ABSTRACT: Shot peening is known to be beneficial for improving fatigue life and stress corrosion resistance of components. Shot peening has historically lacked definition of qualitative process variables and optimum quantitative levels. This problem is compounded by lack of definitive process controls for consistently reproducing the process variables affecting workpiece performance. The authors chose shot peening media as first of a series intended to holistically examine which peening variables affect workpiece performance, how performance is affected, and how these can be metered, controlled, and/or documented. Peening media problems are categorized into seven groups. Each is examined conceptually as to effect on workpiece life. Determination is made as to available equipment, quality assurance, and documentation tools.

INTRODUCTION

A) AN HISTORIC PERSPECTIVE

Shot peening has long been known to be useful in extending the fatigue life and improving the stress corrosion resistance of metallic components which undergo cyclic tensile loads.

During World War II, when shot peening was first widely used in the United States, it was often used as a means of upgrading the performance of lower strength, but more available materials than were originally intended when the components were designed. The catalyst for the significant increase in use of the process during this period was not a great process breakthrough, but rather a dearth of high strength materials in the greatly increased quantities required.

Today, many engineers are hesitant to utilize the peening process due to a general lack of definitive information about how and why the process works and what is needed to consistently control and reproduce it.

Most metallurgical processes experience a period of development when critical process variables are identified, an understanding of how the process interacts with the workpiece microscopically and metallurgically is achieved, and optimum levels of each variable are quantified for given sets of conditions. The development of heat treating technology over the past decades is an excellent example.

In 1943, John Almen, widely considered the father of modern shot peening, wrote, "Although no super-strength alloys have been discovered and no such discoveries seem to be imminent, there is much that can be done to increase materially the fatigue strength of any machine parts made from our ordinary structural materials. This fatigue strengthening doesn't require changes in design or in material, and in fact it does not require processes that are fundamentally new or untried. It is merely the extension of processes that, on the whole, have long and honorable histories, and the avoidance of processes and practices..."
that are now known to reduce fatigue strength." (1).

Today's transportation industry manufacturing imperatives of cost control, higher system load requirements, reduced product weight, and reduced product fuel consumption are providing impetus for the advancement of shot peening process technology. In some ways, it is reminiscent of the 1940's as the shot peening discipline has not made any great technical breakthroughs that stimulated this need, but rather marketplace needs have been the catalyst to increased process research.

B) AN HOLISTIC APPROACH TO 
    REPRODUCIBILITY.

As in any metallurgical process, there are three distinct conceptual areas to be addressed:

1) Basic research in understanding the metallurgical mechanics of the process.

2) Applied research into how particular components or fatigue specimens of particular materials react to particular process variable levels.

3) Development of holistic procedures for controlling and reproducing consistent quantitative levels of the qualitative optimums of all production process variables and sub-variables which can change the effectiveness of the process in serving its intended function.

Historically, the majority of published technical literature on shot peening dealt with aspects of problem B, identifying specific effects of specific peening parameters on specific components. All too often, however, these studies displayed a lack of exhaustive variable control; and therefore lack the validity of well founded research. The First and Second International Conferences on Shot Peening in 1981 & 1984 saw a significant increase in studies dealing with problem A. The authors believe that these have laid a conceptual foundation for equally significant future increases in understanding the peening process.

It is, however, the author's opinion that there is a lack of understanding of the process variables which can alter the effectiveness of the process. How these variables vary, interact, and qualitatively and quantitatively affect the workpiece in actual production is an area lagging far behind studies in both Problem A and B. Knowledge of optimums at engineering levels is of little use in production if identification of variance from acceptable variable and sub-variable is inadequately addressed. The peening process, like any other metallurgical process cannot be depended upon to consistently reproduce the desired result unless the critical variable and sub-variable levels are maintained within specified parameters known to yield the results desired.

This lack of process control technology and production reproducibility has made shot peening the process of last resort for many engineers when seeking to design additional strength into a component. While substantially more research is needed in both the area of metallurgical mechanics of shot peening and in identifying optimum parameters, an holistic approach to production monitoring, control, and documentation of all variables and sub-variables affecting workpiece performance is critical to production reproducibility of process benefits.

Variables like peening intensity are relatively simple in concept. They are relatively complex in execution as large numbers of intensity sub-variables and combinations of sub-variables can significantly affect workpiece performance, often without a change in Almen intensity. The concept of objective quantifiable process control is particularly important in the peening process as there has historically been a lack of a non-destructive test for shot peening, and only through recognition during the process of out of tolerance process variables can less than optimum process results be avoided.

