AMERICAN GEAR MANUFACTURERS ASSOCIATION

Shot Peening of Gears

AGMA INFORMATION SHEET

(This Information Sheet is NOT an AGMA Standard)

American Gear Manufacturers Association –

Shot Peening of Gears

1 Scope

The purpose of this document is to provide an informational tool for gear designers interested in the residual compressive stress properties produced by shot peening and its relationship to gearing.

Information on shot peening and residual stress is subject to some interpretation; therefore, this document is classified as an information sheet and not a standard. This document intentionally avoids any reference to quantifying potential increases in gear ratings through the use of shot peening. Any ratings increase attributed to shot peening should be agreed upon between the gear manufacturer and purchaser, and preferably verified through testing.

This document is intended for use by those experienced in gear materials and design. It is not intended for use by the engineering public at large.

Annex A provides figures and tables in U.S. customary units.

2 Normative references

The following documents contain provisions which, through reference in this text, constitute provisions of this information sheet. At the time of publication, the editions were valid. All publications are subject to revision, and the users of this information sheet are encouraged to investigate the possibility of applying the most recent editions of the publications listed.

ANSI/AGMA 1012-G05, *Gear Nomenclature, Definitions of Terms with Symbols*.

AMS-S-13165, *Shot Peening of Metal Parts* (formerly MIL-S-13165).

3 Theory of shot peening

The primary purpose for shot peening is to induce beneficial residual compressive stresses in the subsurface layer of a part. This occurs by bombarding a metal's surface with small, round particles called shot. Each impact of the shot media has the effect of leaving a small hemisphere of residual compressive stress that occurs from localized yielding of the base material at the point of shot impact. The material's surface attempts to restore itself, but is restrained by adjacent material, resulting in a residual compressive stress. Through repeated impacts that create overlapping dimples, a uniform layer of residual compressive stress can be expected, provided the shot peening process and media are carefully controlled.

During service, a gear root fillet is subject to repeated bending loads. These loads generate applied tensile stresses which are highest in the material's subsurface layer. With the addition of shot peening, applied bending stresses are opposed by residual compressive stresses that have the effect of resisting fatigue crack initiation and growth throughout the compressive layer. For bending fatigue improvement, shot peening should extend, as a minimum, from the bottom of the root fillet past the tangent point between the root and flank.

The beneficial characteristics of residual compressive surface stresses are associated with their effects on fatigue crack initiation behavior. Net stress is the summation of applied and residual stress. When the magnitude of the residual compressive stress is greater than the magnitude of the applied tensile stress, a net compressive stress is created. In theory, fatigue cracks will not initiate in a net compressive stress zone. In addition, fatigue cracks do not propagate as readily in a compressive stress zone.

Residual compressive surface stresses are effective in improving bending fatigue life in the elastic material behavior (high cycle fatigue) regime. Loading in the plastic material behavior (low cycle) regime eliminates life improvement effects of residual compressive stresses. Failures in the elastic material regime generally initiate at the surface, making surface compressive stresses effective.

Residual compressive stress can fractionally increase the elastic endurance strength or significantly increase high cycle fatigue life. Endurance strength improvements with compressive stress are not a direct correlation and only applicable in the elastic behavior regime. For example, introduction of 700 MPa of residual compressive stress does not translate to a 700 MPa improvement in endurance strength. The bending fatigue improvement trends with shot peening are shown in figure 1.

Gear designs typically experience bending fatigue enhancement when properly shot peened. Since gear manufacturing techniques and applications differ dramatically, it is difficult to predict specific bending fatigue increases.

Shot peening may be used to mitigate conditions that reduce high cycle fatigue behavior such as geometrical stress risers, machining stresses, grinding damage, or intergranular oxidation. When using shot peening to mitigate stress riser effects, the depth of the compressive layer must exceed the stress riser depth.

The response of surface microstructures to shot peening is highly dependent on the amount of retained austenite. Shot peening will induce sub-microscopic dislocations, strain induced phase transformations, or both. The retained austenite transformation may improve residual compressive stress effects due to the volume increase that occurs with martensite transformation.

4 Effects of shot peening

The shape of a typical residual stress curve from shot peening is shown in figure 2 and is a function of the hardness and strength of the material at the surface. Heat treatment and surface microstructure have significant effects on the residual stress resulting from shot peening.

The important features of this curve are discussed below.

4.1 Maximum compressive stress

Maximum compressive stress is proportional to the hardness and strength of the gear material's surface being shot peened. For steel gears, a user can approximate this value by multiplying the ultimate tensile strength by a factor of 55%. For example, a gear surface with a hardness of 55 HRC (2000 MPa tensile strength) will produce a maximum compressive stress of about 1100 MPa.

