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Shot Peening Process Controls Ensure Repeatable Results

by John S. Eckersley. Reprinted with permission from *Shot Peening Theory and Application.* Edited by Dr. A. Niku-Lari. First published by IITT-International, www.iitt.com

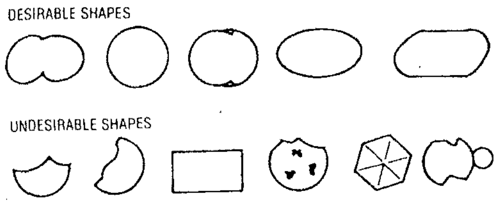


Fig. 1. Peening Media

INTRODUCTION

Shot peening is a cold working process applied to the surface of metal parts to increase their resistance to fatigue, fretting fatigue, stress corrosion cracking, corrosion fatigue and various other tensile stress related metal failures. Shot peening has also been used effectively to form aerodynamic curvatures into large sculptured panels such as aircraft wing skins, some over 90 feet (30 m) long. In all cases, the effectiveness of the process is due to the introduction of residual compressive stresses into the surface of the parts. When a metal surface is indented, a residual compressive stress is induced as the subsurface material attempts to push out the indentation and restore the surface to its former condition. Shot peening, by bombarding the surface with millions of tiny spheres of steel, glass or ceramic, totally covers the surface with indentations, creating an even layer of compressive stress that is at its maximum, just below the surface and is at least equal to 50% of the ultimate tensile strength of the metal.

It becomes immediately apparent that, for shot peening to be consistently effective and reproducible, a number of parameters must be controlled. Among the most important:

1. The peening media.
2. The energy of the shot stream.
3. The percentage of indentation of the part surface.
4. The repeatability of the peening machine.

SPECIFICATIONS THAT CONTROL SHOT PEENING

There are innumerable "company" specifications for shot peening particularly, as you might expect, in the aircraft and automotive industries. Most are based on three "industry" specifications:

1. MIL-S-13165, Shot Peening of Metal Parts. (1)
2. AMS 2430 Shot Peening. (2)
3. AMS 2431 Peening Media. (2)

A new specification is almost ready for publication by the SAE. Entitled "Computer Monitored Shot Peening", it will in all likelihood have the designation AMS 2432.

Over the years, these specifications have become increasingly stringent. For instance, in the early seventies, the Revision B of the Military Specification MIL-S-13165 essentially "outlawed" peening with hand held nozzles in favor of the use of automated machines. Now, Revision C, just published, includes the use of computer monitored equipment.

The United States Naval Air Command recently set up a review team to look at shot peening practices. The team reported that "There is no evidence of substantial problems resulting from the use of peening, but the potential for problems where large enhancement is provided, and the wide variation in industry practices, led the team to the conclusion that a policy which imposes controls is needed". (3) They recommended the "immediate" use of computer monitored shot peening for any new design that is depending on shot peening for life enhancement.

The importance of tight controls cannot be overemphasized because to date there is no non-destructive production method of determining the quality of the peening on a part after the peening has been performed.

THE PEENING MEDIA

The Aerospace Materials Specification #2431 covers seven types of peening media: Cast Steel Shot, Regular and Hard; Conditioned Carbon and Stainless Steel Cut Wire; Peening Balls; Glass Shot and Ceramic Shot. The specification imposes limitations on chemistry, size, sphericity, permissible numbers of misshapen or broken particles, soundness absence of hollows, cracks, etc. and hardness (Fig. 1). The limits are tighter than for non-aerospace specifications as might be expected and it is also the first time that just about all the readily available types of peening media are addressed in a single document. AMS 2431 does not address the uses and characteristics of each of the shot types so a review here might be useful. AMS 2431 assigns a separate /# to each type so the same numbering system will be used here:

AMS 2431/1 - CAST STEEL SHOT, REGULAR (45-52 HRC)
A general purpose medium for parts of a hardness less than 52 HRC. (Fig. 2)

AMS 2431/2 - CAST STEEL SHOT, HARD (55-62 HRC)
Similar to regular, it is recommended for parts harder than 55 HRC. Breakdown rate is high, particularly when peening hard parts, but the magnitude of compressive stress generated on hard parts is significantly higher than when regular shot is used. Can be used on softer parts with no inconvenience, provided broken particles are kept below specification requirements.