This paper is the first of a series of papers intended by the authors to holistically address the subject of obtaining shot peening process consistency and reproducibility. Due to the complexity of the subject, it is essential to note three points:

1) This paper is not meant to examine every aspect of every process
application. The individual applications of the process must be examined individually by the engineer as to its unique problems. This effort is rather a general outline of procedure for those wishing to apply the process.

2) Only the areas of the shot peening process directly related to the shot particles utilized and the means to achieving consistent results currently available to users of the process will be examined. Future efforts in this series will address other parameters and variables of the peening process.

3) There are applications where the use of peening medias other than cast steel shot or glass beads (such as stainless cut wire) are a viable engineering and economic alternative. Cast steel shot and glass beads are by far the most widely used medias for shot peening and, as such, are the main subject of discussion. Some discussion of ceramic peening medias takes place as these emerging medias appear to be viable alternatives to glass beads.

VARIABLES THAT CAN AFFECT THE PEENING PROCESS

Any holistic examination of the shot peening process requires an examination of the types of variables involved and how they interact. Fig. 1 is a synopsis of variable groups.

Any changes in variables on the left hand side of the centerline in Figure 1 such as workpiece shape, depth of maximum applied shear stress, type of applied load, and many others, may result in a change in optimum energy transfer and/or procedural variables.

Once acceptable tolerances for these opitima and their sub-variables have been chosen through fatigue testing the consistent reproduction of specific quantitative amounts of each variable and its sub-variables is paramount.

Almen Intensity, the peening process' current measure of the aggregate effect of process variables on a representation of the workpiece, can remain constant even though a change in two or more variables has removed the process from the "sweet zone". (For further information on the subject of the Almen strip, see "Defects and Virtues of the Almen Strip." H. Fuchs, 1984.) Figure 2 is an example of the lack of performance which can result if the proper intensity parameters and tolerances are not chosen and adhered to.

FIGURE 2.

The shot peening process is procedurally fragile, as relatively small changes in variables or sub-variables will yield large changes in workpiece performance. Peening intensity however, is only one of dozens of variables and sub-variables which can effect workpiece performance. As such consistency and control of all of the variable inputs affecting workpiece performance on the right side of the centerline of Figure 1 is essential to obtaining consistency in the resultant process output; fatigue life, stress corrosion resistance, and load carrying capability increase.
The availability today of inexpensive microprocessing and electronic monitoring and test devices, some of which were cost prohibitive or unavailable in the 1970's coupled with existing quality assurance and documentation techniques and procedures had made possible significant advances in the reproducibility of the peening process for most users. As such, they provide significant increases in the amount of benefit which can be dependably derived from shot peening.

Figure 3 illustrates the problems present in a client's existing process when Airtech Precision Shot Peening, Inc. was asked to consult with the user of an airblast shot peening operation. It is important to note that both sets of results were obtained at the same Almen intensity values and that both process procedures met all applicable U. S. Military Specifications. Only by utilizing exhaustive process control were the results in Figure 3B obtained.

**PROCESS VARIABLE QUALIFICATION AND QUANTIFICATION**

Energy transfer and procedural variables and sub-variables defined by the shot peening media itself, and the means of controlling, monitoring, and documenting the levels of each variable and sub-variable are addressed as follows:

I. NOMINAL SHOT SIZE
II. SHOT SHAPE
III. SHOT SIZE UNIFORMITY
IV. SHOT FLOW RATE
V. CAST STEEL SHOT INTEGRITY
VI. SHOT CHEMISTRY AND MISCONSTRUCTURE
VII. SHOT HARDNESS

The type of controls utilized are grouped, for the purposes of this paper, into three areas:
1) PEENING EQUIPMENT CONTROLS
2) QUALITY ASSURANCE PROCEDURES
3) DOCUMENTATION

I. NOMINAL SHOT SIZE

Choosing shot size in developmental test work is of great importance as the size of shot not only affects Almen Intensity, but can affect the distribution of residual stresses for a given Almen Intensity. (6)

Additionally, a variation in shot size for a given Almen Intensity may affect workpiece surface integrity, and hence fatigue life. (5)

As a general rule, unless test data on the particular workpiece in question indicates otherwise, the smallest shot size that can be utilized to achieve the specified peening should be used. (6) See Figure 4.
EQUIPMENT CONTROLS

In-process equipment controls for nominal shot size are identical to those outlined in the section of this paper dealing with "SHOT SIZE UNIFORMITY".

QUALITY ASSURANCE

The critical Quality Assurance functions for shot size are:

1) purchasing correctly sized shot
2) verification of correct sizing in receiving and in-process inspection.

