, a zero point is randomly selected and increasing compressive stresses are shown by movement from left to right from a vertical datum point. Increasing tensile stresses can be shown by moving from the datum point from right to left. The stress distribution through the member can be shown graphically if the peened surface is at the top of the member. The greatest magnitude of the compressive stress will occur at the top of the peened member, or slightly below the surface, and will be approximately 50-60% of the ultimate tensile strength of the base material, as illustrated in Fig. 2.

The depth of the compressive stress is a function of the kinetic energy imparted to the peened surface which, in turn, is a function of the mass times the velocity of the shot. This depth of compression, or the point at which compressive stresses change to tensile stresses (referred to as core tensile), also reflects hardness of the material (see Fig. 3).

This kinetic energy is measured by a standard known as an "Almen" strip, described more fully below. Figure 3 illustrates that from left to right on an intensity curve, the intensity with which a part is being peened increases. At a given intensity (a measurement of the kinetic energy), the depth of compression is deeper on a softer than on a harder metal. This depth of compression is critical because it cannot exceed 10% of the thickness per side of the peened material.

When a shot peened part has an external load applied to it, the off-setting tensile stress produced by the load will decrease the magnitude of the compressive stress introduced by peening. This compressive stress will be retained if the part is loaded no more than 40-50% of the material's ultimate tensile strength, or below its elastic limit or yield point.

Figure 4 charts a part that has a stress distribution without an external load (residual stress). Upon application of the load, the curve will shift as shown by the solid line.

How Does Shot Peening Work?

In 1971, Central Foundry Div/GMC

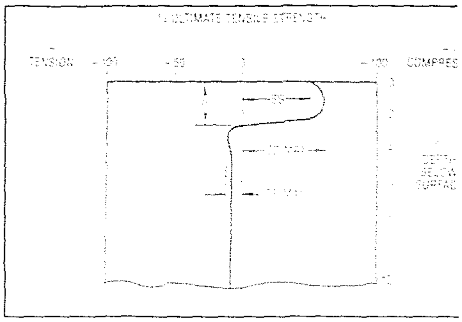

Fig. 1. Residual stress profile created by shot peening shows the maximum compressive stress (CS Max) occurs at a distance slightly below the shot peened surface. Depth of compression is defined by (d).

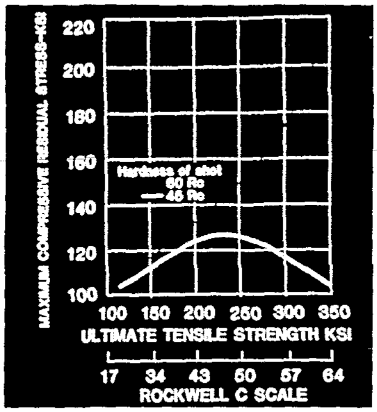

Fig. 2. Residual compressive stress magnitude is approximately 50-60% of the ultimate tensile strength. To retain this relationship, above $45R_c$, special hard shot must be used.

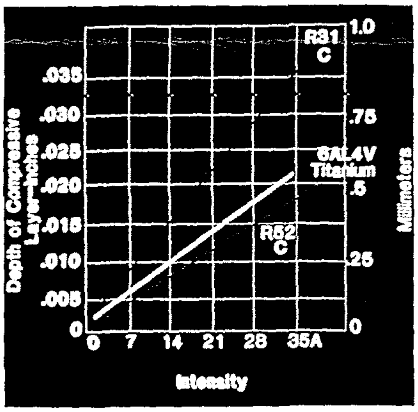

Fig. 3. The depth of the residual compressive stress is a function of how hard the part is peened (intensity) and the hardness of the target material. By selecting an intensity and intersecting an appropriate hardness of a material, the depth of compression can be determined.