From figure 2, it should be noted that:

- The maximum compressive stress remains relatively unchanged regardless of peening parameters, as it is primarily a function of the material's surface hardness and strength;

- The maximum compressive stress usually occurs slightly subsurface;

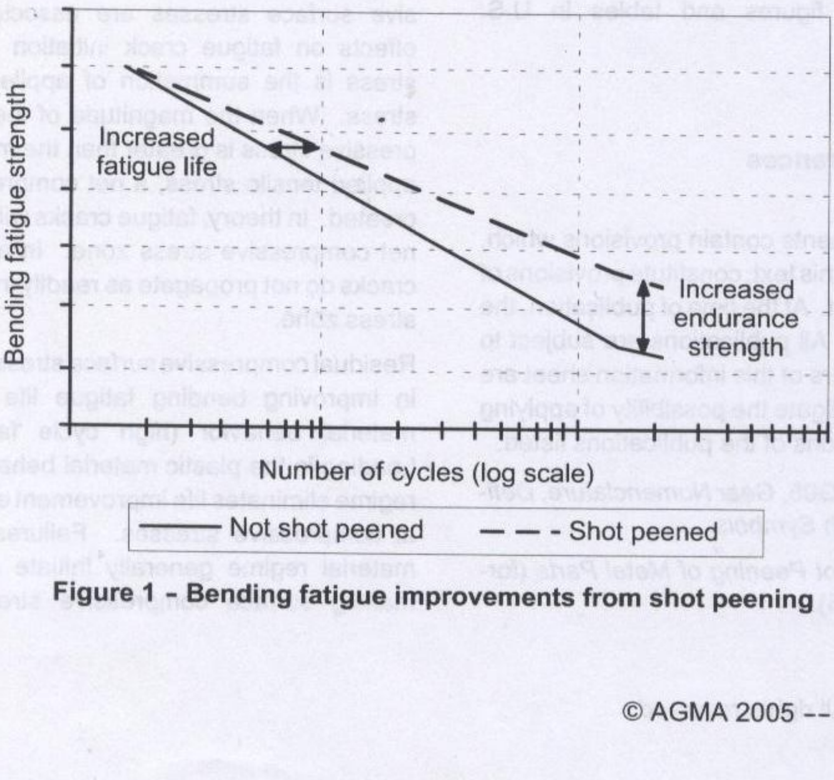


Figure 1 - Bending fatigue improvements from shot peening

- When the gear material is harder than the shot peening media, the resulting maximum compressive stress is reduced. In addition, surface finish is less affected when using shot media that is softer than the base material.

4.2 Depth of compressive layer

The depth of the compressive layer from shot peening is a function of the peening parameters and material properties, primarily surface hardness. Larger shot media and higher shot velocity increase the impact energy and also the depth of compressive layer. Harder gear materials respond with shallower depths of compression. The depth of compressive layer versus Almen intensity can be approximated as shown in figure 3, assuming shot media is as hard or harder than the surface being shot peened. See 7.3.1 for discussion on Almen intensity.

It is important to remember that while the surface has a residual compressive stress condition, there is a depth at which the stress field goes through the neutral axis and then becomes tensile.

Gear heat treatments that induce residual compressive stress (e.g., carburization, induction hardening) will produce a residual stress curve after shot peening that does not cross the neutral axis near the surface. The depth of the compressive layer is defined as the depth where the positively sloping portion would cross the neutral axis if it were extended as shown with the dotted line in figure 4.

4.3 Surface residual compressive stress

The following statements and figure 5 generally apply to the surface compressive stress:

- The surface compressive stress is usually less compressive than the maximum compressive stress.
- As shot velocity is increased for a selected shot size to achieve a deeper depth of compression, the magnitude of surface compressive stress generally decreases. This tradeoff should be considered when selecting shot peening parameters.
- A larger shot size at the same shot peen intensity as a smaller shot size will generally result in an improved surface finish and more surface compressive stress relative to the maximum compressive stress. Compressive depth properties should be similar provided both shot sizes are used at the same intensity. The larger shot size has more mass and would require a lower velocity than the smaller shot size to achieve the same intensity. The larger shot size spreads the impact location over a greater surface area resulting in less dimpling.
- A rougher surface finish is generally indicative of a more aggressive shot peen with more pronounced "peaks and valleys".
- A finer surface finish is generally indicative of a less aggressive shot peen with less pronounced "peaks and valleys".