This is accomplished via sieve analysis.

Calibrated test sieves of the mesh sizes listed in MIL-S-13165B, Table I for the shot size utilized should be stacked together with a catch pan on the bottom and a lid on the top. A weighed sample is then placed in the top screen, the lid placed on, and the assembled sieves shaken for a period of a few minutes, insuring that the assembly is always oriented with the lid facing up. The shot remaining on each screen is measured by weight as a percentage of the entire test sample and compared to the acceptable tolerances listed in MIL-S-13165B, Table I.

DOCUMENTATION

Detailed records of the sieve analyses of each peening operation should be kept. These should include the following as a minimum:

A) Shot size and material
B) Hardness (if metallic)
C) Air pressure and type/size of nozzles or shot wheel type, size, and speed, as applicable
D) Time interval since last test on the shot charge examined
E) Shot vendor

Such records can be extremely useful over a period of time in determining the quality and usable life cycle of shot purchased from various manufacturers.

Receiving inspection sieve test records for new shot, coupled with other information outlined in this paper, will supply insight into the quality and consistency which each of the shot manufacturers can supply.

II. SHOT SHAPE

Shot particles which repeatedly impact a workpiece eventually fracture and break into angular pieces. The impingements left on the workpiece by angular shot edges are angular (3). If broken shot is permitted to remain in the blast stream, the results are a reduction of energy transferred to the workpiece as residual compression and pointed angular impingements which serve as stress risers. These angular impingements have a significantly adverse effect on fatigue life. It is well documented in published literature that grit blasted surfaces of workpieces often have fatigue lives lower than unblasted. Steel grit is nothing more than fractured steel shot. (See (3) for three dimensional drawings of peened and grit blasted surfaces.)

Nor is there a process cost saving resulting from utilizing shot charges with less than 90% spherical shot. As the percentage of broken particle content in a shot charge increases the time required to reach Almen intensity increases, thus affecting productivity. Additionally, the wear of peening machine components is dramatically increased as media broken particle content increases.

Research performed by Airtech Precision Shot Peening, Inc. indicates that small amounts of broken particle content in the shot charge can have a significantly detrimental effect on fatigue life. Indeed any non-spherically shaped shot can be considered degrading to workpiece performance, including oblong, flat sided or otherwise non-spherical particles. Many factors are affected by non-spherical shot including the aggregate energy transferred to the workpiece (Almen intensity) and the homogeneity of microscopic material strain and residual stress patterns. (10)

EQUIPMENT

The percentage of broken particle content in a cast steel, glass, or ceramic shot peening machine shot charge is controlled via a properly designed and balanced air wash or cyclone separator and, optionally, a shot replenishing system. Any peening machine air wash separator must be designed for
precise tuning and ideally should provide for recirculation of marginal material for recleansing. Non-adjustable air wash or cyclone separators are inadequate.

Bucket elevator shot recovery systems used in some cast steel shot peening machines normally use a skimmer plate type of air wash system. These should include adjustable skimmer plates (preferably more than one) with shot bindicator which can automatically shut off shot flow to the air wash if a full curtain of shot is not maintained. The shot projecting device hopper under the air wash should hold enough shot to insure several minutes of shot flow to the shot projecting device(s) if shot flow is temporarily interrupted above the air wash.

Pneumatic shot recovery systems most often utilize a cyclone type shot reclaimer. These should include adjustable air intakes for proper separation. (The design of most cyclone type reclaimers is similar. The effectiveness in removing broken particles varies widely from brand to brand, however, if this type of reclaimer is contemplated, test work should be conducted before purchasing to determine the effectiveness of the particular make and model in separating broken shot at the rates needed for production. Proper dust collector operation is also essential to any air wash system. Fluctuations in air flow will compromise the effectiveness of the air wash. Manometers of manehelic guages measure the pressure differential across the dust bags, and therefore, will indicate variations in air flow, all other variables remaining constant, i.e. fan rpm and condition, dust work condition, and blast gate adjustment etc.)

Air wash separators remove broken particle content by sensing a difference in specific gravity. Spirolators remove broken or non-spherical particle content by differentiating between particle shape. This is normally used only in cast steel shot peening operations where shot particles may be distorted by the casting operation or by plastic deformation caused by impact. By combining an airwash and spirolators in cast steel operations, much more positive control is obtained than by using either independently. The effectiveness of individual spirals in a system is compromised by high flow rates of shot. In such a case, the size of the spirolator system may become too large to be practical as a part of the peening equipment. In such cases, a separate system independent of the peening machine may be necessary where shot is purged from the peening machine on a regular basis and independently separated. Another alternative is to cycle only a percentage of the shot through a spiral reclamation system as it is recovered from the blast cabinet. These needs will occur only in cases where multiple high horsepower shot wheels are involved or unusually high media velocities and/or very hard shot are used.

