Optimum Shot Peening Specification-I

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Abstract: Shot peening is widely recognized as a proven, cost-effective process to enhance the fatigue characteristics of metal parts and eliminate the problems of stress corrosion cracking. Additional benefits accrue in the areas of forming and texturizing. Though shot peening is widely used today, the means of specifying process parameters and controlling documents for process control are not widely understood. Questions regarding shot size, intensity, and blueprint specification to assure a high quality and repeatable shot peening process are continually asked by many design and materials engineers.

This article should answer many of the questions frequently asked by engineering professionals and to further assist companies interested in establishing a general shot peening specification.

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

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

We have assumed that the reader of this article understands the basics of shot peening and its effect on gearing and realizes that shot peening is an effective tool for combating problems of fatigue and stress corrosion cracking, as well as for assisting in forming and correction of shape. A brief discussion of the theory of shot peening is provided, but the reader should consult Refs. 1-4 for a more in-depth review.

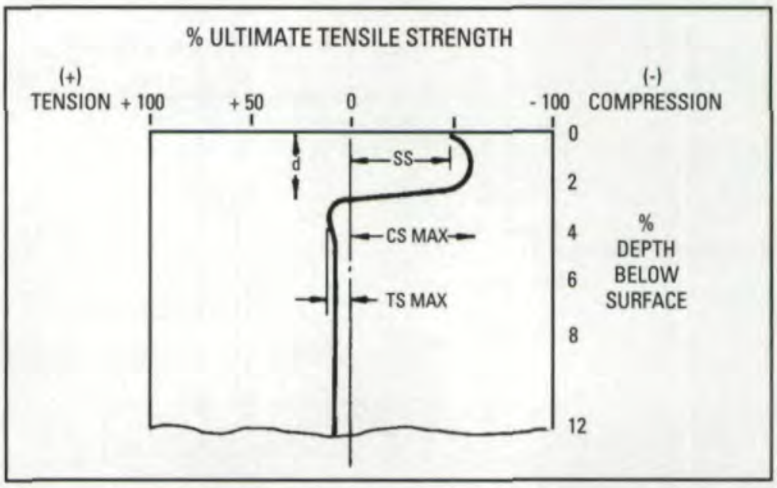

Fig. 1 - Example of residual stress profile created by shot peening.

Shot Peening Theory

Shot peening, by definition, is the bombardment of a 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 application of loads to a component. The magnitude and depth of these compressive stresses are predictable. As shown in Fig. 1,[5] the maximum compressive stress usually occurs at some distance below the peened surface, which is represented by the top horizontal line. Typically, this magnitude of compressive stress (CS MAX) is approximately 50-60% of the ultimate tensile strength of the material, as shown in Fig.2.[6] (Dual intensity peening can move the CS MAX closer to the surface of the peened material.) Since this method is not typically employed, Fig. 1 is adequate for this discussion. The "d" represents the depth of compression or the point at which

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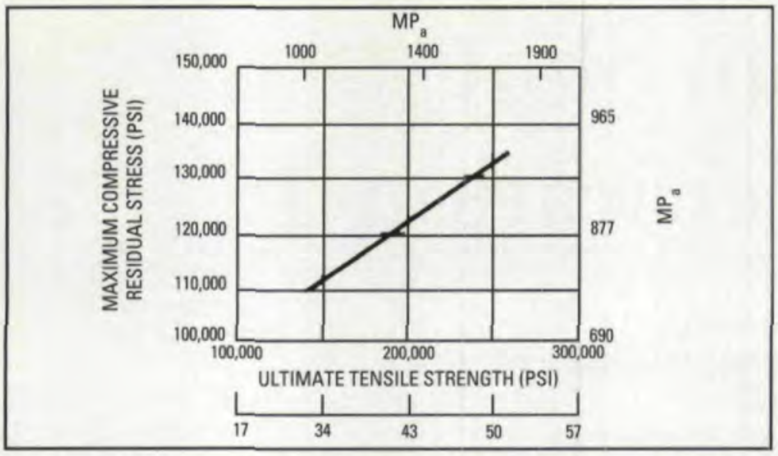

Fig. 2 - Residual stress produced by shot peening vs. tensile strength of steel.