AMS 2431/3 - CONDITIONED CARBON STEEL CUT WIRE SHOT
Cut wire shot is produced by chopping wire into cylinders so that the length equals the diameter and then rounding the sharp corners by repeated blasting against a hardened target. As might be expected, the purchase price of conditioned cut wire shot is much higher than cast steel shot but because it is wrought rather than cast, cut wire shot is very durable. Size uniformity is also a significant feature but small sizes are difficult to produce.

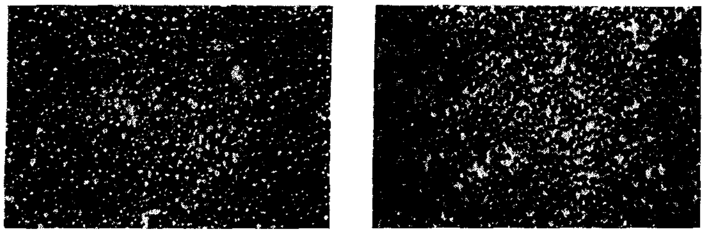


Fig. 2. (A) Unacceptable shot peening media (B) Acceptable shot peening media

AMS 2431/4 - CONDITIONED STAINLESS STEEL CUT WIRE SHOT

Stainless cut wire shot has all the advantages of the carbon steel variety with the additional one that it does not leave iron deposits on the peened surface. This property is particularly useful when peening nonferrous parts which otherwise must be decontaminated. Comparatively, hardness is low and purchase price high.

AMS 2431/5 - PEENING BALLS

Used almost exclusively for Peen Forming, peening balls can be as large as 1/2 inch (13mm) in diameter, though 1/8 (3mm) and 1/4 inch (6mm) are more common. Toughness to resist breaking is the most important parameter.

AMS 2431/6 - GLASS SHOT

Although the breakdown rate is high, glass shot has some interesting advantages:

1. Chemically inert glass shot will not contaminate the part being peened. It is often used in a secondary peening to reduce the residual iron left by cast shot.
2. On very hard parts, it has been shown that a secondary peening with small glass shot at a low intensity will increase the magnitude of the surface compressive stress, with a corresponding even greater increase in cycles to crack initiation.
3. Glass shot, unlike other media, is available in sizes below a nominal 0.007 inch (0.2mm) down, in fact, to 0.0015 inch (0.04mm). This very small medium is useful for peening into tight radii such as are found in thread roots. A word of caution: the surface in the roots must be smooth because only a very shallow depth of compression is generated by such small shot.
4. Glass, of course, has much less mass than steel and can therefore be used where a low level of energy transfer is required; for instance, on very thin parts.
5. Glass shot is useful as a blast cleaning medium which at, the same time, can enhance the surface properties.

AMS 2431/7 - CERAMIC SHOT

Made by fusing zirconium oxide powder in a glass binder, ceramic shot is very hard and inert. It is more durable than glass but it is also expensive to buy. A lower breakdown rate makes the condition of the ceramic shot easier to maintain than glass in the peening machine.

The above specifications are essentially for purchasing of peening media. However, the soon to be published AMS XXXX "Computer Monitored Shot Peening" specification, which is a user rather than purchasing document, references AMS 2431 by requiring that the shot in the peening machine be maintained to the same standards. Other specifications have their own "condition of shot" tables that specify the maximum amount, by particle count or by weight, of undesirable shapes that can be allowed in the machine charge. In either case, the amount is minimal for good peening practice and dictates that the user either changes the charge often or has machines equipped with devices that automatically maintain the shot condition by removing both sub-size and broken particles. These devices consist of vibrating screens that control the size content and classifying spirals that control the shape content. It is essential that round, correctly sized media be used to provide an even depth of compressive stress in a surface covered with round shallow dimples free from sharp, angular indentations.

TRANSFERRED KINETIC ENERGY

Soon after "shot blasting" was determined to be beneficial on valve springs for the Buick and Cadillac engines in 1928, it became necessary to find a means to ensure some degree of repeatability. Those involved knew, of course, that kinetic energy was being transferred by the shot to the springs but to measure the mass and velocity of millions of pieces of shot inside a machine was next to impossible and far from practical. Even if it were possible, three other critical factors would have been left out of the equation since what was of real interest was not really how much energy was in the peening media *but how much of this energy would be transferred* to the steel of the springs. This transferred energy would also be affected by the hardness of the spring steel, the hardness of the shot and the angle of impingement between the shot and the surface.