An automatic shot replenishing system maintains a constant supply of shot in the peening equipment by compensating for the removal of broken particles and is a particularly essential ingredient for a properly functioning system which peens with one type of shot on one type or similar type workpieces (i.e. shape, material, hardness, etc.). Once the entire reclamation system is properly adjusted, spherical shot with insignificant amounts of broken particle content can be maintained.

QUALITY ASSURANCE

Assuming that sizes below the acceptable range are removed, the percentage of unacceptable particles, (broken and out of round) can be determined by two methods:

1) Visual examination of a sample of shot in one layer which completely fills an area of 1" square, for S390 and up, and .5" square for smaller sizes. By counting the number of broken and out of round particles, a percentage of unacceptable particles can be determined. MIL-S-13165B, Table I lists the maximum number of unacceptable particles. Although Table I is specified for new shot, as discussed elsewhere it should be the minimum criteria for in-process shot as well. Figure 7 in MIL-S-13165B illustrates unacceptable shapes.

2) A gravity separation system utilizing a slightly inclined (5-10 degree) 12 inch long plane vibrating at high frequency, low amplitude can also be utilized. By placing a measured sample of the shot in question (usually 10 grams) on the highest portion of the vibrating...
inclined plane, measuring the mass of the shot that rolls off the lowest end of the plane after 10 seconds and subtracting this figure from the mass of the entire sample, a very accurate percentage of broken or unacceptably shaped shot can be obtained.

In experimentation, the authors have found that Method #1 is not nearly as accurate as Method #2 and will, in fact, vary significantly from one sample to the next. This is quite probable due to the relatively small size of the sample. We suggest using Method #2.

The control of shot sphericity should start with the shot manufacturer. Shot complying with MIL-S-13165B recommendations for new shot should be a minimum standard for new shot. This can be obtained either by purchasing Military Specification shot or by processing SAE J444 specification shot to MIL-S-13165B standards. A shot processing plant consisting of spirator and vibrating screens similar to those outlined in this paper provides such capabilities.

DOCUMENTATION

There is no known method for continually documenting in-process shot shape. Thus all documentation must be performed upon samples and recorded on a routine basis as discussed above. Accurate records should be kept to identify any patterns of non-compliance.

III. SHOT SIZE UNIFORMITY

Obtaining consistent shot peening results requires that the peening shot in a machine be of a uniform close tolerance size. The section of this paper dealing with nominal shot size describes the cause/effect relationship of shot size variance. The range of sizes present in a peening machine shot charge also affects the amount of energy transfer to the workpiece. (7) For a given Almen arc height, two different residual stress profiles can result from two different shot size ranges or "mixes" in a shot charge. See Figure 5.

This presents a particularly insidious problem with cast steel shot as individual particles in a shot charge will not break down uniformly as to rate of fracture or size of fractured pieces. Some shot will shatter or fracture into two or more large pieces while others will flake at the surface leaving relatively spherical particles of different sizes.

Routine Almen arc height checks during production will not necessarily reveal the problem; (see Figure 5) and it is difficult and time consuming to identify the problem by examining the workpiece surface.

For glass beads and ceramic shot medias, since neither flakes nor cold works into smaller spherical shapes than the original shot particle, merely ordering new medias which are consistent in size is sufficient for controlling the range of spherical particle sizes. This, of course, is true as long as care is taken to insure that the shot does not become contaminated with other new media of different sizes. MIL-G-9954A should be specified for all requirements of glass bead. There is currently no U.S. Military specification for ceramic peening shot.

Cast steel shot size uniformity control is a more complex problem. As new shot is added to replace shattered particles, a relatively large range of acceptably spherical shot sizes will be present. While this is decidedly good in many blast cleaning operations; it is decidedly not in peening.
The inherent problem is that obtaining a constant cast steel shot size mix in non-uniformly sized shot charges, where each nominal size makes up a consistent percentage of the whole, is difficult, relatively expensive, of questionable technical value and unnecessary. It is far easier and much more cost effective to maintain a constant, close tolerance shot size mix. See Figure 6 for an illustration of the effect of a range of shot sizes in a machine shot charge on Almen arc height.