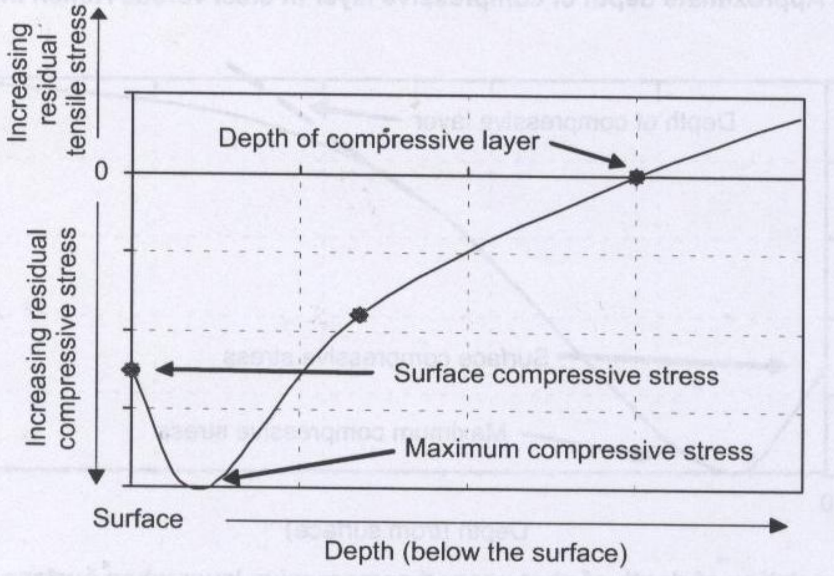
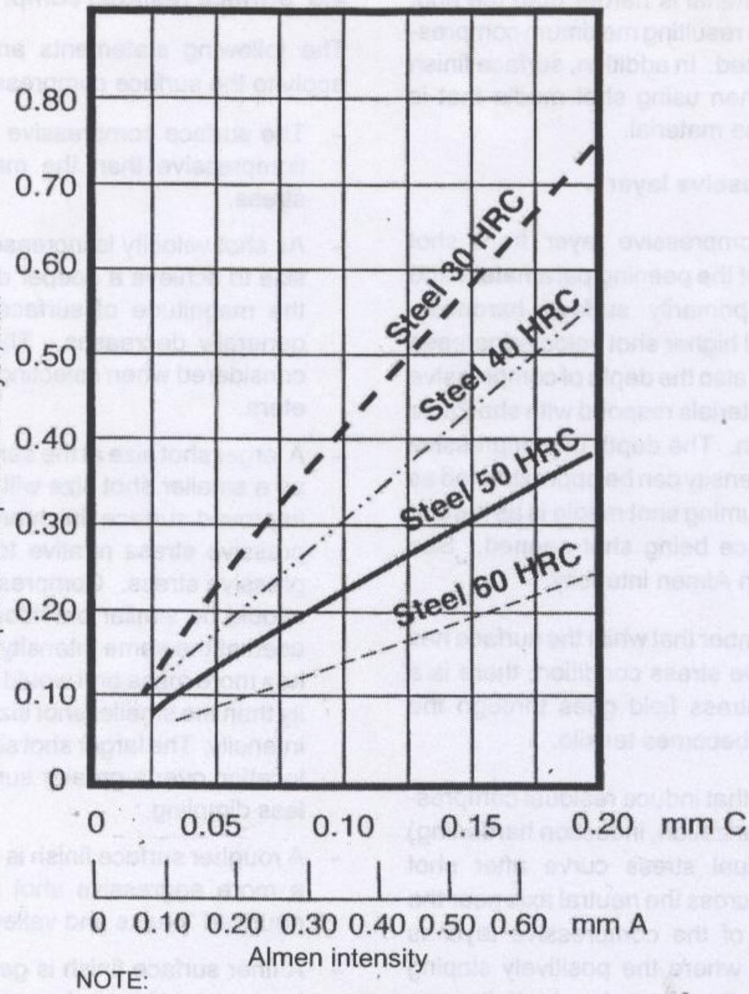


Figure 2 - Typical residual stress curve from shot peening



NOTE:
1) See 7.3.1 for explanation of intensity values.
2) See annex A for English equivalent.

Figure 3 - Approximate depth of compressive layer in steel versus Almen intensity

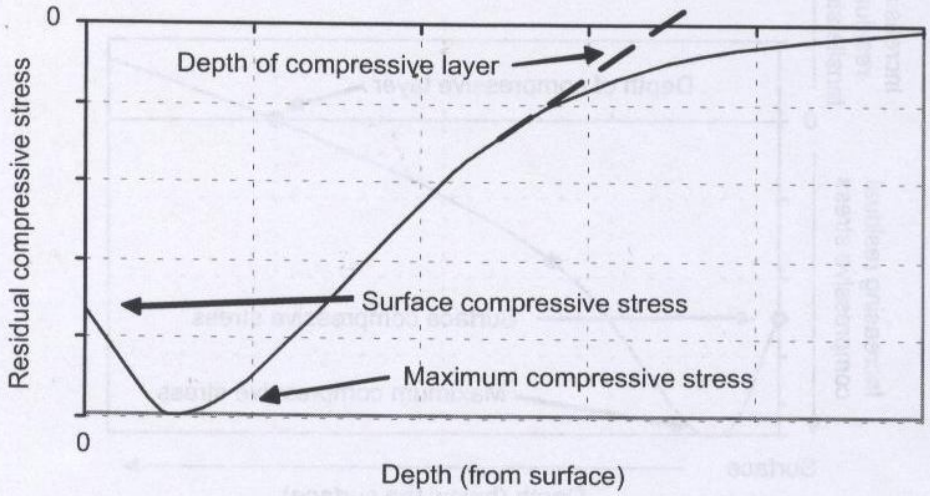


Figure 4 - Extrapolation of depth of shot peened compressive layer when surface has residual compressive stress prior to shot peening

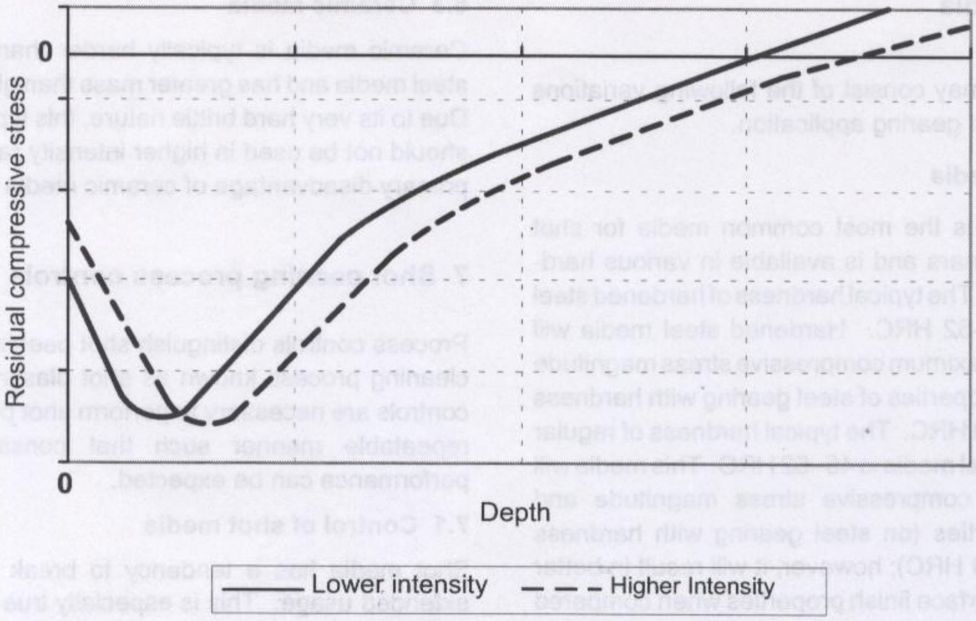


Figure 5 - Relative changes from various shot peening intensities using the same shot size

