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CREATING AN IN-HOUSE SHOT PEENING SPECIFICATION FOR GEARS
Part 1

Whether large or small, companies can take certain steps to ensure reliable shot peening specifications for the gears they process. Learn how in this first of a two-part article.

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Shot peening is widely recognized as proven, cost-effective process to enhance the fatigue characteristics of metal parts and eliminate the problems of stress-corrosion cracking. Forming and texturizing are added benefits.

Though shot peening is widely used today, the means of specifying process parameters and controlling documents for process control are not widely understood. Many design and materials engineers continue to ask questions about shot size, intensity and blueprint specification to assure a high quality and repeatable shot peening process.

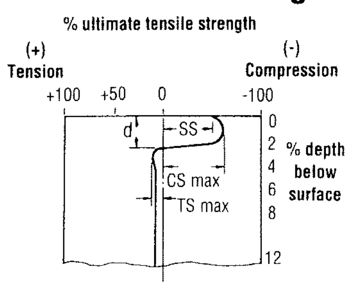
Many existing internal company specifications are adequate, but many are not because they have not been updated to coincide with the improvements in shot peening technology over the past years. Companies considering creation of an in-house specification for gears or interested in revising an existing specification should consult a knowledgeable shot peening authority.

For smaller companies and those that less frequently specify the shot peening process, good specifications that can be used as a reference are readily available. Two of these are Military Standard MILS-13165-B and AMS 2430.

Shot peening is an effective tool for combating fatigue and stress-corrosion cracking, as well as assisting in forming and shape correction. By definition, shot peening is the bombardment of the surface of a material by small spherical media (the shot) to produce a thin layer of high magnitude residual (or self) compressive stress.

This residual or self stress is introduced into a material prior to any actual applications of loads to a component. The magnitude and depth of these compressive stresses are predictable. As shown in Figure1,[5] the maximum compressive stress usually occurs at some distance below the peened surface, which is represented by the top horizontal line.

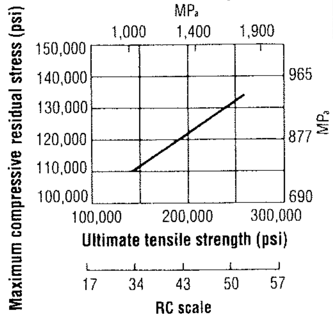
Figure 1
Residual Stress Profile After Shot Peening



The maximum compressive stress usually occurs at some distance below the peened surface.

Typically, this magnitude of compressive stress (CS max) is approximately 50 to 60 percent of the ultimate tensile strength of the material, as shown in Figure 2.[6] (Dual intensity peening can move the CS max closer to the surface of the peened material.) Because this method is not typically employed, Figure 1 is adequate for this discussion. The d represents the depth of compression or the point at which the compressive stress induced by the peening crosses the neutral axis and becomes tensile.

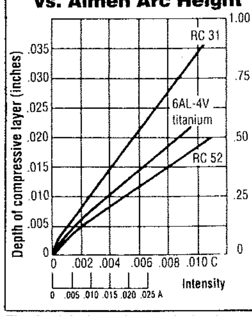
Figure 2
Residual Stress After Shot Peening vs. Tensile Strength



Typically, the magnitude of compressive stress is 50 to 60 percent of the ultimate tensile strength of the steel after shot peening.

The depth, as shown in Figure 3, depends on the hardness of the target material and the mass and velocity of the shot. Essentially, the softer the target material, the deeper the depth of compression at a given intensity. For example, at a 15A Almen intensity on a 52 RC material, the depth of compression will be about 0.008 in. Additional curves for various materials are available in reference No. 5.

Figure 3
Depth of Compression vs. Almen Arc Height



The depth is dependent on the hardness of the target material and the mass and velocity of the shot. The softer the material, the deeper the depth of compression at a given intensity.