**THE EFFECTS OF SHOT SIZE NON-COMFORMITY ON ALMEN ARC HEIGHT**

**INDICATED ALMEN ARC HEIGHT**

| S | 2.30 |
| S | 1.90 |
| S | 1.10 |
| S | 0.70 |

**EXPOSURE TIME**

**FIGURE 6.**

**PEENING EQUIPMENT**

The most inexpensive and productive means of controlling the range of cast steel shot size is through a multideck vibrating screen unit placed between the shot recovery and reclamation system (normally a bucket elevator or pneumatic conveyor followed by an airwash separator) and the shot propelling device shot hopper.

By choosing screens that yield shot sizes listed in Table I of MIL-S-13165B, a consistently narrow range of shot size can be maintained. (Through experimentation the authors have noted that the wire cloth mesh size utilized in a vibro-screening separation operation may yield shot slightly smaller than this dimension due to its rapid motion. Verification of correct nominal sizing should be made using test sieves of the proper size when the screening system is installed.)

**QUALITY ASSURANCE**

Shot size range for new or in-process shot should be plotted per Table I, MIL-S-13165B using calibrated test sieves. Your Quality Control Department should test new shot and in-process shot at predetermined intervals to determine its conformance to this specification, Table I.

MIL-S-13165B lists another table, (Table V) for in-process shot which is much less stringent. New SAE specification shot sizing is also much less stringent. Through testing, the authors have determined that allowing the shot to go to the size ranges defined by MIL-S-13165B, Table V and/or SAE specification will widen the scatter range of fatigue test results. As such we view either as an unacceptable alternative to MIL-S-13165B, Table I. It is a relatively inexpensive, straightforward task to maintain MIL-S-13165B, Table I standards. Nothing else should be acceptable in peening applications where the fatigue life, stress corrosion resistance, or load carrying benefits of the peening process must be depended on to enhance component performance.

Glass beads and ceramic shot tend to shatter when fracture occurs with the result that the media particles are either spherical and of the proper size or fractured, angular, and significantly smaller than the proper size. The effect of the broken particles that result are addressed in the section of this paper that addresses shot broken particles.

**DOCUMENTATION**

Routine Quality Control inspection of the condition of vibro screens and the size of particles passing through should be established as the in-process screens will wear over a period of use. Accurate records over a period of time will outline critical intervals when routine repair/replacement should take place as a scheduled part of preventive maintenance. Records from receiving inspection of shot received will provide information as to the quality of the shot supplied by your vendors.
IV. SHOT FLOW RATE

Shot flow rate is defined as the amount of peening media flowing, in mass per time unit, to a shot projecting device. This will quite obviously affect the number of shot particles striking the workpiece and hence, coverage, Almen saturation, and workpiece saturation. The phenomena of peening coverage, Almen saturation and workpiece saturation are dependent on shot flow rate. These, while similar, have been widely misapplied as being synonymous.

It is not necessary for our purposes to define Almen and workpiece saturation in terms of metallurgical mechanics, but rather to come to a conceptual understanding of how it affects the process and how it differs from coverage. Those wishing more information on peening saturation metallurgical mechanics should see published works by S.T.S. Al Hassani, (2); S.A. Mequid, (3); H. Fuchs, (8); and others discussing the subject in depth.

Coverage is a measure of the quantitative amount of a peened workpiece surface which has been obliterated by shot impingements. It is expressed as a percentage of the entire area to be peened. A surface cannot be more that 100% covered. Coverage does not measure in any way the quality of impingements, the qualitative or quantitative energy transfer to the workpiece, or whether the workpiece has been repeatedly cold worked by repeated shot impingements in an area.

Almen Saturation is a calculation of the amount of time required, at constant process parameters including shot flow rates, for Almen arc height to reach stabilization. See Figure 7A.

It is important to note that Almen saturation is only meaningful in determining optimum process parameters when two concepts are accounted for:

A) Almen strip placement must represent the workpiece area to be peened as closely as possible. Representation of radii, small areas to be peened, workpieces smaller than an Almen strip, etc. are difficult.

B) Almen strips are 1070 steel, 44-48Rc, and will achieve saturation and coverage differently over time than other harder or softer materials.

Almen saturation is a measure of stabilized aggregate energy transfer to a 1070 test strip, while coverage is a visual examination of a peened surface.

If Almen Saturation is calculated on the basis of shot flow rate at a fixed blast cycle time, the results are as depicted in Figure 7B. Figure 7A and 7B are graphic illustrations of the parallel nature of effects of shot flow rate and blast exposure time on Almen Saturation.