- Using the proper shot intensity range for a given shot size is important. Using very high intensities for a given shot size in an attempt to achieve deep compressive layer properties is not recommended because of the potential of reducing the compressive surface properties . Refer to table 1 for guidelines on appropriate intensity ranges for various shot sizes.
- Should the designer wish to maximize compressive depth and surface compressive properties, a dual shot peen is recommended. This consists of two shot peen operations. The first shot peen is usually performed with a larger media at a higher intensity to achieve compressive depth properties. A second shot peen operation is usually performed with a smaller shot size at a lower intensity to improve the surface finish and resulting surface compressive stress.

5 Shot delivery methods

Acceleration of the shot media is generated by one of the following methods.

5.1 Air pressure/nozzle

This method uses a compressed air system to deliver the shot through a nozzle(s). Shot velocity is adjusted primarily by modifications in air pressure settings and nozzle orifice size. This is the preferred method of shot peening gears as the nozzle(s) can be directed at specific locations, such as the gear root.

5.2 Centrifugal wheel

This method uses a paddle wheel configuration where shot is fed into the center of a rotating wheel. The rotation of the wheel accelerates the shot. Shot velocity is adjusted primarily by modifications in wheel speed settings. The primary advantage of a centrifugal wheel is that large volumes of shot can be delivered in short time periods.

Table 1 - Shot size versus intensity range

Cast steel shot size	Recommended intensity range, mm	
	Minimum	Maximum
70	0.20 N	0.18 A
110	0.10 A	0.25 A
170	0.15 A	0.35 A
230	0.20 A	0.45 A
330	0.30 A	0.55 A
460	0.40 A	0.18 C
550	0.12 C	0.20 C

6 Shot media

Shot media may consist of the following variations depending on gearing application.

6.1 Steel media

Steel media is the most common media for shot peening of gears and is available in various hardness grades. The typical hardness of hardened steel media is 55-62 HRC. Hardened steel media will provide for maximum compressive stress magnitude and depth properties of steel gearing with hardness exceeding 50 HRC. The typical hardness of regular hardness steel media is 45-52 HRC. This media will induce less compressive stress magnitude and depth properties (on steel gearing with hardness exceeding 50 HRC); however, it will result in better tooth flank surface finish properties when compared to the surface finish of similar sized hardened steel media. Steel media is available in the following variations.

- Cast steel media. This is the most common shot media in usage. The media is manufactured such that it is essentially "mini-castings" in spherical shape. Cast media is susceptible to porosity and media breakdown with extended usage. Cast media is available in both regular and hardened grades.
- Cut wire media. Cut wire is a more expensive media that is manufactured by cutting a wire into cylindrical shapes that have similar length and diameter. For shot peening the media should be purchased in a fully conditioned state where the cylindrical corners are rounded to produce a near-spherical shape. Cut wire media is less prone than cast steel media to breakdown. Cut wire media is available in both regular and hardened grades.

6.2 Glass media

Glass media is typically harder and has less mass than hardened steel media. Use of this media results in higher magnitudes of residual compressive stress at the surface and shallower depths of the compressive layer. Glass beads produce improved surface finish when compared to hardened steel media (55-62 HRC). Care should be taken when using glass media as it has a greater tendency to break down during usage due to its brittle nature. Disadvantages of glass media include higher cost due to greater consumption rates during usage.

6.3 Ceramic media

Ceramic media is typically harder than hardened steel media and has greater mass than glass media. Due to its very hard brittle nature, this type of media should not be used in higher intensity ranges. The primary disadvantage of ceramic media is cost.

7 Shot peening process controls

Process controls distinguish shot peening from the cleaning process known as shot blasting. Proper controls are necessary to perform shot peening in a repeatable manner such that consistent gear performance can be expected.

7.1 Control of shot media

Shot media has a tendency to break down with extended usage. This is especially true when shot peening hardened gearing with glass beads or cast steel media. To properly control shot media the user should have sufficient tools for inspecting, screening and removing undersized and broken shot media.

To induce consistent residual compressive stress, shot media diameter must be controlled, with a predominantly spherical shape. When shot media diameter varies beyond specification, the peening impact energy (intensity) varies accordingly as it is a function of both media size and velocity.

When shot media breaks down, the round spherical shape will usually change to a shape with abrupt corners. The amount of broken media must be controlled as sharp corners striking a gear surface at high velocity are detrimental to the gear surface. Figure 6 shows a spiral separator used for removing broken shot media.

Shot media should be inspected for both undersize and broken or deformed particles using the following criteria:

- Undersized media: Undersize media is inspected by utilizing a screening mechanism to determine that not more than 20% falls through a specified sieve size for each shot size (see table VII in AMS-S-13165).
- Broken or deformed media: Steel and glass media are inspected to assure that no more than 10% of the media is broken or deformed. For ceramic media, 5% is the maximum limit. Inspection is a visual examination of one layer of shot to determine the percentage of broken or deformed media. Additional specifications are in table I in AMS-S-13165.