The purpose of introducing compressive stresses into a part is to prevent fatigue failures, which typically are propagated through a component in regions of tensile stress. Changing tensile stresses to compressive stresses at the surface of a component where fatigue usually occurs limits crack initiation and propagation.

Residual tensile stresses can decrease the fatigue life of a component. Compressive stresses, however, tend to increase fatigue life. Some machining processes introduce unwanted tensile stresses into a part prior to any applied loading. If these factors are not taken into consideration, premature component failure can occur.

Controlling the Process

Certain basic controls must be introduced into any in-house company specifications on shot peening. Specifications, such as AMS 2430 and military specifications MILS-13165-B, deal extensively with controls.

To assure proper shot peening, an engineer must:
- determine the intensity
- maintain and control the integrity of the shot
- assure complete coverage
- determine whether computer-controlled equipment or automated equipment will be used.

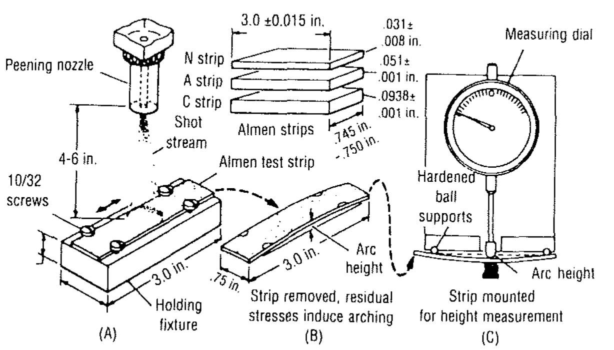
Without proper shot peening controls, repeatability and desired product reliability will not be maintained. The process would degenerate into nothing more than a blasting operation as used in cleaning and potentially lead to severe damage to the fatigue properties of a part.

Intensity is determined by application of a shot stream to a metal strip known as an Almen strip. Three gauges of these strips exist: **N, A** and **C.**

The **N** strip is used for light-intensity peening, **C** is used for high-intensity and **A** for medium-range peening. The proper strip is selected and mounted on an Almen block, and a shot stream is applied to the exposed surface.

After proper exposure time, the strip is removed from the block, as shown in part **A** of Figure 4. The strip deflects upward toward the peened surface (see part **B** of Figure 4), and the arc height is measured by an Almen gauge (see part **C** of Figure 4). The arc height of the strip and the amount of time the strip was exposed to the shot stream are noted.

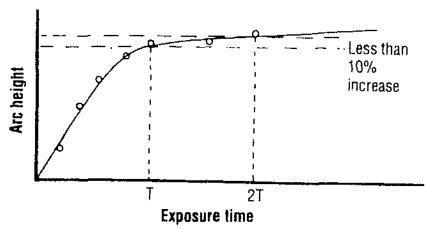
Figure 4
Almen Strip System



Intensity is determined by applying a shot stream to an Almen strip. After exposure, the strip is removed from the block (A). The strip deflects upward toward the peened surface (B), and the arc height is measured by an Almen gauge (C).

Additional strips of the same type then are exposed to shot streams for increasingly longer periods of time. The information from all these strips is used to plot a saturation curve (Figure 5) to assure that the equipment setup has been properly made for repeatability of the desired intensity.

Figure 5
Saturation Curve

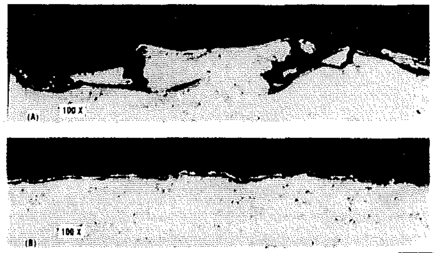


The information from Almen strips exposed to shot for increasing periods of time are used to plot a saturation curve.

Numerous controls go into this aspect of the peening process. The primary purpose of maintaining proper shot control is to prevent degeneration of the round shot into broken shot that typically is used in a blasting operation.