John Almen finally developed a system that bears his name and incorporates all the factors plus being sufficiently practical for shop use. The Almen system is still in use and, despite some inherent inaccuracies, has not been improved upon, though efforts are being made to do so. Almen used standardized, flat strips of spring steel (Fig. 3) which take on a curvature when exposed to a shot stream on one side. The degree of curvature is proportional to the intensity of the kinetic energy in the shot stream. Once the strip is fully covered with peening impressions, the degree of curvature is relatively unaffected by exposure time. The curvature of the strip is measured on a special Almen depth gage in thousands of an inch or hundredths of a millimeter and that number becomes the Almen Intensity. Three thicknesses of Almen strips (N, A & C) cover normal range of intensities. The depth of the curvature on the A strip is approximately equal to the depth of the compressive stress layer on spring steel. Charts exist from which to calculate for other materials (4).

In practice, a Saturation Curve must be developed to determine the point at which the Almen Strip becomes fully

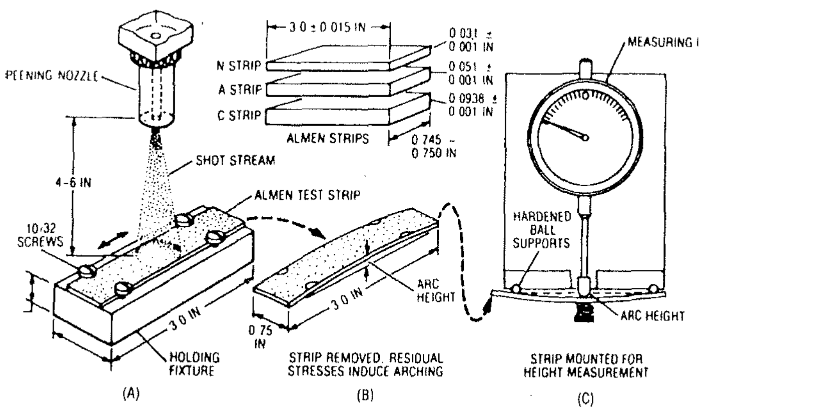


Fig. 3. The Almen strip system

covered by peening impressions. Almen Blocks are mounted on a scrap part in the critical locations, which should be marked on the part drawing. Almen Strips are held down on the Blocks by four screws and the scrap part with the Strips is placed in the shot stream and exposed for a relatively short time. The depth of curvature or arc height of the strips is read in the Almen Gage and marked on a graph that plots the arc height against exposure time (Fig. 4 & 5). A separate graph or Saturation Curve is used for each location. The process is repeated, using new Almen Strips each time, until the curve linking the points flattens out so that by doubling the exposure time results in no more than 10% increase in the arc height. Almen Intensity has then been reached and must fall within the range indicated on the drawing or specification. If it does not, the shot velocity and/or the shot size must be adjusted and a new Saturation Curve prepared before the parts can be peened.

Almen Intensity, then, becomes an elegant method of measuring, relatively, the energy that is transferred from the peening media to the surface of the part. From the Almen Intensity can be calculated the approximate depth of the compressed layer on the part in relation to the part material. However, it must be noted that the exposure time required to reach saturation on the Almen Strip is usually different from the exposure time required to correctly shot peen the part.

PEENING COVERAGE

The correct exposure time is governed by a number of factors mostly unrelated to the Almen Strip: (Fig. 6)