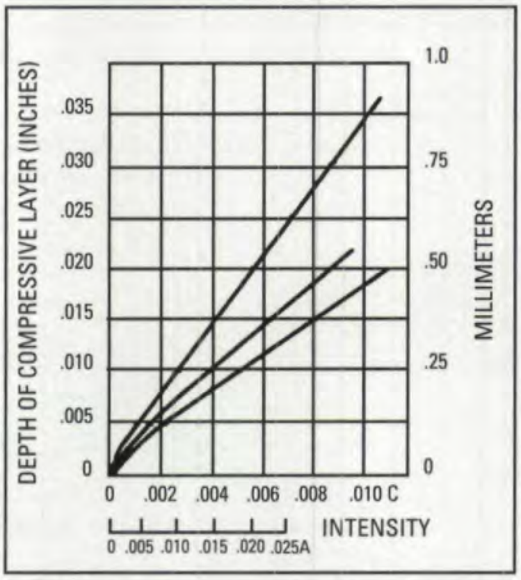

Fig. 3 - Depth of compression vs. Almen arc height.

the compressive stress induced by the peening crosses the neutral axis and becomes tensile.

The depth, as shown in Fig. 3, is dependent 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 52R_c material, the depth of compression will be about .008". Additional curves for various materials are available in detail in Ref. 5.

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

Residual tensile stresses can decrease the fatigue life of a component. Compressive stresses, however, tend to increase fatigue life. Some machining processes will 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.

Shot Peening Controls

Certain basic controls must be introduced into any in-house company specification on shot peening. *Specifications*, *such as AMS 2430* and Military Specification MILS-13165-B, deal extensively with these. Since the intent of this article is to better enable the design engineer to properly specify other areas, we will touch briefly on the controls. The reader should consult reference sources which more thoroughly explain these points.

To assure proper shot peening the engineer must: A) determine the intensity; B) maintain and control the integrity of the shot; C) assure that coverage is complete; and D) ascertain 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 will then degenerate into nothing more than a blasting operation, as used in cleaning, potentially leading to severe damage to the fatigue properties of a part.

INTENSITY - Intensity is determined by application of a shot stream to a metal strip known as an Almen strip. Three gauges of these strips exist: The "N" strip, the "A" strip, and the "C" strip. The "N" strip is used for light-intensity peening, the "C" strip for high-intensity peening, and the "A" strip for medium-range peening. The proper strip is selected, mounted in an Almen block, and a shot stream is applied to the exposed surface. After proper exposure time, the strip is removed from the block (Fig. 4a). The strip deflects upward toward the peened surface (Fig. 4b), and the arc height is measured by the use of an Almen gauge (Fig. 4c). The arc height of the strip and the amount of time the strip was exposed to the shot stream are noted.