Left in an improperly controlled state, broken shot could produce unacceptable surfaces, as shown in **A** of Figure 6. Properly peened surfaces produced by controlled shot should appear as seen in **B** of Figure 6. The primary equipment used to ensure shot integrity is a classifier, which not only segregates improperly sized shot from good shot, but also segregates irregularly shaped shot from the desired round peening media.

Figure 6
Control Shot for Proper Surface



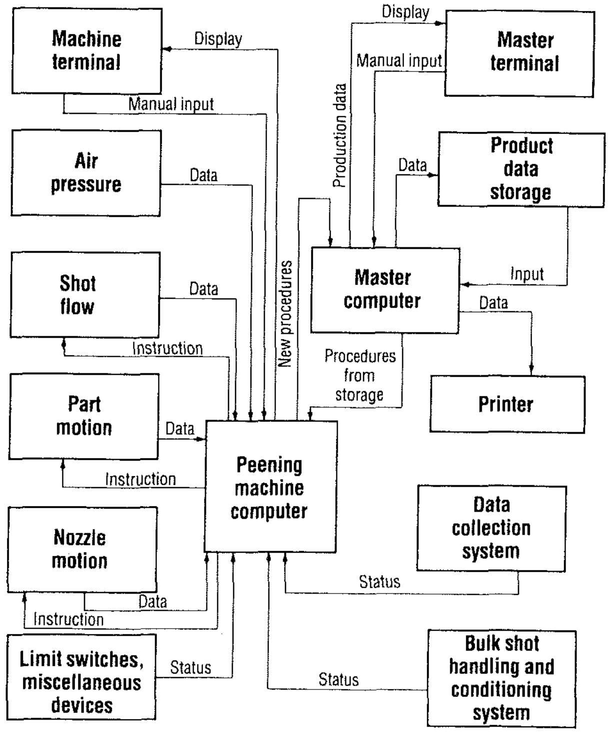
Improperly controlled shot caused the surface damage seen in photo A. Good shot control produced the acceptable surface in photo B.

Besides the classifier, techniques to qualify the shot prior to use should include methods that determine porosity, breakdown of shot, hardness and metallurgy. To neglect this aspect of controls could hasten degeneration of the process into blasting rather than peening. This would be analogous to striking the surface of the material with the claw end of a hammer rather than the ball end.

A properly peened surface has many overlapping dimples, referred to as an orange skin or orange peel effect. A partially covered surface never should be seen. Proper coverage can be determined with a 10 power (10x) magnifying glass or by the Peenscan process. The Peenscan method lets you view coverage of a surface with ultraviolet light after it has been treated with a material similar to a dye penetrant, which is removed by a peening operation. Areas that have not been peened properly glow under a black light.

The engineer must determine whether the equipment to be used is computer controlled or automated without computer control. Computer-controlled equipment typically is used for more sophisticated parts and when repeatability and computer printouts for monitoring process variables are required. This is the most sophisticated and usually most expensive peening methods. Figure 7 shows a samp[le] of a software path-flow diagram, with primary monitoring points o[n] the left.

Figure 7
Software Path-Flow Diagram



Computer-controlled shot peening equipment is the most sophisticated, assuring repeatability and constant monitoring. Primary monitoring points are shown on the left-hand side of the diagram.

Automated machinery without computer control usually employs manual load and unload of equipment. The machine automatically peens a part for a set cycle without computer monitoring or operator involvement. Most parts are peened in this manner.