1. Part hardness. It quickly becomes obvious that a part substantially harder than an Almen Strip will require longer exposure. The peening dimples will be smaller on the harder material and more dimples will be required indicating a longer exposure time to produce full coverage or total obliteration of the surface. Conversely, on softer parts, less exposure is usually required.
2. Shot hardness also affects coverage rate for essentially the same reasons given above. Softer shot will produce smaller dimples on harder parts, requiring more exposure.
3. Shot size. Small shot covers the surface much faster than large. The reverse is true for intensity: higher intensities will result in faster coverage for the same shot size.
4. Surface condition. If a surface, particularly a hard surface, has visible machine marks, greater exposure will be needed to peen down the high spots so that the low spots can be peened. Sometimes, if the machine grooves are significant, two sizes of shot may be indicated: First, small shot to get into the grooves, followed by large to produce sufficient depth of compression.
5. If the material work hardens substantially, additional exposure time may be indicated.
6. Part geometry also must be taken into account. A fatigue-critical fillet may be "shaded" so that the overall part may get more than full coverage while sufficient exposure time is allowed to get full coverage in the fillet. The additional coverage is not a problem except in the case of nickel-base materials used in jet engines. Extended coverage (over 500%) on these materials has been shown to cause strain hardening and a small loss of fatigue strength when compared to normal coverage. Because jet engine components are usually repeened at overhaul to restore compressive stresses and also the complex geometry requires long exposure times to reach, for instance, the pressure faces in the dovetail slots, a method known as "coverage mapping" has been devised. A fluorescent tracer (see below) is used to determine the time required to reach full coverage on the various areas of the part. In production, the part is masked, leaving exposed only the areas requiring maximum peening time. As the part is being peened, the masks are removed to expose, in turn, areas that require less peening time that all critical areas receive essentially the same coverage.
7. Most specifications allow holes to be peened externally at 45° that is as long as the depth of the hole does not exceed the diameter. If the hole will be peened from both ends, the depth may be equal to twice the diameter. Deeper holes must be peened internally. Usually, holes smaller than 3/8 inch (10mm) are not required to be peened unless they are specifically so designated on the part drawing. Holes down to 0.080 inch (2mm) can be peened successfully but coverage determination inside small holes is very difficult unless a fluorescent tracer is used.

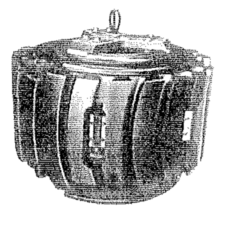


Fig. 4. Almen Fixture

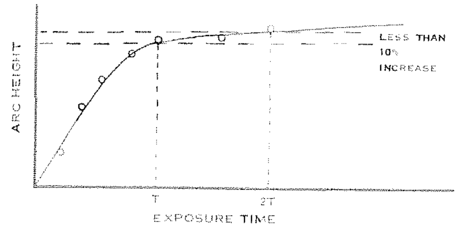
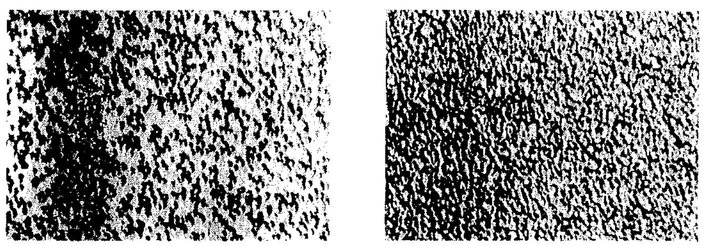


Fig. 5. Saturation Curve

Determination of coverage in many circumstances is not easy even when a decision is made as to how much coverage is appropriate for a given part. 100% coverage is the point at which the surface is totally covered in peening dimples which then translates to exposure time in the peening machine for a given set-up. On relatively soft parts, this visual determination can be achieved with a 10x magnifier which works well unless there are many parts, large surface areas or restricted line of sight (as in holes). On very hard parts (carburized gears, for instance) visual determination is difficult and requires a very practiced eye. Using greater magnification does not help.

A fluorescent tracer lacquer system, such as PEENSCAN (5.), called out in MIL-S-13165, is highly effective (Fig. 7). Basically, the part is coated with the lacquer and, after drying, peened at increasing time increments until no more lacquer is visible on the surface under black (UV) light. Because of the high visibility of the fluorescent dyes, 100% coverage determination can be quickly achieved. The 100% coverage time can then be factored to suit those circumstances as outlined in 1-7



(A) (B)

Fig. 6. Shot peening coverage (A) partial (B) full

above. There has been some concern as to the linearity of PEENSCAN on very hard parts, where it is most useful. A simple test using Almen Strips hardened to 58-60 HRC determined that PEENSCAN removal does indeed coincide with saturation and 100% coverage at this hardness level.

Coverage is the most critical parameter in shot peening; even more so than intensity. Yet deciding how much coverage is correct and then determining that the part has received the correct coverage requires considerable experience and know-how. If there is to be an error, it should be on the side of too much coverage, rather than too little. Insufficient coverage can create surface tensile stresses which, particularly in the case of stress corrosion cracking, can be disastrous. On the other hand, for high production parts, unnecessarily long exposure times will be cost prohibitive.