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

SHOT INTEGRITY - Numerous controls go

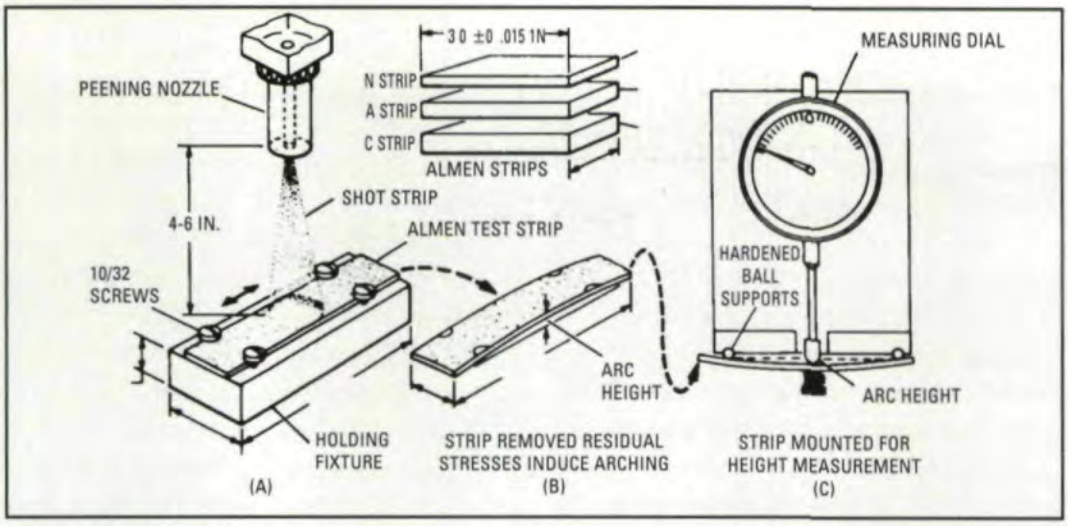

Fig. 4 - The Almen strip system.

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 would typically be used in a blasting operation. Left in an improperly controlled state, shot of the latter type could produce unacceptable surfaces, as shown in Fig. 6a. Properly peened surfaces produced by controlled shot should appear as shown in Fig. 6b. The primary equipment used to assure 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.

In addition to use of the classifier, techniques to qualify the shot prior to use should include methods to determine porosity and means to determine breakdown of shot, as well as a method to confirm proper 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, which should be used for peening.

COVERAGE - A properly peened surface should have many overlapping dimples, referred to as an "orange skin" or "orange peel" effect. (See Fig. 7b.) Fig. 7a represents a partially covered surface and should never been seen. Proper coverage can be determined by the use of a ten power (10x) magnifying glass or by the Peenscan® process. The Peenscan process is a method of viewing coverage of a surface by ultraviolet light after it has been treated with a material similar to a dye penetrant, which is

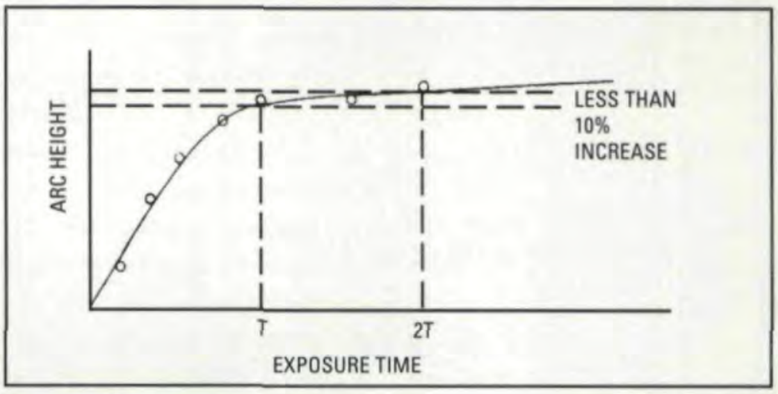

Fig. 5 - Saturation curve.

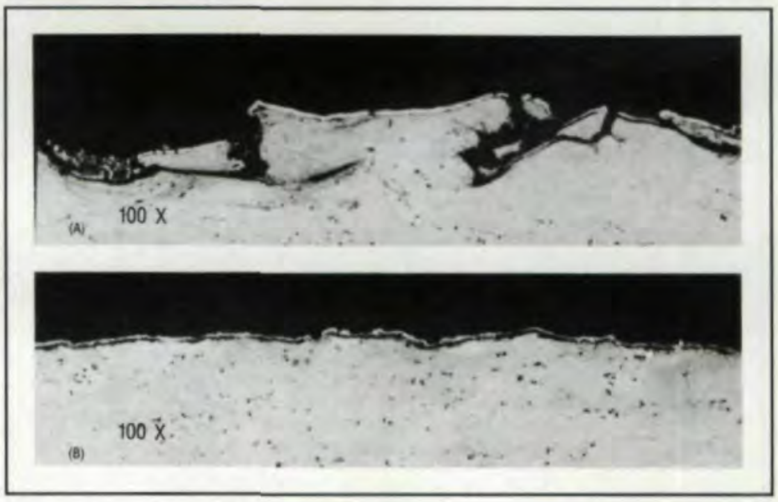

Fig. 6 - A) Surface damage caused by poor shot control. B) Acceptable surface accomplished through good shot control.