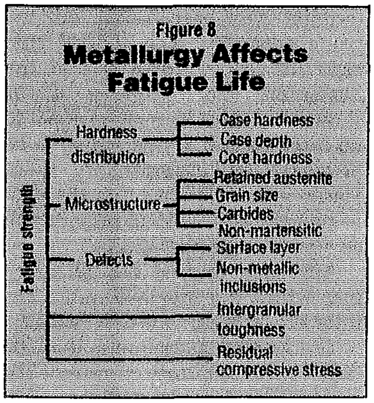
Considerations

Besides assuring good controls to assure repeatability, certain considerations should be applied to any gearing before any shot peening specifications are made. They include but are not limited to the following:

- application
- geometric configuration of part
- material hardness and heat treatment used
- material
- surface finish requirements before and after shot peening
- optional peening methods and additional considerations—strain peening, dual-intensity peening, plating and salvage methods, contour correction (forming) peening, increasing wear due to work hardening, porosity (closure in powdered metal parts and castings), salvage/grinding both before and after, and stress-corrosion cracking.

The primary consideration in shot peening gears is to determine if the process is to be used to increase bending fatigue strength of gear teeth, increase surface fatigue life, or change the texture to either break up continuous machining marks or to aid lubrication of the gear face.

Numerous variables enter into how the gear's ultimate fatigue strength will be determined. Figure 8 shows the variety of possibilities. Residual compressive stress has specific effects on fatigue and on hardness and microstructure.



Numerous metallurgical variables affect a gear's ultimate fatigue strength.

As noted by Dudley and Seabrook,[9] shot peening is beneficial, and the fillets at the gear root should be peened. The authors show no hesitation in recommending the practice of shot peening for carburized and hardened teeth despite their high hardness and brittleness.

Typically, a gear has 20 to 30 percent additional load-carrying capability if its root fillets are peened. Similar results were noted on through-hardened and induction-hardened gearing. (See reference No. 10 through No. 12.)

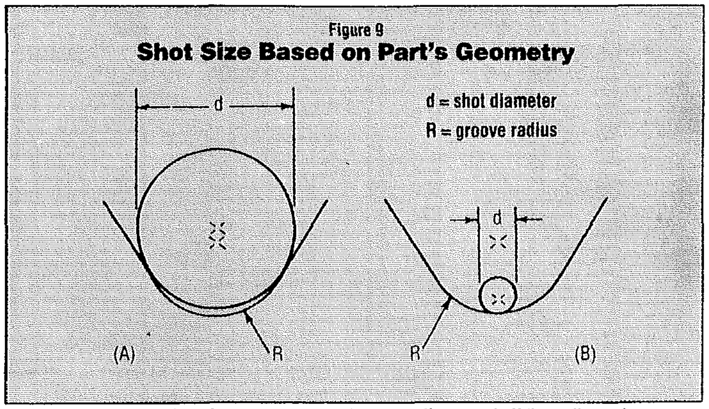
It also should be determined if surface pitting found at the pitch line is the primary fatigue concern, or whether fatigue at the root because of tooth flexure is primary. NASA tests on the effect of surface fatigue life of carburized and hardened spur gears[13] noted a 60 percent increase in the life of gears that are shot peened to combat this phenomenon. Another consideration is whether the peening will be used primarily to improve surface finish, called texturizing, rather than to introduce beneficial residual compressive stresses.

The texture produced by the peened surface consists of homogeneous, overlapping dimples that can be used to eliminate stress risers produced by various machining processes, such as hobbing. Generally, this operation is performed in the "green state" of the gear just prior to heat treatment. Proper shot selection depends on how disrupted the surface will be. At a given intensity, large shot produces a smoother finish than small shot.

Another way to produce a texture is to carburize the gears, slow cool to a hardness higher than the green state, follow with a texturizing shot peening process, and then fully harden. Any compressive stresses produced prior to heat treatment will be dissipated due to the heat treatment. Shot peening after heat treatment will be required to produce a surface with compressive stresses if either of the two fatigue conditions also need consideration.

An additional consideration is whether the dimpling will be used to aid gear lubrication. But this rarely is the primary consideration.

