Image Analysis of Shot Peening Media

by

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Abstract

Of all the important characteristics of shot peening media, by far the most critical are size and shape. New technology is presently available that is capable of evaluating both size and shape simultaneously. Image Analysis is a computerized vision system able to accurately measure size (diameter) and shape (roundness) of shot particles. Image Analysis offers substantially improved precision and accuracy in measurements of media size and shape while providing data which is more detailed and descriptive than possible with traditional methods: Sieve Analysis (size) and Visual Inspection (shape).

Key Words

Image Analysis, Sieve Analysis, Visual inspection, Shot, Size, Shape, Diameter, Roundness, Digital Micrometer

Introduction

The previous five International Conferences on Shot Peening have documented that the advantages and benefits of shot peening and applications are ever increasing: improvement of fatigue and stress corrosion resistance; form parts or correct their shapes; establish uniform and repeatable surface texture (1, 2, 3, 4, 5). But after many many years and thousands of successful applications, there is still no non-destructive method available to evaluate proper shot peening in the vast majority of applications which are in fatigue and stress corrosion improvement. It is even more essential in today's business environment that the shot peening process be strictly controlled in order to insure repeatability and reliability from part to part and from lot to lot. However during the past few years, significant advances have been made which improves repeatability and reliability of shot peening processing equipment as well as peening media:

1. Equipment - Robotic and computer controlled shot peening equipment is now available to assure precise control over most critical process parameters for each part processed.

2. Monitoring and Documentation Systems - Systems and instrumentation are in use today that monitor critical process parameters such as shot flow, air pressure, nozzle, wheel and part position and document that the part, or parts have been processed according to the applicable requirements.

3. Specifications - In recent years, most industry-wide and many user specifications have been revised and tightened to incorporate the new technology advances in equipment, improved media, monitoring and documentation systems.

4. Media - During the past decade, media with improved consistency and increased durability are now available and in use (6, 7). For example, more and more companies are using conditioned cut wire shot due to its improved durability, higher resistance to fracture, reduced dust levels and lower surface contamination.

In evaluation of shot peening parameters, the single most important parameter continues to be the media itself. Without the proper shot in the machine, all other peening parameters will be meaningless and the desired results (repeatable and predictable fatigue or stress corrosion resistance) will not be achieved. Of the major characteristics of shot peening media, by far the **most important are size and shape** since they are the characteristics that deteriorate with use.

For the past 40 or 50 years, media size has been evaluated by Sieve Analysis (SA) and shape has been evaluated using Visual Inspection (VI). In recent years, a new technique capable of evaluating both size and shape of shot peening media has become available. This technique is Image Analysis (IA). The intent of this paper is to describe IA, how it works, to discuss the correlation between IA and the traditional methods SA and VI, and to present potential applications within the shot peening field.

Traditional Techniques

SIEVE ANALYSIS - Size evaluation of peening media is normally done by SA. During SA, a representative sample of media is taken and a known weight of this sample is poured on the top sieve of a stack of four or five sieves. The sieve stack is arranged in order from the largest sieve on top to the smallest sieve on bottom. The sieve stack is then placed into a device that shakes the sieves at a predetermined rate for a specified period of time; providing hundreds and thousands of opportunities for each particle to pass through the sieve openings. After the sieves are shaken, they are removed and the amount (weight in grams) of material remaining on each sieve is determined. Equipment used in SA are shown in Figure 1 which includes the sieve stack, scale, timer, sieve brush and collection pan. Test results normally are reported as Percentage of Total Weight.