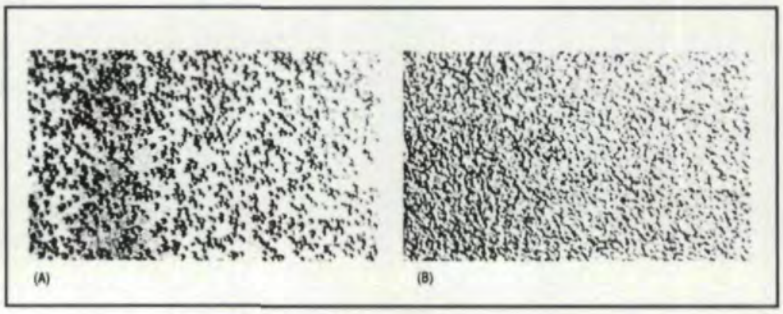

Fig. 7 - Shot peening coverage. A) Partial. B) Full.

removed by a peening operation. Areas that have not been peened properly will glow under a black light.

EQUIPMENT TO BE USED - The engineer must determine whether the equipment to be used is computer-controlled or automated without computer control. Computer-controlled equipment will typically be used for more sophisticated parts and where repeatability and computer printouts for the monitoring of process variables are required. This is the most sophisticated (and usually most expensive) peening method. A sample of a software path flow diagram is shown in Fig. 8. Primary monitoring points are shown on the left-hand column.

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

Considerations for a Shot Peening Specification

Now that we have briefly discussed the theory of shot peening and the necessity for good controls to assure repeatability, the following considerations should be applied to any gearing. These items should be reviewed in any general specification before any shot peening specification is made. They include, but are not limited to, the following:

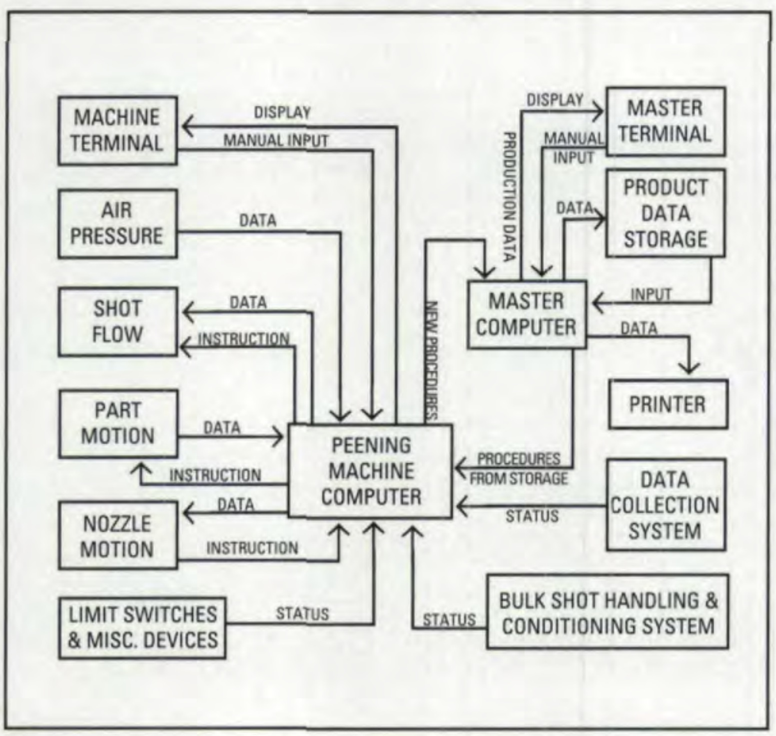

Fig. 8 - Software path flow diagram.

- Application
- Geometric configuration of part
- Material hardness and heat treatment
- Material
- Surface finish requirements before and after shot peening
- Optional peening methods and additional considerations, which might include the use of:
  - 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 - before and after
  - Stress corrosion cracking.

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

Numerous variables enter into how the gear's ultimate fatigue strength will be determined. Fig. 9 shows the variety of possibilities. We will specifically address the effect that the residual compressive stress has on the fatigue strength, along with the effect on hardness and microstructure.