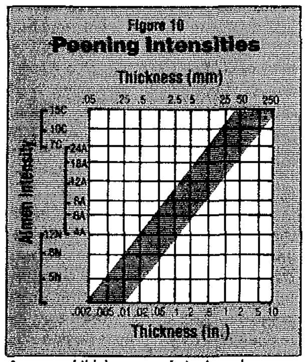
After determining the reason for shot peening, the next step is to determine shot size based on the part's geometry. The general rule used for MIL 13165-B is that the maximum shot diameter **d**, as shown in Figure 9, must be equal to no more than 1/2 R (the radius to be peened). For example, in **A** of Figure 9, it is obvious that the shot is too large and will not provide full coverage in the fillet radius.



Generally, maximum shot diameter must equal no more than one-half the radius to be peened. For this part, (A) shows a shot size that is too large (d=22R), while (B) shows the maximum shot size permitted according to military specifications (d=½R).

After determining the geometry into which the shot will move, the intensity of the shot is determined.

The general guideline is that the depth of compression cannot be greater than 10 percent of the thickness of the part. Figure 10 provides an example of a range of thicknesses of steel that can be peened at a given intensity and illustrates the range of intensities that can be used for any given thickness. For example, at a 4A intensity, steel thicknesses from 0.018 in. to 0.15 in. can be peened. Figure 10 indicates that a steel part with a cross section of 0.150 in. can be peened with an intensity as low as 4A and as high as 14A.

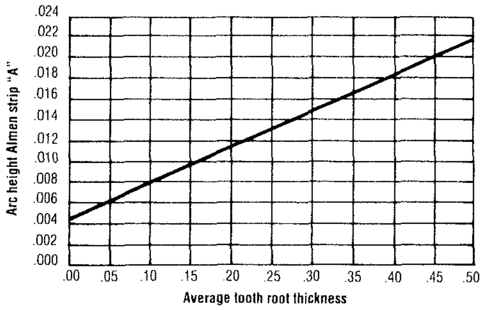


A range of thicknesses of steel can be peened at any given intensity. Generally, the depth of compression must not be greater than 10 percent of the part's thickness.

Optimum selection of the correct intensity is a function of shot size used, coupled with the hardness of the target material. Curves that provide examples for depth of compression should be used, but remember that the depth of compression must not exceed 10 percent of the thickness of a part per peened side or a total of no more than 20 percent of the cross section of a component.

Figure 11 shows Almen intensity as a function of average tooth root thickness. Note that it does not take into account various hardnesses of gear teeth, which could have an effect on selecting an optimum peening intensity. Still, it can be used as a guideline for carburized and hardened gears.

Figure 11
Average Tooth Root Thickness



Although this figure shows Almen intensity as a function of average tooth root thickness,[15] it does not take into account various hardnesses of gear teeth, which could affect selection of optimum peening intensity. This chart can be used for carburized and hardened gears.

Realizing some of the difficulties in selecting an optimum shot intensity for a given gear type and material, the American Gear Manufacturers Association provides a list of typical shot size and intensity for shot peening based on diametral pitch as a guide.[16] Henry Fuchs' paper, "Optimum Peening Intensities", explains in depth a method for selecting optimum peening intensities.[17]

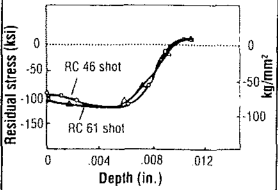
In general, when a shot size is selected based on the gear's geometry, the maximum intensity should be used. The maximum intensity should provide a depth of compression not exceeding 10 percent of the gear's cross section at any point where the shot stream comes into contact with the thinnest cross section of that gear. To do this, proper charts showing depths of compression generated as a function of material type and hardness should be reviewed. See Figure 3 or Reference 5.

Heat Treat Methods

After the application, shot size and intensity have been determined, the next step is to determine if the intensity selected is correct to meet the depth of compression based on the material hardness. Figure 2 shows that the higher the ultimate tensile stress, the higher the magnitude of compressive stress. The 50/60 percent relationship of the compressive stress to the ultimate tensile stress is maintained as long as shot hardness is equal to or greater than the surface hardness of the gear.