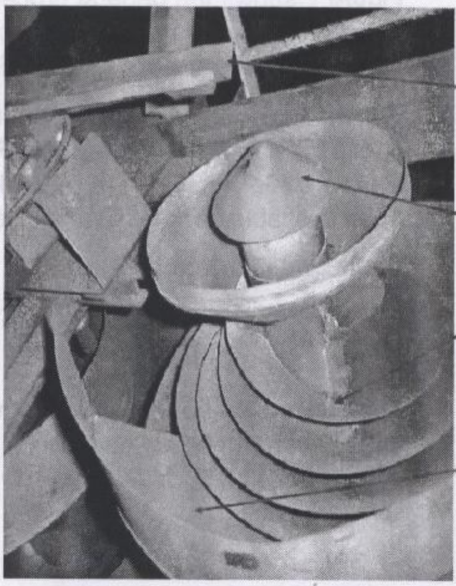


Figure 6 - Spiral separator for removing broken shot media

Should the media fall out of specification in either category, it requires replacement or suitable screening means to bring it back to within specification.

Shot media must be inspected based on the time of usage. Generally, steel media must be inspected every 8 hours, glass media must be inspected every 2 hours, and ceramic media must be inspected every 4 hours.

Additional information on shot media specifications can be found in AMS-S-13165.

7.2 Verification of coverage

Complete coverage of a shot peened surface is crucial to performing high quality shot peening. Each shot peen dimple is considered a localized area of residual compressive stress such that overlapping dimples create a layer of compressive stress.

Overlapping dimples covering all of the original surface area is considered full coverage. Generally, coverage should not be less than 100% in the areas selected to be shot peened.

The time to achieve 100% coverage is considered the coverage time. If coverage is specified to be greater than 100% (i.e., 150%, 200%) the processing time to achieve 100% coverage is increased by this multiple (i.e., 1.5x, 2x). This is considered a safety factor related to peening coverage time.

Harder gear surfaces result in smaller peening dimples given the same peening parameters. This increases the time to achieve 100% coverage. Very hard gear surfaces and light shot peening parameters can result in peening dimples which are not visible without magnification. In these cases, other controls are necessary, as detailed below.

Smaller shot sizes will achieve coverage more rapidly than larger shot sizes, because more shot per unit time can exit a specific nozzle. However, dimple sizes are not directly proportional to shot sizes. A 50% increase in shot size will produce less than a 50% increase in dimple size.

Methods to verify coverage:

- Magnification – A 10x or 20x magnified view is generally used for most gear surfaces, especially if the surface hardness is 50 HRC or less. When surface hardness is approximately 60 HRC, a magnification glass may be insufficient, as peening dimples become very small to non-visible.
- Fluorescent tracer dyes – When checking multiple surface locations such as gear roots, blind holes, large surface areas, or very hard surfaces, fluorescent tracer dyes are preferred. The dye is applied prior to shot peening. Each shot impact removes the dye at its impact location. The surface is then inspected under black light conditions where incomplete coverage will be indicated with glowing dye.

- Other methods – Other surface removal techniques, such as machinist blue dye, operate on the same principles as fluorescent tracer dyes, but are not as reliable.

7.3 Shot intensity control

Shot intensity is a measure of the impact energy striking the gear from the shot stream. Shot intensity is a function of the shot diameter, shot mass and shot velocity.

7.3.1 Intensity measurement

Shot intensity is measured on a test coupon called an Almen strip.

Intensity is determined by measuring the distortion (arc height) of an Almen strip that has been shot peened on one side only. Almen strips are measured on the non-peened side after they are released from a mounting block that holds the strip during peening.

Figure 7 shows the general procedure of using an Almen strip. Additional specifications on the procedure and equipment are in AMS-S-13165.

Almen strips are manufactured from SAE 1070 spring steel hardened to 44-50 HRC. Strip dimensions are 76.2 mm x 19.1 mm x thickness. There are three available thickness variations:

- "N" Strip: 0.79 mm
- "A" Strip: 1.29 mm
- "C" Strip: 2.39 mm

The conversion between Almen intensity designations are shown below and also in figure 8 that has the N, A, and C scales next to each other for comparison.

- 3 N ~ 1 A (9 N ~ 3 A)
- 3.5 A ~ 1 C (21 A ~ 6 C)