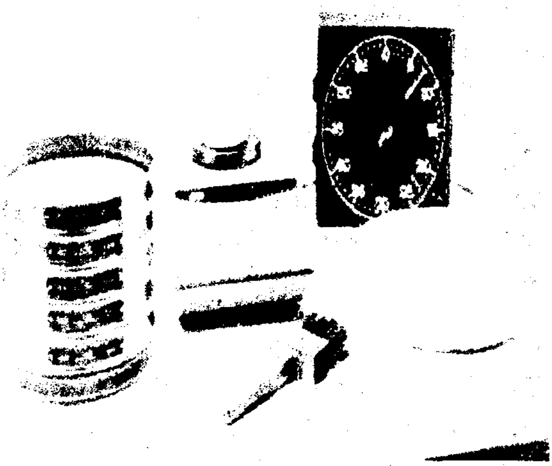

Figure 1 - Sieve Analysis Equipment

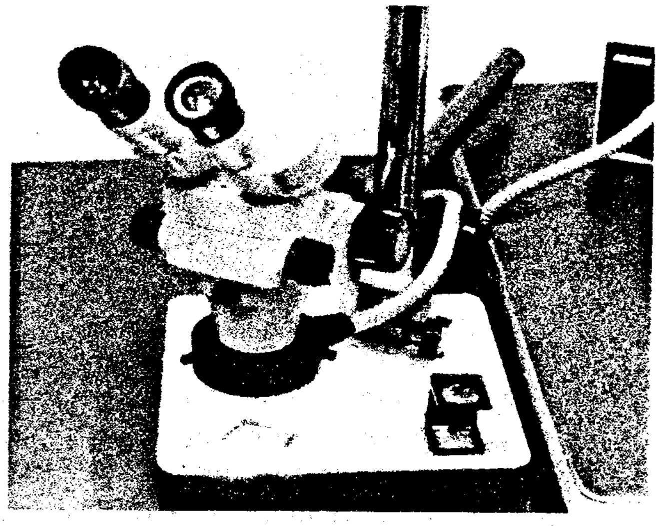

Figure 2 - Visual Inspection Equipment

The determination of proper shake time for the shaking device should be stressed. If the sieve stack is shaken for a time less than the minimum shake time (MST), results can be incorrect and also inconsistent. Table 1 illustrates the importance of shake time in SA. Minimum shake time can be determined by shaking the same sample a number of times; each longer than the previous. It is suggested that the MST be defined as the shortest time at which there is no more than one-half percent (0.5%) change in the results for all sieves used. For the sample tested in Table 1, MST would be fifteen (15) minutes.

Table 1 - Influence of Shake Time in Sieve Analysis

Sieve Size	5 min.	10 Min.	15 Min.	20 min.
18 mesh	16.1	15.4	14.6	14.6
20 mesh	42.2	42.7	43.5	43.4
25 mesh	30.3	29.9	29.5	29.5
30 mesh	8.8	9.2	9.5	9.4
Pan	2.7	2.8	2.9	3.1
Total	100.0%	100.0%	100.0%	100.0%

As the sieve stack is shaken, the particles that are much smaller than the sieve opening will quickly pass through the sieve. Particles closer in size to the sieve opening will take longer to pass through the sieve; with the particles almost the same diameter as the sieve opening taking the longest time. Therefore, the closer the particle size to the sieve opening, the longer the MST will become. In Table 1, as run time increases from 5 to 20 minutes, more and more particles pass through the 18 Mesh sieve, and to a lesser extent the 25 Mesh sieve. The amount retained on the 20 Mesh sieve (and 30 Mesh sieve) increases as particles pass through the sieve above until there is almost no further change. At this point, one should be confident that the test results are representative of the sample.

Industry Standards and specifications, developed over many years, require shake time for 35 mesh sieves or coarser (larger) to be five (5) minutes plus/minus five (5) seconds and for sieves finer (smaller) than 35 Mesh to be ten (10) minutes plus/minus five (5) seconds. Based on the test results given in Table 1, there would be a significant difference in test results reported after five (5) minutes shake time than after fifteen (15) minutes. There can be significant variation between two companies testing the same sample of media (with each company using their own sieves) of as much as plus/minus five (5) percent. This variance can be improved by using specially matched and calibrated sieves made from the identical screen cloth. Also, new sieves can be made using special screen cloth that has been very closely controlled during manufacture. Specially matched or manufactured sieves can reduce the variation between two companies measurements to plus/minus two (2) to three (3) percent.