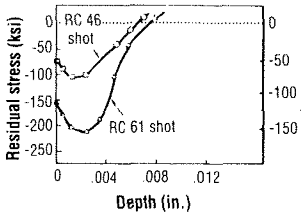
Figure 12 clearly shows that when the target material hardness closely approximates the shot hardness, no difference occurs in the magnitude of the compressive stress or the depth of compression. However, when the target material hardness is greater than the shot hardness, a significant decrease in the residual compressive stress magnitude results (RC 46 shot curve at a maximum compressive stress of 100 ksi vs. RC 61 shot, providing in excess of 200 ksi) as well as a decrease in the compression depth. See Figure 13. This was confirmed when tests were performed peening high-strength steel using not only RC 65 shot but also ceramic shot and RC 46 cast steel. In Figure 14, average fatigue life was higher for both ceramic and hard shot than for RC 46.

Figure 12
Peening 1045 Steel At RC 48



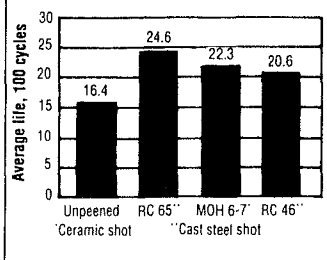
When the target material hardness closely approximates the shot hardness, no difference occurs in the magnitude of compressive stress or depth of compression.

Figure 13
Peening 1045 Steel At RC 62 with 330 Shot



When target material hardness is greater than the shot hardness, a significant decrease in residual compressive stress magnitude results, as well as a decrease in compression depth.

Figure 14
Fatigue Life vs. Shot Hardness

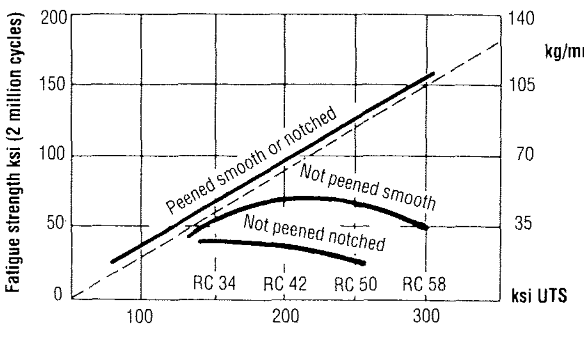


Average fatigue life was higher for both ceramic and hard shot than for RC 46 shot after shot peening high strength RC 55 steel.[19]

The benefits of using hard shot on high hardness gear materials was further demonstrated in a paper by Miwa, et al.[8] Further support for using high hardness shot for high hardness materials rather than increasing the intensity of shot peening is provided in Reference 20.

As the hardness of a material increases so does the ultimate tensile strength of that material. However, as the hardness increases, a noticeable decrease in the fatigue strength in some materials may result because of an increase in notch sensitivity and brittleness, as shown in Figure 15. For those steel specimens shown at a hardness above RC 42 that have not been shot peened, fatigue strength decreases as ultimate tensile strength increases. By changing to peening with hard shot and peening the high strength steel, not only will a higher ultimate tensile strength result, but the fatigue strength of the material also will be increased.

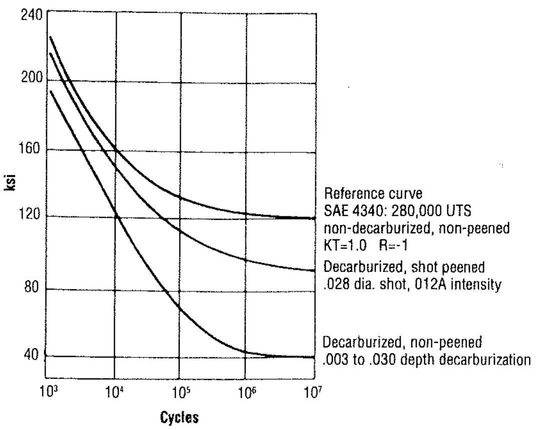
Figure 15
Tensile Strength Affects Fatigue Limits



As hardness increases, a noticeable decrease in the fatigue strength in some materials may result because of an increase in notch sensitivity and brittleness.[5, 21]

An additional consideration is whether decarburization may occur in heating the steel. Decarburization, the loss of carbon at the surface of a ferrous material, can result in the loss of fatigue strength of high strength steel. Figure 16 shows how shot peening can restore almost all the fatigue strength that had been lost.