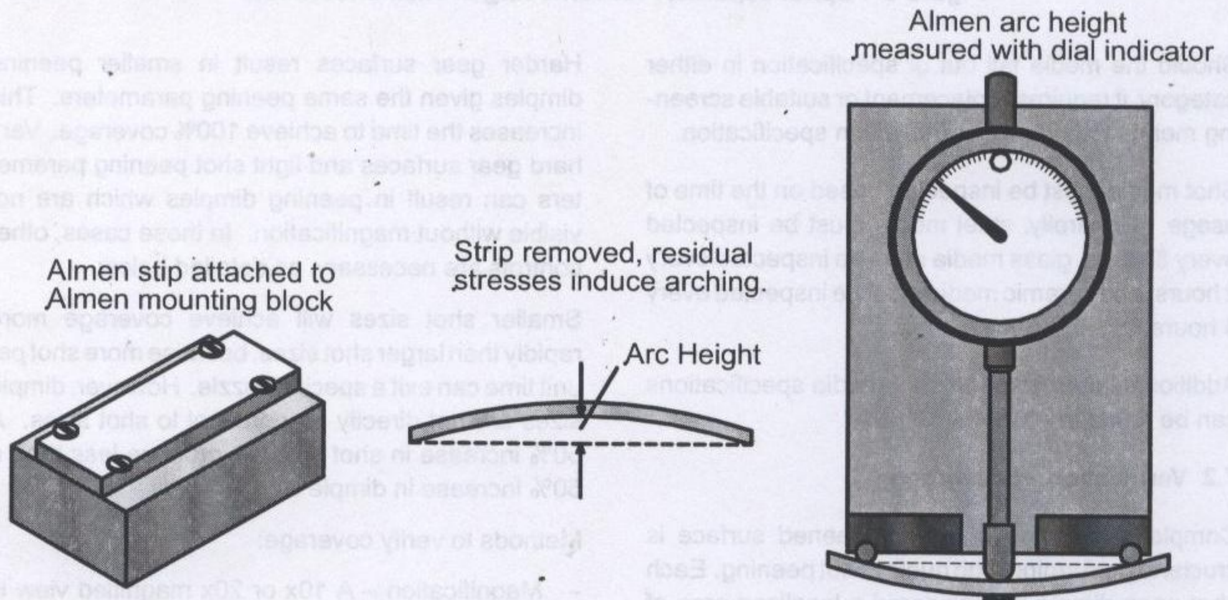
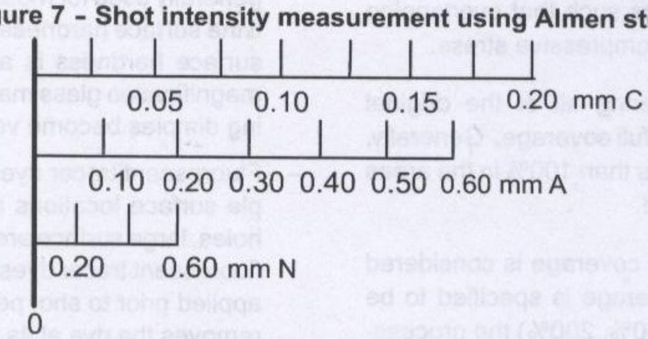


Figure 7 - Shot intensity measurement using Almen strip



NOTE: See Annex A for English equivalent.

Figure 8 - Comparable intensity values between N, A, and C scales

"N" strips are used for light duty shot peening applications. "A" strips represent the majority of peening applications including gearing. "C" strips are used for heavy duty peening applications.

The allowable arc range of an Almen strip is 0.08 mm to 0.61 mm. If a specified intensity falls outside of this range the next higher or lower Almen strip should be used. A shot peener should not interchange Almen strips (for example an A strip for an equivalent N strip) without consent of the gear manufacturer.

In order to verify consistency of shot peening, Almen strips should be shot peened in a fixture representative of the actual part to the saturation time as described in 7.3.2. Almen strips should be run before a batch of parts are shot peened and also following completion. This ensures the peening machine is delivering the shot properly, and that the settings have not changed throughout processing.

Almen blocks should be mounted on a spare part or a representative geometry such that the Almen strip is peened in a similar orientation as an actual part. See figure 9.

7.3.2 Saturation

Saturation is defined as the time to establish Almen intensity, which is the earliest point where doubling the peening time produces less than a 10% increase in Almen arc height. To determine the saturation point, a curve of arc height versus peening time is generated by processing a series of Almen strips in fixed machine settings. See figure 10.

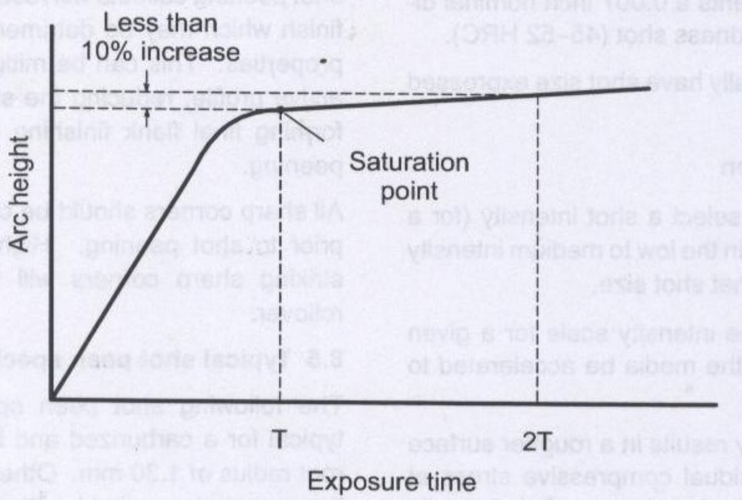


Figure 10 - Saturation curve

Saturation establishes the actual time to reach intensity of the shot stream at a given Almen strip location for a particular machine setup.