VISUAL INSPECTION - Shape evaluation of shot peening is traditionally done visually. A representative sample of the media is taken and a single layer of the sample is obtained, usually on a piece of clear tape. The layer is taken so that hundreds of particles of shot fully cover the surface of the tape. Next a specified area for that shot size is determined and each particle in that area is evaluated using 10x to 30x magnification; with, preferably, a stereoscopic microscope. The shape of each particle is judged to be either acceptable or unacceptable by the inspector according to sketches found in the applicable specification/s. Figure 2 shows equipment used in visual inspection, including a stereo microscope and 10x magnifier. Figure 3 shows acceptable and unacceptable shapes defined in MIL-S-13165 (8) specification. Table I of MIL-S13165 (8), a commonly used shot peening specification in the United States lists Media, Area of particles to be viewed and the Allowable Number of Unacceptable shapes per shot size. (For example, when evaluating S-330 shot a layer of media 12.7 mm x 12.7 mm should be viewed and no more than 16 Unacceptable Shapes are allowed.) As media size increases, it is necessary to observe larger areas in order to view a statistically relevant number of particles. The number of unacceptable shapes allowed by MIL-S-13165 is intended to be about 10% of the particles viewed; which is rather generous. Other specifications (9) try to reduce the number of unacceptable shapes to three percent (3%) or less; with no more than one to two percent (1%-2%) potentially damaging sharp edge particles allowed. Visual Inspection is highly subject to inspector interpretation, experience and error.

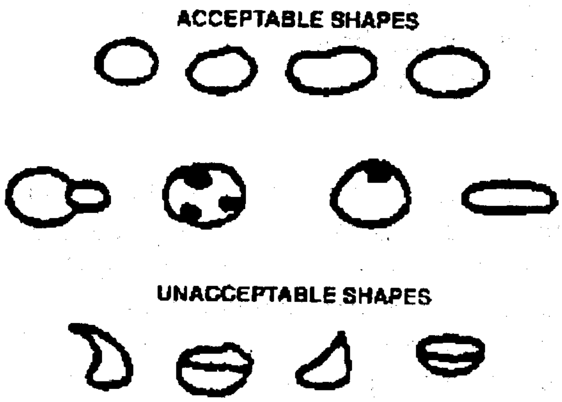

Figure 3 - Shapes MIL-S-13165

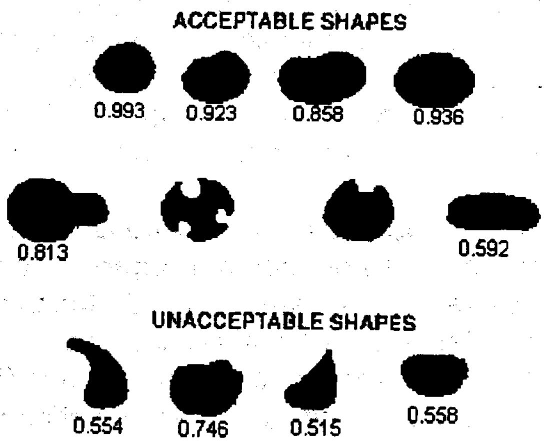

Figure 4 - Roundness MIL-S-13165 Shapes

Image Analysis

IMAGE ANALYSIS - IA can be defined as the use of digital computers to manipulate pictures or images for the purpose of extracting information about features within the images. An IA system typically consists of a video camera, high resolution monitor, magnifying device, and computer such as those shown in Figure 5. In IA a representative sample of media is taken and a single layer of particles is placed under the magnifying device. The video camera projects the shot particles on the high resolution monitor where they can be digitally measured using the computer. IA software is designed to measure the size (diameter) of each particle in the field as well as determine its shape (roundness).