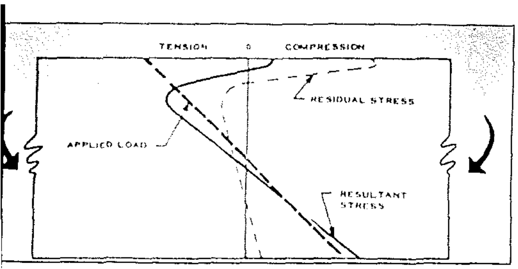

Fig. 4. Resultant distribution of stress in a shot peened beam with external load applied is illustrated. Solid line is the resultant.

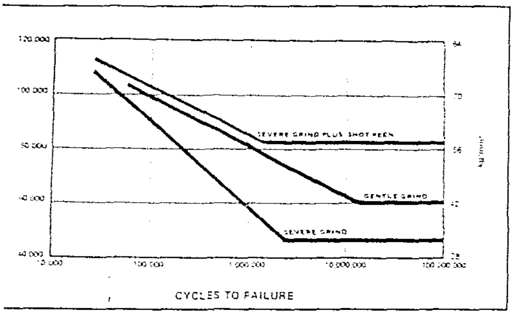

Fig. 5. The graph shows that by peening after the grinding operation, the endurance limit of the part can be increased even above the original gentle grind design condition. A part designed for a gentle grind, but has had a severe grind performed on it, could be salvaged by a shot peening after the severe grind operation. The resultant condition could have a higher fatigue strength than the design condition.

ran many laboratory and proving ground tests that demonstrated the engineering feasibility of nodular iron gears. An SAE paper (#820696; Neil Lottridge and Robert Grindahl) summarized the results of the testing done by GMC's Pontiac Div from 1971-1977 on nodular iron hypoid gears for automobile rear axles.

Pontiac engineers found that, unlike steel, the hardening heat treatment for ductile iron results in a small residual tensile stress at the material's surface. Since bending failures are the result of tensile stresses at the surface, ADI gears would not have the fatigue resistance of carburized steel. Residual compressive stresses were introduced into the material by shot peening.

The benefits of the use of ADI with shot peening produced a gear with good fatigue life, 10% lighter weight, less noise because of the dumping capacity, greater torsional ultimate strength and, because of the graphite in the nodular iron, improved score resistance.

Since shot peening introduces a compressive stress that prevents crack propagation or movement, it can also be used to prevent pitting problems at a gear pitch line. This was proven on carburized and hardened gears in NASA tests; shot peening increased gear life 60%. It was found that subsurface cracks produced by loads at the gear face tended to move toward the surface, and that the compressive stresses aided in preventing this crack movement.

In addition to the improved fatigue characteristics, ADI responds favorably to work hardening that can improve its wear characteristics. This is the result of cold working, causing retained austenite to transform to martensite.

Both the benefits in the improved fatigue strength and increased surface hardness were shown in a paper presented to the International Conference on ADI by Blackmore and Harding on "The Effects of Metallurgical Process Variables on the Properties of Austempered Ductile Irons."

In addition, the dimpling produced on the gear teeth provides tiny reservoirs to aid in the retention of lubrication.

Though gearing has been the primary beneficiary of shot peened ADI, other applications using this combination of materials and process are common, i.e., shot peening fillet radii on crankshafts and camshafts.

In cases where severe grinding operations are performed on a part, the resultant surface tensile stresses can have a negative impact on part endurance. Peening after the grinding operation can increase the endurance limit even above the original gentle grind design condition, as shown in Fig. 5.

When fatigue problems occur, one of the solutions is to eliminate stress risers in the part by polishing or other surface refining process. Though the stress riser in the material tends to be reduced, any subsequent scarring of the surface in application can greatly reduce any benefits of the polishing operation. Costs to refine a surface finish to finer than a 125 RMS will usually increase substantially.

Instead of polishing the surface, shot peening will produce a compressed stress layer below the surface of the material that will prevent crack propagation and increase fatigue strength. Not only can this be used as a salvage technique, but it can be used as a cost reducer by eliminating the need for the added polishing costs.

In cases where uniform casting texturing is required, the controls used in the peening process can impart a finish that is homogeneous in appearance. In this situation, the benefits of the compressive stress to produce improved fatigue strength may not be critical, and surface texture selection will most likely determine shot size and application intensity.