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 carburized and hardened teeth, despite the high hardness and brittleness. Typically, 20-30% additional load-carrying capability is anticipated if root fillets are peened. Similar results were noted on through-hardened and induction-hardened gearing. Gears are probably the second-most commonly peened item in this country, so further discussion on this point is not necessary. (See Refs. 10-12).

It should also be determined if surface pitting found at the pitch line is the primary fatigue concern, or whether fatigue at the root because of the tooth flexure is primary. Tests by NASA on the effect of surface fatigue life of carburized and hardened spur gears(13) exhibited a 60% increase in life of the gears when shot peening was used to combat this phenomenon.

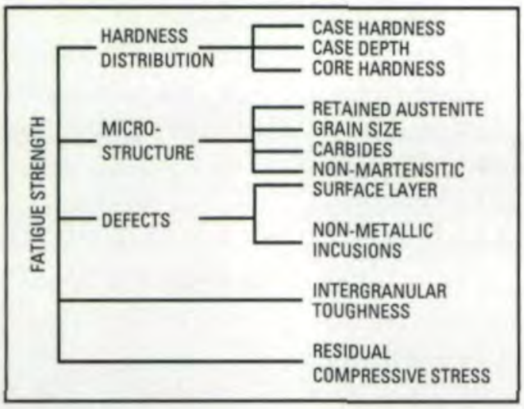

Fig. 9 - Metallurgical factors affecting the fatigue strength of gears.

The question of which fatigue problem is of primary concern is important when making a proper shot size selection. This will be considered further in the following section on geometry.

A third consideration is whether the peening will be used not primarily to introduce beneficial residual compressive stresses, but rather to improve surface finish. The texture produced by the peened surface consists of homogeneous, overlapping dimples which can be used to eliminate stress risers produced by various machining processes, such as hobbing. Typically, this operation is performed in the "green state" of the gear just prior to heat treatment. Proper shot selection is dependent on how disrupted the surface will be. At a given intensity, a larger size shot will produce a smoother finish than small shot.

An additional consideration is whether the dimpling will be used to aid in gear lubrication. This, however, is rarely the primary consideration. A variation of the use of different sizes of shot to produce a texture is to carburize, then slow cool to a hardness higher than the "green state," follow with a texturized shot peening, and then fully harden. Any compressive stresses produced prior to heat treatment will be dissipated in either texturizing case. Shot peening after heat treatment will be required to produce a surface with compressive stresses if either of the two fatigue conditions also need to be considered.

GEOMETRIC CONFIGURATION OF A PART - After the reason for the use of the shot peening has been determined, the next step is to determine the shot size based on the geometry of the part. The general rule used per Military Specification MIL 13165-B states that the maximum shot diameter "d," as shown in Fig. 10, must be equal to no more than 1/2 R (the radius to be peened). For example in Fig. 10a, it is obvious that the shot is too large and will not provide full coverage in the fillet radius.

After determination of the geometry into which the shot will move, the intensity of the shot must be determined. The general guideline is that the depth of compression cannot be greater than 10% of the thickness of the part. Fig. 11 provides an example of a range of thicknesses of steel that can be peened at a given intensity. *The chart also illustrates the range of intensities that can be used for any given thickness.* For example, at a 4A intensity, steel thicknesses from .018" to .15" could be peened. The same graph indicates that a steel part with a cross-section of .150" could be peened with an intensity as low as 4A and as high as 14A. Optimum selection of the correct intensity is a function of the size of the shot to be used, coupled with the hardness of the target material. Curves which provide examples for depth of compression should be used, remembering that the depth of compression cannot exceed 10% of the thickness of a part per peened side, or a total of no more than 20% of the cross section of a component.