Workpiece saturation is a concept drawing on both Almen Saturation and coverage. If a given quantitative level of energy transfer to an Almen strip in Almen intensity correlates with optimum performance on a particular workpiece, then depending on the physical and chemical characteristics of the workpiece it may require a smaller or greater number of impingements for a given area to obtain this optimum level of energy transfer to the workpiece. Almen intensity, (an Almen arc height at Almen saturation,) is therefore, a measure of aggregate energy transfer to a
test strip at constant parameters in a given time which may or may not correlate with the optimum amount of workpiece exposure time to shot impinging the surface at the same parameters as the test strip. If the impingements on the workpiece are not resulting from secondary impacts, lower velocity shot, or low impact angles, then 100% coverage and part saturation will occur simultaneously. Complex shaped workpieces, improperly positioned or worn shot projecting devices, and many other circumstances can create conditions where 100% coverage and 100% workpiece saturation do not occur simultaneously. It is therefore important to examine a shot peening operation from a conceptual standpoint to ascertain if this description is true for the operation. Because there is currently no means of definitively verifying that these circumstances are occurring, this conceptual analysis becomes of further importance.

### The Effects of Variation in Saturation and Coverage Levels

The effects of less than 100% coverage have been well documented. As much as 50% of the total benefit derived from shot peening can occur between 90% and 100% coverage. (4)

The effects of multiples of 100% saturation are less well documented, but are equally as detrimental in at least some materials, with specimen fatigue life benefits derived from peening being reduced by as much as 50% at 200% Almen Saturation. (4) and (5) Although more information is needed on this subject, there is evidence that the workpiece life reduction at multiples of 100% saturation is caused by microcracks developed in the surface of the workpiece from repeatedly cold working the same areas. (4) and (5). See Figure 8.

**FIGURE 8**

Since changes in shot flow rate can cause dramatic changes in workpiece performance, process benefit reproducibility requires shot flow monitoring and control.

**Equipment: Shot Flow Controls**

In the past, shot flow rate on both wheel and air blast peening equipment utilized a fixed or mechanically adjustable feed valve of some type. In wheel type peening equipment, an ammeter on the wheel drive motor provides better information, but can be misleading if bearings are worn, contaminated with abrasive dust, or over lubricated, situations not uncommon in blast equipment. Although the best available controls at the time, these types of shot flow controls proved inadequate for consistently reproducing constant shot flow rates. Sine wave fluctuations in the amount of shot being delivered to a shot projecting device are very common. These types of controls are simply inadequate to detect the relatively small amounts of shot flow rate fluctuations which can affect workpiece performance. The typical practice of an equipment operator listening for shot flow surges while the peening equipment ran, and subsequently adjusting the feed valve to eliminate audible surges is far
too crude for consistency and extremely unreliable from operator to operator.

Several types of automatic electronic shot flow controls have been developed, the most successful of these being the magnetic shot flow meter for cast steel shot operations. Currently manufactured by several companies, the electronic shot flow meter can work on the basis of an alarm system which provides automatic immediate process shutdown if out of tolerance fluctuations are experienced.

Also available from a more limited number of sources is an electronic shot flow controller. These instruments are a simple, exacting, and reliable means of controlling shot flow. When changing workpiece diameter or the size of the area to be peened, a part requires the fine tuning of shot flow rates to achieve 100% coverage over the areas to be peened without workpiece saturation overpeening any areas, shot flow meters and controllers offer exacting calibration, control, and reproducibility.

Any shot peening process which is depended upon for delivering fatigue life or other workpiece performance characteristics should include shot flow meters and preferably, meters and controls, for each shot wheel or nozzle utilized.

QUALITY ASSURANCE

Shot flow meters should be calibrated as a part of your routine calibration system. This calibration is accomplished via a catch test where shot is blasted into a container for a fixed time cycle. The shot in the container is weighed and the blast cycle time divided by the number of minutes to arrive at a mass per unit time figure. This is compared against the reading on the meter itself. Care should be taken to utilize a container which will retain all of the shot from the blast. Shot flow meter vendors should be able to supply such a container.

Preset shot flow rate tolerances should be relatively small with an automatic process shutdown preferable for out of tolerance parameters. Settings of ±5% should be considered the maximum allowable. ±2% is preferable and easily achievable with shot flow controls. These settings will require a delay timer when the machine blast cycle is initiated to discount the initial surge of shot flow typical of most blast machines.

DOCUMENTATION

The coupling of strip chart recorders to shot flow meters is an inexpensive and definitive means of documenting the actual flow rates during the process. This is particularly important as there are currently no Non-Destructive Tests for shot peening or part saturation; and as such the input process variables and sub-variables are the only direct means of measuring process effectiveness.