To retain the fatigue strength benefits produced by peening, no more than 10% of the depth of compression can be removed by the subsequent machining operation. Shot peening should be performed after heat treating so that the compressive stresses and reduction of fatigue strength are not dissipated as heat treating temperature approaches stress relieving temperature.

Shot Peening Controls

Getting all of the advantages of shot peening requires following strict controls. These include:

- method of determining intensity;
- system to maintain shot integrity;
- method to check coverage of peened areas;
- decision to use automated or computer controlled equipment.

There are no known techniques for measuring compressive stresses, but laboratory experiments using X-ray diffraction can substantiate the stress distribution curves that show the magnitude of compressive stress and depth of compression. The three keys to successful shot peening are the ability to determine and maintain proper intensity, shot integrity and properly judging the coverage of the peened area.

Intensity—This control point is gaged by Almen strips of which there are three types: N, A and C. They are used to determine the various ranges of shot intensity, and are made of SAE 1070 spring steel uniformly hardened and tempered to a 44-50R_c. They also are used to calibrate the peening equipment.

For each calibration test, several Almen strips of a single thickness (N, A or C) are clamped to a test fixture, known as an Almen block, and exposed to a shot stream for varying time periods. When the strip is removed from the block, it will curve upward toward the side that has been peened.

This arc height is measured for each strip, using an Almen gage. The longer the strip has been exposed to the shot stream, the greater the deflection of the strip. If an A strip is exposed to a shot stream to produce a deflection of 0.015 in., the intensity is measured as a 0.015A intensity (see Fig. 6). The measured strips are then used to chart a saturation curve that plots the arc height versus the exposure time.

For a particular machine setup, the region being sought to develop an ideal

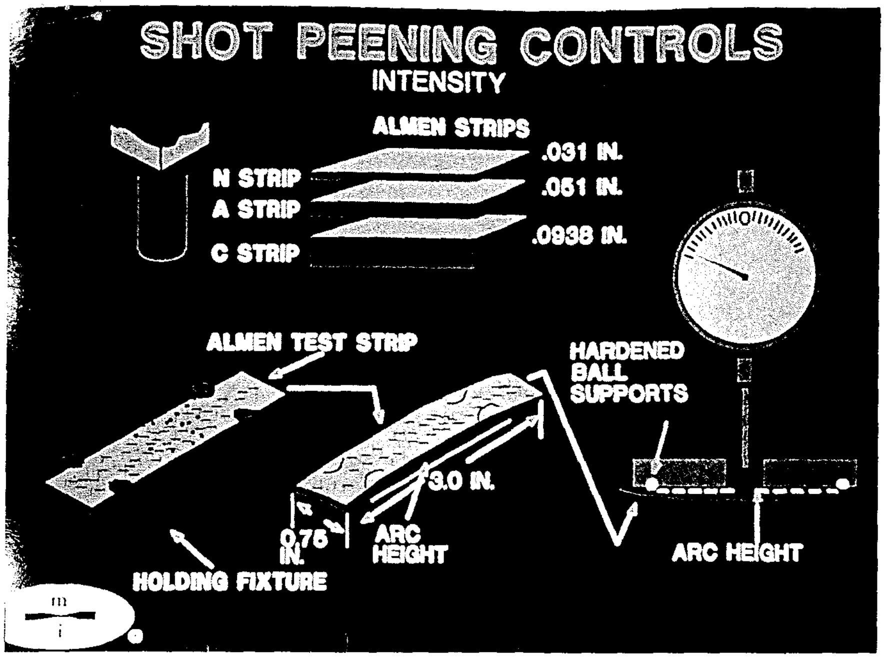

Fig. 6. The Almen strip is peened in the block, removed, the arc height measured by an Almen gage and the results recorded on a saturation curve.