Figure 16
Effect of Shot Peening on Decarburization



Shot peening is capable of restoring almost all fatigue strength lost as a result of decarburization in high-strength steel.[22]

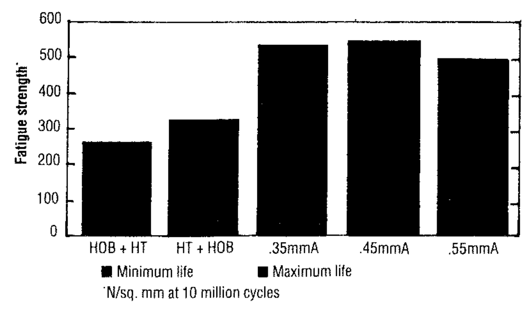
If decarburization may occur, incorporating shot peening into a part's design can ensure component integrity. Essentially, the hardness of the material must be considered to determine the depth of the compressive stress, whether hard shot is to be used and whether decarburization will be a factor.

Material Consideration

Another major consideration is to determine if the media and intensity chosen to this point will have any adverse or additional desirable effects on the target material. Representative curves of shot peened material of a similar nature are helpful in calculating the depth of compressive stress,[5] but certain questions must be answered:

- Will the selected peening media contaminate the target material? For instance, the use of cast steel shot on an austenitic stainless steel may require chemical passivating or other mechanical cleaning methods.
- Would it be preferable to use other peening media, such as stainless steel, ceramic or glass?
- Is work-hardening possible and/or desirable? For example, austempered ductile iron (ADI) not only responds well to shot peening by increasing fatigue strength but also has the added benefit of work-hardening. Fatigue strength increases for ADI at various peening intensities as shown in Figure 17. Reference No. 23 through No. 26 support not only the fatigue benefits for ADI but also the improved wear characteristics caused by desirable work-hardening. Other materials, such as high manganese-content steel and austenitic stainless steels, also will readily work-harden.

Figure 17
Processing Variables Affect Bending Fatigue Strength



Processing variables affect the bending-fatigue strength of austenitic-bainite (K9805) gear teeth: measurement after 10 million cycles, heat treatment after hobbing, hobbing after heat treatment, shot peening 0.35mm Almen A, shot peening 0.45 Almen A, and shot peening 0.55 mm Almen A.

- Does the material have a tendency towards different microstructures, such as retained austenite? If the retained austenite is excessive, significantly reduced compressive stress magnitudes will be noted unless hard shot is used.[8]
- Will the material respond favorably to the selected shot size or should an alternate size be used? For instance, aluminum alloys respond better at a given intensity to larger shot at a low velocity than to small shot at a higher velocity. Though both conditions could produce the same intensity, larger shot is more desirable if geometric constraints allow it.
- Is the gearing of a powder metallurgy? Special considerations must be made if it is. However, if handled properly, fatigue life improvement due to increased hardness and due to residual compressive stresses is possible.[27]

Surface Finish

Additional consideration should be given to the desired surface finish before and after shot peening.

Note that a shot peened surface's overall dimension will increase slightly because new measurements are taken at the tops of peaks produced by the dimpling action. This growth depends upon hardness of target material as well as shot size and intensity used, but typical growth rarely exceeds 0.0005 in. per side. If this size change will be detrimental from the standpoint of fit, samples of the material should be peened experimentally before working with actual parts. All typical drawing dimensions should reflect dimensions prior to peening.