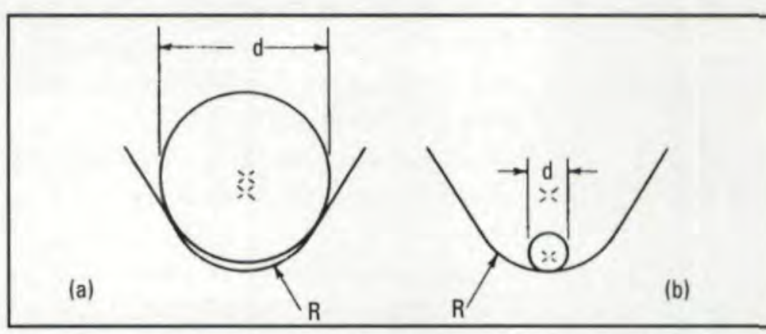

Fig. 10 - Shot diameter d and groove radius R. A) Shot size too large, d = 2.2 R; B) Maximum shot size permitted by Ref. 9, d = 1/2 R.(14)

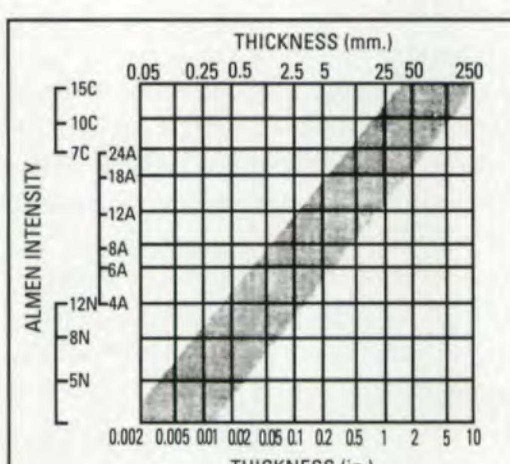

Fig. 11 - Peening intensities commonly used on steel parts of different thickness.(14)

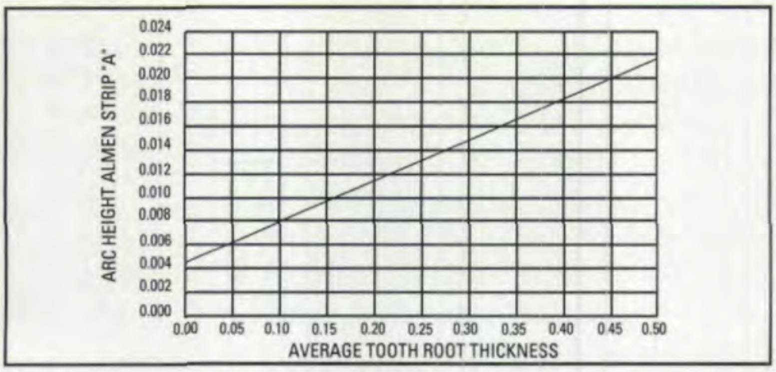

Fig. 12 - Average tooth root thickness.[15]

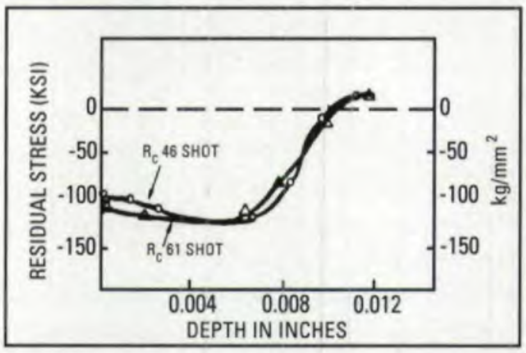

Fig. 13 - Peening 1045 steel at R_c 48.[18]

Fig. 12 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, but it could be used as a starting guideline for carburized and hardened gears.

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

In general, once a shot size is selected based on the geometry of the gear, the maximum intensity should be used. This maximum intensity should provide a depth of compression not exceeding 10% of the cross section of the gear 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 Fig. 3 or Ref. 5).

MATERIAL HARDNESS AND HEAT TREATMENT METHODS - After the application, shot size, and intensity have been determined based on the part geometry, the next step is to determine if the intensity selected is correct to meet the depth of compression based on the material hardness. As shown in Fig. 2, the higher the ultimate tensile stress, the higher the magnitude of compressive stress. The 50-60% relationship of the compressive stress to the ultimate tensile stress is maintained as long as the shot hardness is equal to or greater than the surface hardness of the gear.