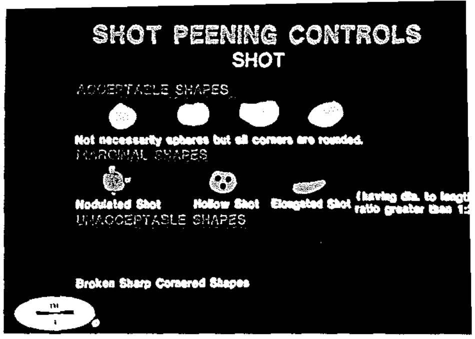

Fig. 7. Many different materials can be used for shot peening, though cast steel shot is the most common. Whatever material is used, it is imperative that it be kept round and uniformly-sized since sharp-cornered or uneven shot may produce harmful effects.

exposure time for a specified intensity is the beginning of the saturation range. This saturation range is defined by military standards as the area on the curve where there will be less than a 10% increase in the arc height of the strip after doubling exposure time.

The saturation curve is an important part of the controls used because proper intensity is important in determining the success or failure of a part in fatigue. Too high a shot mass or velocity may damage the gears; too low in exposure time will produce residual compressive stresses that are insufficient.

Maintenance of Shot Integrity—The second control is maintenance of the size and shape of the spherical, nonporous metal peening media. When metal strikes metal, something will break. In a shot peening operation, the shot will break or degenerate into unacceptable shapes and sizes. If these shapes are used in the peening operation, stress risers can be produced on the peened surface due to the sharp-edged media configurations (see Fig. 7).

In addition, shot mass is reduced with a proportionate decrease in intensity. It is mandatory that shot be inspected at regular intervals to prevent shot deterioration into unacceptable shapes and sizes.

Since shot is expensive, typically as it degenerates it is removed from the machine and classified. Without this control, the shot will degenerate and produce a process that resembles shot blasting. Subsequent degradation of the process will adversely affect not only repeatability, but fatigue characteristics as well.

This is done in a machine called a classifier, which uses a series of screens located below a hopper to sift the improper sizes from the good sizes. After the shot has been separated by size, it is metered into a spiral. Shot that is spherical will roll to the outer edge of the spiral as it moves down and will drop off into the next lower spiral. By the time the shot has traveled through the screens and the spiral, it will be sorted by size and shape.

Coverage—A surface that is to be peened should be completely dimpled, and not have any areas not covered with indentations. These areas are surrounded by compressive stresses, yet they are areas of tensile stress. If a root fillet on a gear, for instance, had only partial coverage, the flat or undimpled areas now would carry higher tensile stresses and premature gear failure is possible.

On harder surfaces, this dimpling becomes more difficult to detect with the naked eye. The two acceptable techniques that have been developed to determine proper coverage are visual examination, using a 10X magnifying glass, and examination by Dyescan, using the Peenscan process. Visual inspection is self-explanatory; a knowledgeable inspector "reads" the peened surface to check full coverage.

Inspection using Dyescan is accomplished by coating the surface to be peened with the Dyescan liquid. Under normal lighting the surface will appear glossy, but under "black light" the Dyescan-coated surface will glow. After a machine has been calibrated for intensity and shot integrity, the Dyescan-coated part is placed in the machine and peened. The Dyescan can only be removed by a direct impingement on the surface, or by impingement from no more than 15 degrees of dead center.

After the surface of the part has been peened, the part is removed and inspected under black light. The areas that have not been peened correctly will glow, an indicator of incomplete coverage. Percentage of coverage also can be determined by observation at the surface. Coverage less than 100% is unacceptable, and increased peening time is necessary. Only the initial setup piece and selected pieces during the part run are inspected by Peenscan.

Additional Controls—The state of the art in peening controls indicates a trend toward the use of microprocessors for data storage and display of part setup. This, coupled with interlocks to the process machinery, sensors to monitor shot flow, turntable rotation and other critical control areas, is part of a new generation of peening controls. Violation of the monitoring points will signal a microprocessor to automatically shut the process down.

Shot peening and ADI can be a very viable team capable of providing a cost-effective product to the customer; the key to its success, however, depends heavily on adequate control of all the component parts of the shot peening process. Improper controls could negate all of the advantages that make it so practical. ***mc***

For a free copy of this article circle No. 314 on Reader Action Card.