As a general rule, original surface finishes above 125 RMS can be improved by peening, whereas surfaces below 125 RMS generally will be increased in surface roughness, depending on material type and hardness, shot size and intensity. Samples should be provided to confirm desired results.

If a surface finish is required that will be finer than one produced by shot peening, certain machining processes may be performed after peening. Cool processes, such as lapping and honing, are allowed because they do not generate much heat and will not dissipate compressive stresses. However, material removal must be limited to no more than 10 percent of the depth of compression. Additional material removal will adversely affect all peening benefits.

References

1. Lawerenz, M. "Shot Peening and its Effect on Gearing." SAE Paper 841090, March 1984
2. Daly, J. "Boosting Gear Life Through Shot Peening." *Machine Design,* May 12, 1977.
3. Koinis, X. "Shot Peening—A Viable Method to Extending Component Life." SAE Paper 891932, September 1989.
4. Burrell, N.K. "Improved Gear Life Through Controlled Shot Peening." *Gear Technology,* September/October 1986.
5. Fuchs, H.O. *Shot Peening Stress Profiles,* 1987.
6. "Protective Shot Peening of Propellers." R.F. Broderick Technical Report 55-56, Parts I, II, III. Wright Air Development Center.
7. Shot Peening Applications. Metal Improvement Co., Seventh Edition, 1989.
8. Miwa, Y., et. al. "Carbonitriding and Hard Shot Peening for High Strength Gears." SAE Paper 88066.
9. Seabrook, J.B. and Dudley, D. "Results of a Fifteen Year Program of Flexural FatigueTesting of Gear Teeth." August 26, 1963.
10. Haas, L. "How to Extend Gear Life." *Machine Design,* May 15, 1973
11. "Shell Pinion Concept Boosts Gear Capacity." *Iron Age,* October 11, 1973.
12. Daly, J. "Using Controlled Shot Peening in Original Gear Design." AGMA Technical Paper No. 87, FTM 13.
13. Townsend, D. and Zaretsky, I. "Effect of Shot Peening on Surface Fatigue Life of Carburized and Hardened AISI 9310 Spur Gears." NASA Technical Paper 2047-1982.
14. Fuchs, H.O. *Shot Peening. Mechanical Engineers Handbook,* 1966.
15. Straub, J.W. "Shot Peening in Gear Design." *AGMA* 109. 13. June 1964.
16"Gear Materials and Heat Treatment Manual."*AGMA* 2004-BXX,January 1988.
17. Fuchs, H.O. *Optimum Peening Intensities.* 1987.
18. Lauchner, E. March 1974. Westel Presentation, Northrop Corp.
19. "Hard Shot Peening and Ceramic Shot Peening Effects on Fatigue of High Strength Steel." S. Lee Grumman Aerospace Corp. December 1986.
20. Inoue, K., et al. *Fatigue Strength and Crack Growth of Carburized and Shot Peened Spur Gears.*

21. Horger, O.J. "Mechanical and Metallurgical Advantages of Shot Peening." *The Iron Age,* March 29, April 5, 1945.
22. Bush, W.F. "Fatigue Tests to Evaluate Effects of Shot Peening on High Heat Treated Steel." Lockheed Report No. 9761.
23. Blackmore, P.A. and Harding, R.A. "The Effects of Metallurgical Process Variables on the Properties of Austempered Ductile Irons." First Inernational Conference on Austempered Ductile Iron. April 2-4, 1989.
24. Lottridge, N. and Grindahl, R. "Nodular Iron Hypoid Gears." SAE Paper 820696.
25. "ADI: Status of Emerging Technology." *Power Transmission.* August 1986.
26. Harding, R.A. *The Use of Austempered Ductile Iron for Gears.* 1986.
27. Sonsino, C.M., et. al. "How to Improve the Fatigue Properties of Sintered Steels by Combined Mechanical Thermal Surface Treatments." *Modern Developments in Powder Metallurgy,* Vol. 15-17, 1985.

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