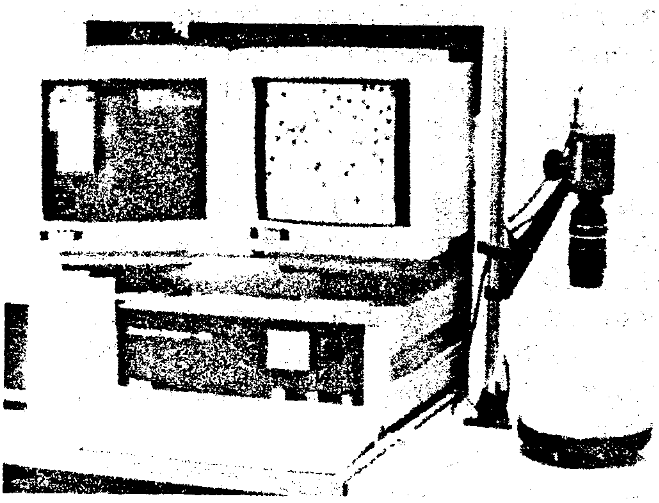

Figure 5 - Image Analysis System

The size of shot particles is normally given as average diameter (or radius) and can be measured in inches or millimeters as desired.

Roundness of a particle is determined by its area and perimeter according to the following well-known formula:

$$\text{Roundness} = \frac{4 \times \pi \times \text{Area}}{\text{Perimeter}^2}.$$

For a perfectly round particle such as a circle, Roundness will be 1.000; and for a straight line (which has no area), Roundness is 0. A square particle will have a Roundness of 0.785 and a 2:1 ellipse will have a Roundness of 0.889. Figure 4 shows the roundness of the particles in Figure 3. Please note that the Roundness of Particles 2 and 3 in Row 2 of Figure 5 are not included since the conditions shown (Hollows and Porosity) are not examples of particle shape, but of "Internal Defects". Acceptable shaped particles have roundness of 0.858 or higher and the unacceptable shaped particles have roundness less than 0.813. A suggested value for acceptable shaped particles would be Roundness = greater than 0.830 with unacceptable Roundness = 0.830 or less.

One of the very important advantages of the IA technique is that the output data provided by IA is much more descriptive than either SA or VI. IA reports a measured value for diameter and roundness for each particle evaluated. This data can then be used to describe characteristics of the sample such as average size and roundness; variation (standard deviation, range) in size and roundness; histograms , SPC charts, Process Capability studies and many other descriptive statistical characteristics. Knowing average size and variation in size of a media is much more relevant than knowing that eighty percent (80%) of the particles passed through a 1.0 millimeter (mm) opening, but would not pass through a 0.8 mm opening.

Correlation

When introducing a new concept, it is helpful to correlate the new idea with existing products or techniques. During 1991 correlation studies were performed in order to learn how IA would correlate with both SA and VI (9). In this study the authors measured the diameters of four different media: S-110, CCW 17, S-280 and CCW 32 using SA and IA and also evaluated the shape (acceptable or unacceptable) of the media. Results of five consecutive size measurements on the same sample for each media showed that IA was **six times** more precise than SA. When evaluating shape of the media, the conditioned cut wire media CCW 17 and CCW 32 did not exhibit any unacceptable shapes, but a correlation was possible with the cast steel S-110 and S-280 media. Table 3 lists this correlation. The Mean percentage **and** the Standard Deviation of unacceptable shapes determined by the two techniques were both within one-half percent (0.5%) of each other - very good correlation.

Table 3 - Shape Evaluation - Visual Inspection Vs Image Analysis

Media	VI Mean	IA Mean	VI Std. Dev.	IA Std. Dev.
S-110	1.73%	2.06%	0.70%	0.31%
S-280	3.38%	3.13%	1.03%	1.09%

A correlation between SA, IA and random diameters measured using a Digital Micrometer (DM) was recently performed by this author. Over six hundred random particles of the same sample lot were measured using IA and a Digital Micrometer. The results are given in Table 4. The correlation between IA and DM is excellent.