REPEATABILITY

Once the intensity and the coverage have been determined, the next concern has to be repeatability. The surface condition, intensity and the coverage must be consistent over the surface of the part and consistent from part to part in a production lot and from one lot to the next; even on different machines. The quality of the shot peening is impossible to measure non-destructively on the part after it is peened. Obviously, peening a hand-held nozzle will not produce consistent results. While manual peening, with proper safeguards, may be the only reasonable alternative for the weldments of a 60 ft. (20m) diameter ammonia storage tank, it is certainly unsuitable for high precision aircraft parts or high volume automotive parts.

Until recently, repeatability was achieved by using automated machines where shot velocity could be preset by air pressure or centrifugal wheel speed. Part and nozzle location, translation and velocity were also preset, as were distance from part to nozzle and angle of impingement. Automated shot peening machines served well in an environment where engineers were content to use shot peening as a fix or as an "add on" for extra insurance. Today the trend in many industries is towards including the benefits of shot peening in the design "allowables" for a given part. An excellent example is the connecting rods

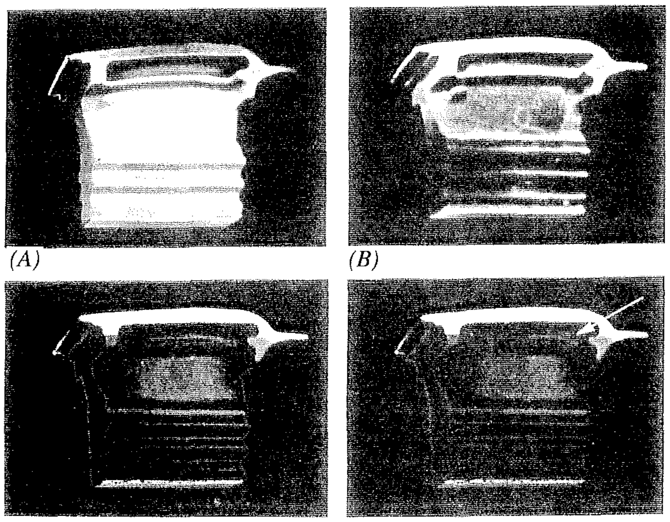


Fig. 7. The Peenscan system. (A) Coated unpeened. (B) Peened 15 seconds, partial coverage. (C) Peened 60 seconds, full coverage (D) Peened 60 seconds, improper nozzle angle in cavity (as shown)

for a high performance passenger car engine. Shot peening was "designed in" so that lighter connecting rods could be used, thereby reducing the rotating mass in the engine with corresponding gains in efficiency and fuel consumption. In a commercial aircraft, the benefits are enormous for allowing just a 2% increase in fatigue strength in the machined components of the airframe, the landing gear and the engines. The question has always remained, though: "Was this particular part peened correctly?" Even in an automated machine, there is little hope of knowing whether a nozzle plugs up momentarily, or if the air pressure falls off or even if the part stops rotating. With the advent of computer monitoring and controlling, these questions can be addressed for each individual part.

Computer monitored shot peening machines "read" all these parameters and more, such as shot flow, every second. If any of the parameters goes out of limit, the machine will shut down and warn the operator of the problem. It can only be restarted when the problem is corrected. In addition, the computer can control or vary nozzles on part translation or rotation. Now, hard data can accompany the part to satisfy the designer's need to document the repeatability: on large surfaces, inside small holes, on hard parts or soft, simple or complex.

CONCLUSION

Computers have brought to shot peening the essential factor that has been missing: the positive assurance that the parts are peened correctly. With this assurance the user industries are moving to take greater advantage of shot peening as they balance lighter designs against longer service lives.

Note: Metric sizes are for reference only and are approximate.

REFERENCES:

1. Complimentary copy of MIL-S-13165 Revision C available from: Metal Improvement Company, 10 Forest Avenue, Paramus, NJ 07652, Tele.: 201/843-7800, Fax number: 201/843-3460.
2. Available from: SAE, 400 Commonwealth Drive, Warrendale, PA 15096, Tele.: 412/ 776-4841.
3. Navair Review Team Report Naval Air Systems Command.
4. "Shot Peening Stress Profiles"; H. O. Fuchs, Editor. Complimentary copy available from Metal Improvement Company (see 1. above).
5. PEENSCAN is a process licensed by Metal Improvement Company (see 1. above)