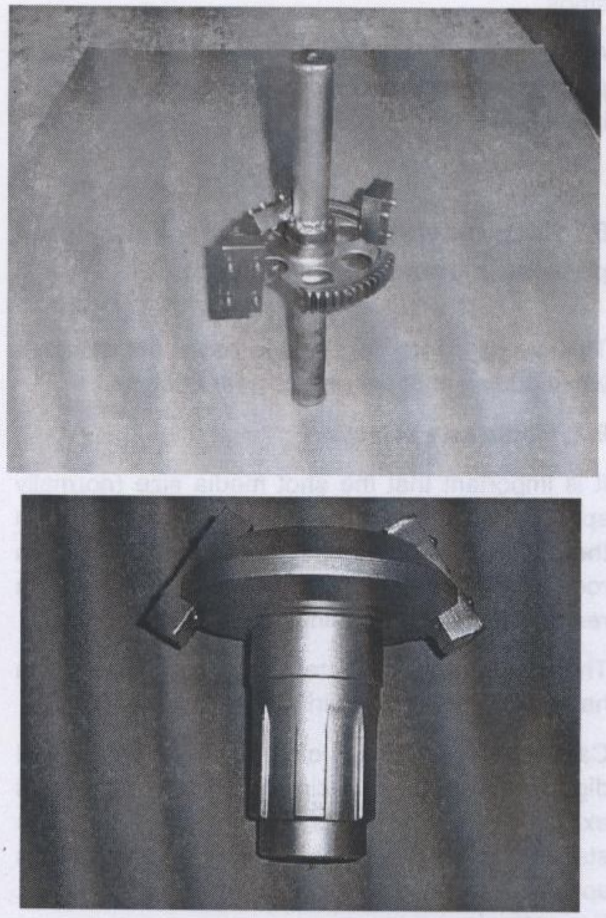


Figure 9 - Examples of Almen block mounting on an actual gear part and on a representative geometry

Saturation time and coverage time will not occur at the same time, as coverage time is measured with a visual inspection on a part surface, and saturation time is measured by processing a series of Almen strips.

A saturation curve should be generated at the time of process development for each location where Almen intensity will be recorded.

8 Recommendations for specifying shot peening parameters

This clause offers guidance to assist the designer when adding shot peening to gear designs.

8.1 Media size selection

It is important that the shot media size (normally specified as diameter) be sufficiently smaller than the geometry requiring peening, generally a tooth root. This is to ensure proper coverage in a reasonably fast processing time.

The largest media diameter should be no larger than half the radius size requiring shot peening.

Cast steel media size is often specified as a 2 or 3 digit number without decimals. The media size is expressed in English units. If an "H" is specified, this stands for fully hardened media. If an "R" is specified, this stands for regular hardness media. For example,

- A 230H shot represents a 0.023 inch nominal diameter fully hardened shot (55-62 HRC).
- A 70R shot represents a 0.007 inch nominal diameter regular hardness shot (45-52 HRC).

Cut wire size will typically have shot size expressed in metric units.

8.2 Intensity selection

It is generally best to select a shot intensity (for a given shot size) that is in the low to medium intensity range achievable for that shot size.

- The high end of the intensity scale for a given shot size requires the media be accelerated to high velocities.
- High media velocity results in a rougher surface finish, reduced residual compressive stress at the surface, and greater chance of shot media breakdown.
- A rough surface finish produced by shot peening on the active flanks can increase the risk of micropitting. See 8.4 for additional discussion.

When the designer requests an intensity that is on the high end of the achievable range, it is usually recommended to use a larger shot size. A larger shot size spreads the impact location over a larger surface area and results in better surface finish and residual stress properties.

Intensity is specified as a range with a spread of usually 0.08 - 0.10 mm for the selected Almen strip. Recommended intensities for a given shot size are shown in table 1 (see 4.3).

One should note that there is overlap in the recommended intensity ranges between shot sizes. This gives the designer flexibility in shot selection.

8.3 Coverage selection

Coverage time should generally not be specified as less than 100%. Additional coverage times may be specified to increase the safety factor associated with achieving coverage. A coverage time of 200% would be double the processing time to achieve 100% coverage.

Coverage time, as measured visually on the part surface, should be specified to develop the processing time, rather than saturation time, which is associated with calibrating the shot peening equipment.

8.4 Additional considerations

When making shot size and intensity selection, the surface finish requirements of the active flanks should be taken into consideration. Higher intensity shot peening callouts will result in a rougher surface finish which may be detrimental to contact fatigue properties. This can be mitigated by masking the active profile, reducing the shot hardness, or performing final flank finishing operations after shot peening.

All sharp corners should be chamfered or radiused prior to shot peening. High velocity shot media striking sharp corners will likely result in edge rollover.

8.5 Typical shot peen specification for gears

The following shot peen specification would be typical for a carburized and hardened gear with a root radius of 1.30 mm. Other shot peen specifications may be suitable depending on the gear manufacturer's requirements.

- Shot peen gear roots with overspray allowed on gear flanks;
- Shot size and intensity: 230H at 0.30 – 0.40 mm A;
- Coverage: Minimum 150% to be verified by fluorescent tracer dye;
- All sharp edges to be broken prior to shot peen;
- Final gear flank finishing operations to be performed after shot peen;
- Mask all finished bearing surfaces prior to shot peen.

Annex A
(informative)
Graphs and figures expressed in U.S. customary units

[This annex is provided for informational purposes only and should not be construed as a part of AGMA 938-A05, *Shot Peening of Gears*.]

A.1 Purpose

This annex contains figures referenced in the information sheet in U.S. customary units.