Table 4 - Correlation Image Analysis Vs Digital Micrometer

Diameters (inches)	Digital Micrometer	Image Analysis
Mean	0.03234	0.03239
Standard Deviation	0.00432	0.00429
Standard Error	0.00018	0.00017
99.0% Confidence Level	0.00045	0.00045

Next, an attempt to correlate both IA and DM diameter measurements with SA was performed. Since SA measures results in units of weight (grams) and both IA and DM measure in units of length, it was necessary to make two assumptions to be able to convert to the same units. One, the diameters of the shot particles that pass through one sieve and are retained on the next size will have a normal distribution between the larger sieve opening and the smaller sieve opening. Two, the density of shot particles is 7.836 grams per cubic centimeter (conditioned carbon steel cut wire shot was used for this test due to its consistent density). The number of particles falling between each two sieves was calculated using a particle diameter equal to the average size of the two sieve openings. For example the number of particles passing a 1.180 mm sieve opening and retained on a 1.000 mm sieve opening was calculated to be 2748 pieces. Table 5 shows the sieve openings used, the amount (grams) of material falling between the two adjacent sieve sizes, the theoretical Weight per Particle (in grams), the Number of Pieces and the Percentage of the Total number of particles. It should be noted that the sieves are listed in order from the smallest opening size to the largest which is the reverse of how they are arranged in the sieve stack.

Table 5 - Calculated Number of Pieces from Sieve Analysis

Sieve Opening	Weight (g)	Wt per piece (g)	Number pieces	% of Total
0.600 mm	9.4	0.001153	8,153	20.68%
0.710 mm	29.5	0.001947	15,152	38.44%
0.850 mm	43.4	0.003247	13,366	33.91%
1.000 mm	14.6	0.005313	2,748	6.97%
1.180 mm				
		Total	39,419	

Tables 6 and 7 list the particle diameter and the number of particles larger than the size listed but smaller than the next size for Digital Micrometer and Image Analysis measurements respectively.

Table 6 - Number Pieces Digital Micrometer

Size	Number	% of Total
0.600 mm	104	16.99%
0.710 mm	244	39.87%
0.850 mm	233	38.07%
1.000 mm	31	5.07%
1.180 mm		

Table 7 - Number Pieces Image Analysis

Size	Number	% of Total
0.600 mm	118	18.79%
0.710 mm	233	37.10%
0.850 mm	247	39.33%
1.000 mm	30	4.78%
1.180 mm		

A correlation can now be made between SA, DM and IA by comparing the Percent (%) of Total for each measurement. Table 8 is a summary of the results of Tables 5, 6, and 7. Each technique measured shot diameters on the same sample as the others. The percentage of total for each size (particles passing through the larger sieve size and remaining on the smaller sieve size) is given in columns 2, 3 and 4. The difference (Δ) between the three techniques are presented in columns 5, 6, and 7. Average difference (Δ) are listed in row 7. One can see that all average differences are within the two to three percent (2.00-3.00%) which is the best precision of the SA technique. SA-IA average difference was slightly better than SA-DM average difference; and the DM-IA average difference was best.

Table 8 - Correlation Sieve Analysis, Digital Micrometer, Image Analysis

Size	SA	DM	IA	Δ SA-DM	Δ SA-IA	Δ DM-IA
0.600 mm	20.68%	16.99%	18.79%	3.69%	1.89%	1.80%
0.710 mm	38.44%	39.87%	37.10%	1.43%	1.34%	2.77%
0.850 mm	33.91%	38.07%	39.33%	4.16%	5.42%	1.26%
1.000 mm	6.97%	5.07%	4.78%	1.90%	2.19%	0.29%
1.180 mm						
Average				2.80%	2.71%	1.53%

Applications

Image Analysis is able to measure size (diameter) and shape (roundness) of as many individual shot particles as one would wish. The measurements can be statistically processed to give a wide variety of results. With Sieve Analysis and Visual Inspection the results are not as descriptive nor as accurate.

Knowing the Average (Mean) Diameter and Standard Deviation of shot peening media is valuable in predicting possible changes in the shot peening process. Example 1, if one media has a Mean Diameter of 0.8 mm and a second media has a Mean Diameter of 0.85 mm, one would expect the larger media to produce a higher peening Intensity and also to exhibit a longer life. Also the larger media may exhibit longer coverage times. Example 2, if one media has a Standard Deviation of 0.04 mm on the diameter measurement and a second media has Standard Deviation of 0.01 mm, one would expect that the peening process using the media with the lower variation will be more consistent as well (less variation in peening intensity and/or coverage times).