Fig. 13 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 ($46R_c$ shot curve at a maximum compressive stress of 100 KSI versus $61R_c$ shot, providing in excess of 200 KSI) results, as well as a decrease in the depth of compression. (See Fig. 14.) This was confirmed when tests were performed peening high-strength steel using not only 65 HRC shot, but also ceramic shot and 46 HRC cast steel. In Fig. 15, average fatigue life was higher for both ceramic and hard shot than for 46 HRC shot.

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 the use of high-hardness shot for high-hardness materials even over increasing the intensity of shot peening is provided in Ref. 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 Fig. 16. For those steel specimens shown at a hardness above $42R_c$ that have not been shot peened,

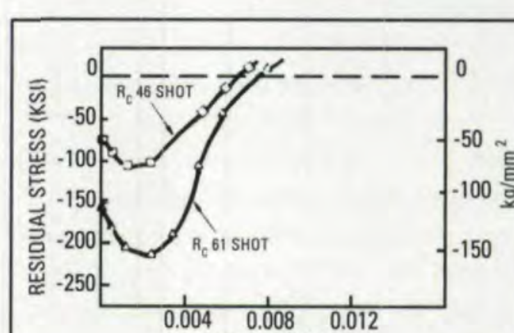

Fig. 14 - Peening 1045 steel at R_c 62 with 330 shot.

fatigue strength decreases as the 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.

An additional consideration is whether decarburization may occur in heating the steel. Decarburization is the loss of carbon at the surface of a ferrous material, and it can result in the loss of fatigue strength of high-strength steel. Fig. 17 exhibits the capability of shot peening to restore almost all of the fatigue strength. If decarburization is suspected, incorporating shot peening into a part design can insure 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 - The fourth 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 determining the depth of compressive stress,[5] but the following factors also must be considered:

Will the peening media selected 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 instance, 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 are shown in Fig. 18. Refs. 23-26 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, will also readily work harden.

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 utilized.[8]

Will the material respond favorably to the shot size selected, or should an alternate shot size be

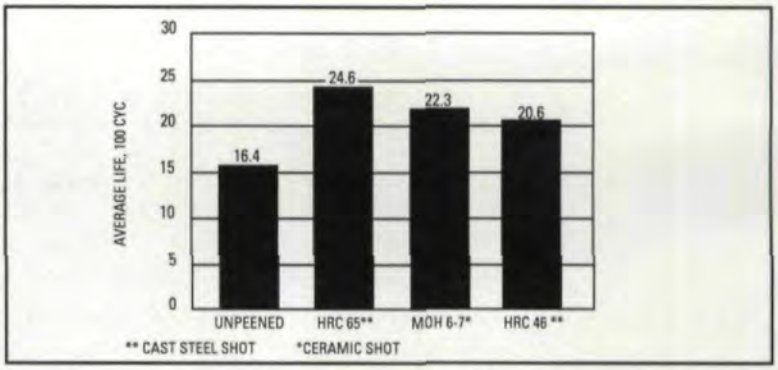

Fig. 15 - Shot peening high strength steel R_c 55. Fatigue life vs. shot hardness.[19]

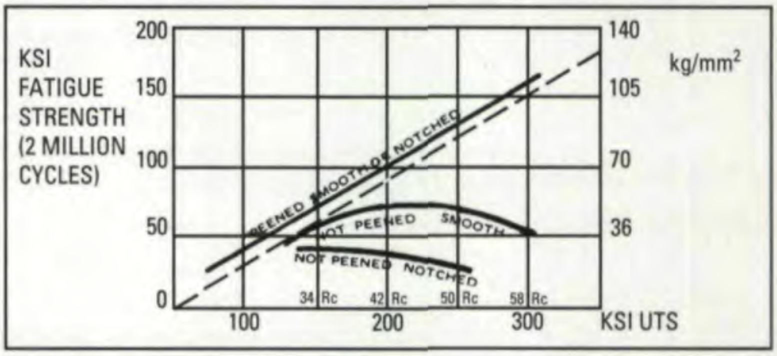

Fig. 16 - Comparison of peened and unpeened fatigue limits for smooth and notched specimens as a functions of ultimate tensile strength of steel.[6, 21]