V. CAST STEEL SHOT INTEGRITY

Cracks, voids, and shrinks in cast steel shot are impossible to avoid entirely due to the nature of the casting process. The amount of these present in shot determines not only its mass (hollow shot is obviously lighter than shot that is not hollow), but, all other factors equal, it determines the shot's ability to withstand repeated impact without fracturing. The quantitative levels of inherent structural soundness and homogeneity in shot is known as shot integrity.

The limitations of the casting process make a total lack of integrity problems currently unattainable in cast steel peening shot.

Ceramic shot is relatively new to the marketplace. One of the authors is, in fact, currently examining the effects of peening with ceramic shot versus peening with glass beads in a preliminary study for an SAE fatigue sub-committee. While ceramic shot appears from preliminary data to be a promising alternative to glass beads, not enough is currently known about the quality of production lots of the media to warrant discussion here.

Glass beads of consistent high quality and lack of integrity problems are available from several sources.

QUALITY ASSURANCE

Shot particle integrity is determined by visually examining shot particles cast into the surface of a plastic plug. The plug is ground leaving shot hemispheres. Military Specification MIL-S-851C, item 3.5.
which limits unacceptable shot to 15%, should be considered the minimum acceptable.

This examination is necessarily subjective. Only personnel trained to differentiate between acceptable and unacceptable shot should be entrusted with this inspection, which should occur as part of receiving inspection. MIL-851-C is the best applicable specification for cast steel shot integrity. When ordering new shot, this should be specified.

**DOCUMENTATION**

The results of the tests outlined above should be recorded and periodically examined to determine patterns in supplier quality.

**VI. SHOT CHEMISTRY AND MICROSTRUCTURE**

**CAST STEEL SHOT**

Shot chemistry and microstructure affect particle breakdown rate and work hardenability. It is desirable to minimize both the broken particle content and work hardenability for the reasons discussed under the section devoted to them. Consistent fatigue life requires stabilization of non-spherical shot content below 10% and shot hardness within a predetermined hardness range. Cast steel shot should conform to MIL-851-C for both chemistry and microstructure. Consistency of cast steel shot chemical content is often a problem as cast steel shot is normally formed from reclaimed scrap, with obvious problems occurring if the chemical content of material placed in the furnace is not closely monitored.

**GLASS BEADS**

High quality sodium glass beads per MIL-G-9954A are required for glass bead peening. Particular attention should be paid to chemical purity as glass beads are normally utilized on non-ferrous materials due to their chemical inertness.

**CERAMIC**

Ceramic shot under study at Airtech Precision Shot Peening, Inc. is made of zirconium oxide or aluminum oxide. Not enough is currently known about these in peening applications to discuss potential problems.

**EQUIPMENT**

There are no peening equipment controls as such for shot chemistry or microstructure.

**QUALITY ASSURANCE**

Cast steel shot chemistry and microstructure should comply with MIL-S-851C, Table I, Type I for maximum life and desired hardenability characteristics. Compliance can be demonstrated and certified by your shot manufacturer(s) or determined by a metallurgical laboratory.

Glass bead chemical content verification can be provided by the manufacturer.

**DOCUMENTATION**

Comparison of manufacturer certification or laboratory results should be performed and recorded for a sample from each container of new shot received. After a history has been established for each vendor, a statistical Quality Control program commensurate with the capabilities of each vendor can be initiated.

**VII. SHOT HARDNESS**

**GLASS AND CERAMIC**

Sodium glass beads per MIL-G-9954A and zirconium oxide or aluminum oxide ceramic shot are significantly harder than most workpieces, are consistent in hardness, and do not work harden. As such, shot hardness is not a factor with glass or ceramic for most applications.

**CAST STEEL SHOT**

An area of the shot peening process commonly overlooked, yet of extreme importance, is the hardness of metallic shot.

Figure 9 illustrates the variation in energy transfer of differing shot hardmesses occurring at identical velocities.

The shape of the softer shot saturation curve is also important.

Metallic shot utilized in blasting and peening will work
harden. The softer the shot, the more it will work harden. 42-48 Rc shot may work harden as much as 10C while 60-65 Rc shot under typical conditions work hardens much less even when used on 60 Rc or harder workpieces.