An obvious application for IA in the shot peening industry is **inspection** of peening media. Media users and manufacturers will be able to use IA to inspect size and shape of shot. The user could use IA for incoming inspection to verify that the media received from their vendor exhibits the specified average (Mean) and minimum variation (Standard Deviation) in size. For the same material, the manufacturer could use IA as an inspection tool (both in-process and final inspection) to assure that the size and shape of their product is within acceptable limits. Finally the user may wish to use IA as a tool to inspect and verify that they are able to maintain their shot peening media within specified limits during processing of their parts.

Since the output of IA is measurements, these measurements can be input into numerous statistical programs which look at data in various ways. One possibility is to input the data into a **Statistical Process Control** (SPC) program. SPC program will be able to present Mean, Range and/or Standard Deviation charts for media size and shape plotted over time. One will be able to evaluate their media to see if their processing is in control and if the media meets specification. A second possibility is to input the measurements into **Process Capability** program to learn whether the media is capable of meeting the specification, or perhaps the specification is too tight or even too loose. These SPC and Process capability programs may apply to both users in incoming inspection and shot peening processing; and media manufacturers for internal quality systems. Corporations applying for **ISO 9000 Certification** must be able to show that they have the capability to properly control and document their manufacturing processes and materials received from their suppliers are similarly under control. IA provides an excellent tool for evaluation and proper documentation of size and shape of peening media for either the media user or manufacturer.

Another intriguing application for IA in shot peening is in **Modeling** the peening process. An interesting paper was presented at ISCP5 (10) that discussed a theoretical basis for shot peening coverage control. The paper made a few assumptions. One assumption is that each shot particle makes the same size impression when impacting the surface of the material peened; which in turn assumes that each shot particle is the same diameter and round shape as all the others. When attempting to model the shot peening process, it will be most helpful to be able to measure and characterize the shot size and shape in an accurate and descriptive manner.

Summary

Image Analysis is an important new technology that enables the user to evaluate size and shape of peening media with more precision and accuracy than traditionally used methods. The more descriptive output data available with Image Analysis can improve product inspection procedures, evaluation of process control status and process capability studies. With the use of Image Analysis, researchers will be able to learn much more about the size and shape variations in new and used peening media; and future modeling efforts regarding the shot peening process may be able to more accurately predict actual results.

References

1. Niku-Lari A, Editor, *First International Conference on Shot Peening*, Pergamon Press, Paris, France, 1981.

2. Fuchs H O, Editor, *Second International Conference on Shot Peening*, American Shot Peening Society, Paramus, NJ, USA, 1984.

3. Wohlfahrt H, Editor, *Third International Conference on Shot Peening*, Deutsche Gesellschaft fur Metallkunde, Oberursel, Germany, 1987.

4. Iida K, Editor, *Fourth International Conference on Shot Peening*, The Japan Society of Precision Engineering, Tokyo, Japan, 1991.

5. Kirk D, Editor, *Fifth International Conference on Shot Peening*, Coventry University, Coventry, UK, 1994.

6. Gillespie R D and Gloerfeld H, *An Investigation of the Durability and Breakdown Characteristics of Shot Peening Media*, Fourth International Conference on Shot Peening, 27-36, The Japan Society of Precision Engineering, Tokyo, Japan, 1991.

7. Gillespie R D, *Shot Peening Media - Its Effect on Process Consistency and Resultant Improvement in Fatigue Characteristics*, *Fifth International Conference on Shot Peening*, Coventry University, Coventry, UK, 1994.

8. MIL-S-13165C US Military Specification, Shot Peening of Metals, 7 June 1989.

9. Gillespie B and Fowler D, *Evaluation of Size and Shape of Shot Peening Media by Image Analysis*, SAE Technical Paper 910926, Warrendale, PA, USA.

10. Kirk D and Abyaneh M Y, *Theoretical Basis of Shot Peening Coverage Control, Fifth International Conference on Shot Peening*, Coventry University, Coventry, UK, 1994.