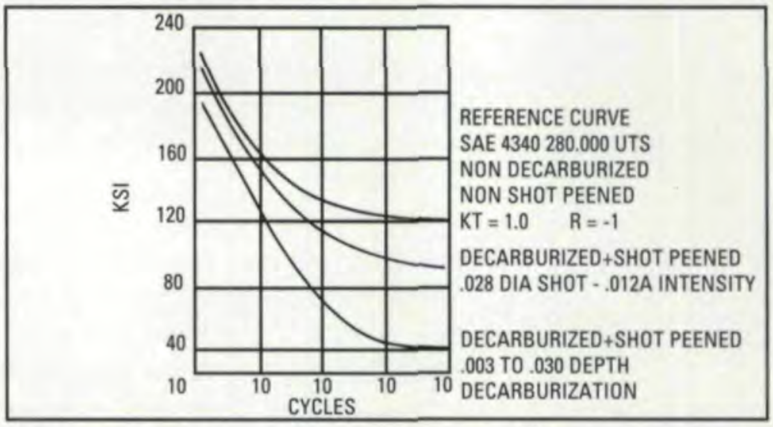

Fig. 17 - Effect of shot peening on decarburization.[22]

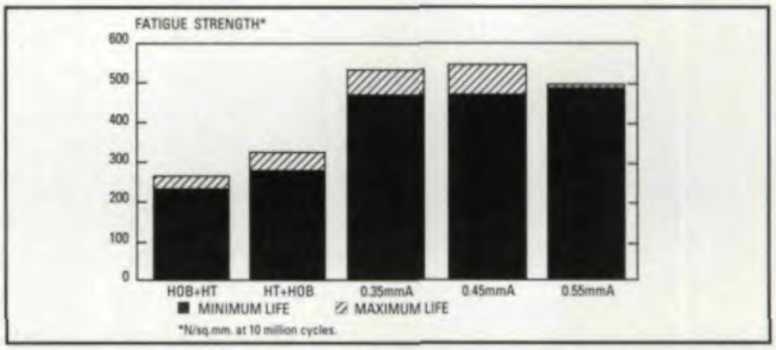

Fig. 18 - The effect of processing variables on the bending-fatigue strength of austenitic-bainitic (K9805) gear teeth: Measured after 107 loading cycles. Heat treatment after hobbing. Hobbing after heat treatment. Shot peening 0.35mm Almen A. Shot peening 0.45mm Almen A. Shot peening 0.55mm Almen A.[23]

selected? For instance, aluminum alloys will respond better at a given intensity to a larger shot size at a low velocity than to small shot at a higher velocity. Though both conditions could produce the same intensity, the larger shot size is more desirable if geometric constraints allow it.

Is the gearing of a powder metallurgy? Special considerations must be made here; however, if handled properly, fatigue life improvement due to increased hardness and residual compressive stresses is possible.[27]

SURFACE FINISH REQUIREMENTS BEFORE AND AFTER SHOT PEENING - Additional consideration should be given to the desired surface finish before and after shot peening. First, note that a shot peened surface's overall dimension will increase slightly because new measurements will be taken at the tops of peaks produced by the dimpling action. This growth is dependent upon hardness of target material as well as the shot size and intensity used, but typical growth rarely exceeds .0005" per side. If this change in size will be detrimental from a 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 guide, original surface finishes above 125 RMS can be improved by peening, whereas surfaces below 125 RMS will typically be increased in surface roughness, depending on material type, material hardness, shot size, and intensity used. Samples should be provided to confirm desired results.

Selective peening can be performed so that seal and bearing surfaces, along with other critical surface finishes, can be protected. These should be noted accurately on all drawings. In addition, any cleanliness requirements should be shown to properly protect these areas during peening.

If a surface finish in a peened area is required which will be finer than that produced by shot peening, certain machining processes may be performed after the peening. Cool processes, such as lapping and honing, are allowable, as they do not generate much heat and will not dissipate compressive stresses; however, material removal is limited to no more than 10% of the depth of compression. Additional material removal will adversely affect all benefits of the peening. ■

Part II of this article will run in our next issue. It will discuss Optional Shot Peening Methods and Specifying Shot Peening.

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