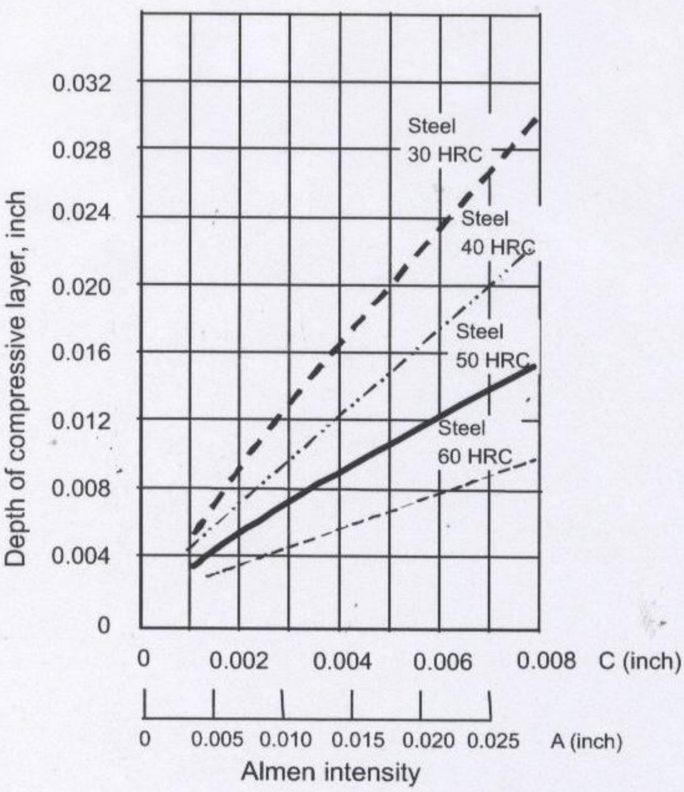


Figure A.1 - Approximate depth of compressive layer versus Almen intensity

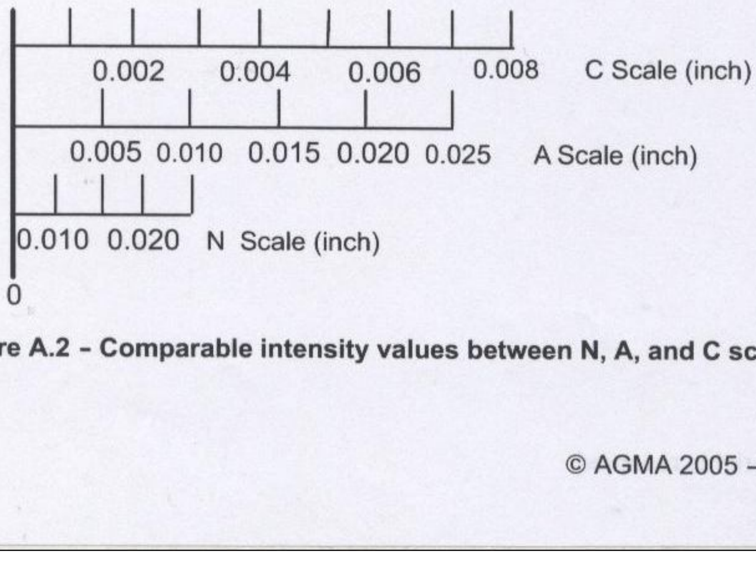


Figure A.2 - Comparable intensity values between N, A, and C scales

Table A.1 - Shot size versus intensity range

Cast steel shot size	Recommended intensity range (inch)	
	Minimum	Maximum
70	0.008 N	0.007 A
110	0.004 A	0.010 A
170	0.006 A	0.014 A
230	0.008 A	0.018 A
330	0.012 A	0.022 A
460	0.016 A	0.007 C
550	0.005 C	0.008 C

Bibliography

The following documents are either referenced in the text of AGMA 938-A05, *Shot Peening of Gears*, or indicated for additional information.

AGMA 923-B05, *Metallurgical Specifications for Steel Gearing*

ANSI/AGMA 2001-D04, *Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth*

ANSI/AGMA 2004-B89, *Gear Materials and Heat Treatment Manual*

ISO 6336-1:1996, *Calculation of load capacity of spur and helical gears - Part 1: Basic principles, introduction and general influence factors*

ISO 6336-2:1996, *Calculation of load capacity of spur and helical gears - Part 2: Calculation of surface durability (pitting)*

ISO 6336-3:1996, *Calculation of load capacity of spur and helical gears - Part 3: Calculation of tooth bending strength*

ISO 6336-5:2003, *Calculation of load capacity of spur and helical gears - Part 5: Strength and quality of materials*

Shot Peening Applications, Eighth Edition, Metal Improvement Company, 2001

American Gear Manufacturers Association

Shot Peening of Gears

AGMA 938-A05

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[Tables or other self-supporting sections may be referenced. Citations should read: See AGMA 938-A05, *Shot Peening of Gears*, published by the American Gear Manufacturers Association, 500 Montgomery Street, Suite 350, Alexandria, Virginia 22314, http://www.agma.org.]

Approved May 3, 2005

ABSTRACT

This information sheet provides a tool for gear designers interested in the residual compressive stress properties produced by shot peening and its relationship to gearing. It also discusses shot media materials, delivery methods, and process controls.

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Foreword

[The foreword, footnotes and annexes, if any, in this document are provided for informational purposes only and are not to be construed as a part of AGMA Information Sheet 938-A05, *Shot Peening of Gears.*]

The purpose of this information sheet is to provide a centralized reference for shot peening information for other AGMA documents. Previously, multiple AGMA documents had varying descriptions of the shot peening process. This information sheet provides a thorough process description to assist the gear designer in understanding and implementing the shot peening process.

The first draft of AGMA 938-A05 was made in August 2003. It was approved by the AGMA Technical Division Executive Committee in May 2005.

Suggestions for improvement of this document will be welcome. They should be sent to the American Gear Manufacturers Association, 500 Montgomery Street, Suite 350, Alexandria, Virginia 22314.

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