Often companies buy regular hardness (42-48 Rc) shot because its fracture rate is lower than harder shot. However, when measuring the life of both 54-60 Rc cast steel shot and 42-48 Rc cast steel shot from work hardness stability to fracture, the difference becomes significantly less. In test work Airtech Precision Shot Peening, Inc. has conducted, peening 52 Rc workpieces, the difference in the stable hardness shot life of shot which was 42-48 Rc when new and shot which was 54-60 Rc when new is insignificant.

Another important factor to be derived from Figure 9 is that the energy not transferred to the workpiece is absorbed into the shot particle as shot particle plastic deformation. The result is often semi-spherical shot that has many flat facets. As outlined in the section on SHOT SHAPE, while realizing that 100% absolutely spherical shot is a practical impossibility, any degradation in general shot spherocity can be considered degrading to workpiece performance.

**EQUIPMENT CONTROLS**

There are no equipment controls as such for shot hardness.

**QUALITY ASSURANCE**

Purchased shot should include sample plugs taken from the container(s) shipped to you. Several hardness tests should be taken on each plug. All readings should be within the specified tolerance. Most shot manufacturers of high quality peening shot will provide this service.

After passing receiving inspection new shot should be conditioned before utilizing it in peening.

If relatively soft workpieces are to be peened, cycle the shot through a wheel type blast machine until Almen arc height stabilizes. If harder workpieces are contemplated, then blasting against a hardened steel plate placed in a similar blast machine until Almen arc height stabilizes is suggested. Use of a wheel type machine is also suggested here for productivity purposes.

This type of media work hardening procedure insures that shot particles utilized in the peening process are relatively hardness stable throughout their life cycle of being charged into the peening equipment to their ultimate fracture and removal from the peening equipment.

**DOCUMENTATION**

All shot containers should be segregated as to new unconditioned, new conditioned, or used in production in addition to their identification as to size and acceptability in meeting applicable specifications. Their status should be further identified by tagging each container with tags designating this.

When the use of a fresh charge of all new conditioned shot is unavoidable, document shot work hardness stability by running the appropriate Almen saturation curve for the parts being peened. Peening on production workpieces should not begin until shot work hardness stability has been achieved.
DISCUSSION

Shot peening has, since its inception, been plagued by the lack of a non-destructive inspection. The recent trend in industry toward more definitive, more objective, and more exacting quality assurance techniques merely heightens this need in the shot peening process. Current industry and U.S. specifications are largely vague, out of date, and at times contradictory and/or inaccurate. Considering the lack of published data on controlling and reproducing the process this is quite understandable.

There is a great need for engineering groups and associations which deal with shot peening to take a leadership role in defining succinct, accurate and encompassing specifications which utilize an increase in understanding of the shot peening process. This information, however, no matter how correctly and completely placed into specifications is of little value if production operations do not have the technical knowledge or equipment necessary to comply.

If shot peening is going to be used as the process of choice for increasing fatigue life, stress corrosion resistance, and load carrying capacity, the means of reproducing the results in production must be equally as sophisticated as the understanding of its fundamental mechanics and the research in application parameters.

Shot peening technology, while making strides in the recent past in the area of optimum process parameter identification, requires much more research to be able to predict what optimum parameters will be for all process variables and sub-variables and how they will affect workpiece performance.

The availability of a non-destructive inspection and accurate specifications would not diminish the need for process control in shot peening but would, as research indicates, only point out the lack of process control widely currently used in the majority of applications.

The central question is much more immediate than one of how the shot peening process will be applied in future design engineering circles. Today's engineer who utilizes the process often relies on shot peening either as a tool to deliver an unknown, but beneficial quantity of component performance enhancement, (an engineering "margin of safety" in cyclically stressed metallic component performance) or as a means of dealing with pressing component life problems under short time constraints.

Numerous times the authors have consulted with users of the peening process where small but decisive variations in one or more process variable levels were resulting in production components obtaining only small fractions of the benefit obtained in pre-production test work. Indeed, at times, the results have been worse than unpeened due to the lack of variables control. The margin of "engineering safety" built into the component by peening is, as a result, often not present.

Because of the lack of process documentation, engineering is often unaware of the problem until a field failure occurs. The lack of process performance is often further clouded by the proximate cause of failure being inconsistencies in material or other processes like heat treating.

The peening process, even if it is to serve as merely an engineering margin of safety, must be reproducible by objective, quantifiable means. The tools and procedures for controlling the shot peening process in a precise objective manner are available today. It is only a matter of intelligent application of these to be able to come to a firm reliance on the quantitative and qualitative results of this process. Only then will the confidence have been generated to utilize shot peening's significant benefits as a design engineering tool for producing lighter, stronger, more cost effective products.

REFERENCES


