Size and Variability of Cast Steel Shot Particles

INTRODUCTION

Size is probably the most important property of cast steel shot. It affects saturation intensity, coverage rate and depth of work-hardened layer. Any variability of shot size is therefore important. Specifications, such as SAE J444 and AMS 2431, <u>nominate</u> cast steel shot size in terms of sieving results. Hence we have <u>nominal shot sizes</u> based on sieve mesh spacing. Cast steel shot size can also be associated with the diameter of a sphere. That is convenient because (a) cast steel shot particles are <u>approximately</u> spherical and (b) a sphere is the only geometrical figure that has only one dimension. Association of a particle's size with sphere diameter is based on the concept of its "equivalent sphere".

The "equivalent sphere" of an individual shot particle is one that has the same volume as that of the particle (and therefore the same mass). Fig.1 illustrates the difference between sieve spacing and equivalent sphere as methods for sizing shot particles.
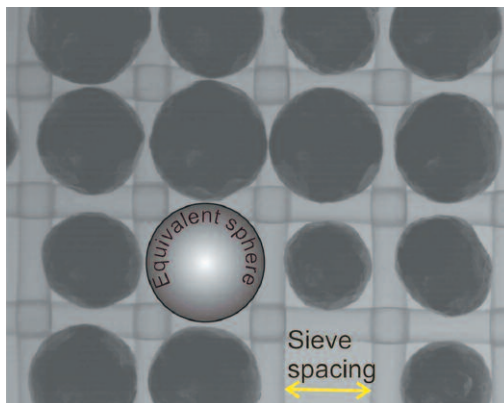

Fig.1 Cast steel shot particles on a nylon sieve.

Cast steel shot is available in a wide range of sizes. Fig.2 illustrates the size range covered by specification SAE J444. The 'S numbers' correspond to specified sieve spacings.

Each nominal size corresponds to a range of diameters. This range is associated with the methods used for producing and screening cast steel shot. Variability is accommodated in specifications – normally by stating the <u>range of permitted values</u>. The greater the range, the larger is the possible variation of peened
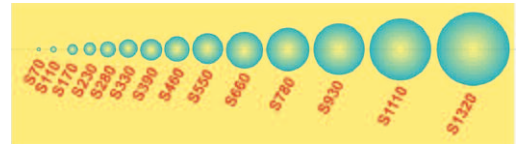

Fig.2 Nominal shot sizes as specified in J444 – with equivalent spheres drawn to scale.

component properties. On the other hand, the smaller the range the more expensive it is to produce and maintain shot that will satisfy the specification. We tend, however, to take specifications for granted, without considering their fundamental significance. It can be argued that:

"Specifications exist in order that a user can be assured that a product will be of a required standard".

All peening specifications are based on the **definition**, **measurement** and **variability restriction** of particular parameters. These three factors should be clearly stated and be as unambiguous as possible.

New and used cast shot differ significantly in terms of their size distribution. Any given batch of shot gets smaller with use due to wear. Used shot will therefore contain worn particles and additions of new shot – together with a significant proportion of relatively-small particles – produced as shot breaks down in service. The terms "virgin shot" and "maintained shot" are appropriate to distinguish the two conditions. A completely new charge of shot can simulate steady-state maintained shot by using a "commissioning mix". For example, maintained S230 can be simulated by mixing virgin shot grades of S110, S170 and S230.

NOMINAL SHOT SIZES

Nominal shot sizes give an indication of the <u>average size</u> of the particles in each class. If we assume that each shot particle is spherical and that the steel has a density of 7860 kg/m^3 then we can calculate the average particle mass - see Table 1 on page 26.

A 100g sample is commonly specified for test purposes so that it is of some interest to note how many particles there are per sample. These range from millions to thousands

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Table 1. Nominal Shot Sizes derived from J444 using 'Equivalent Sphere' principle

SHOT	DIAMETER		MASS	PARTICLES
	- inch	- mm	- mg	per 100g
S70	0.0070	0.1778	0.02313	4,322,983
S110	0.0110	0.2794	0.08976	1,114,037
S170	0.0170	0.4318	0.33134	301,808
S230	0.0230	0.5842	0.82055	121,869
S280	0.0280	0.7112	1.48046	67,547
S330	0.0330	0.8382	2.42362	41,261
S390	0.0390	0.9906	4.00052	24,997
S460	0.0460	1.1684	6.56441	15,234
S550	0.0550	1.3970	11.22045	8,912
S660	0.0660	1.6764	19.38894	5,158
S780	0.0780	1.9812	32.00414	3,125
S930	0.0930	2.3622	54.24643	1,843
S1110	0.1110	2.8194	92.23404	1,084
S1320	0.1320	3.3528	155.11154	645
Ratios highest/lowest	19:1	19:1	6700:1	6700:1

depending on shot size. 100kg of S110 circulating in a peening unit will consist of about a billion shot particles!

PRODUCTION VARIABILITY

Nominal shot size is a fixed quantity whereas actual samples contain a range of sizes. This range depends on production variability and associated screening procedures.

Cast steel shot is produced directly from the liquid state. The method employed is the prime cause of size variability. Liquid steel is poured from a ladle into high-pressure jets of water. The water jets break up the steel stream into tiny droplets that solidify to become shot particles. Droplets strive to reduce surface energy by minimizing the surface area-to-volume ratio. A spherical shape has the smallest surface area-to-volume ratio. Hence, as-cast shot particles approximate to spheres. Fig.3 illustrates possible variations of shot particle sizes produced by one ladleful of steel. These are close to what are called "normal distributions". The distribution has a mean that can be controlled, to a limited extent, by factors such as water jet pressure and geometry. Variation about the mean can be quantified by its variance value (square of standard deviation).

The mass/size variations shown in fig.3 include only a small proportion of the most commercially-important shot sizes (such as S110, S170 and S230). A grit fraction could go directly to crushing - because the water-quenched state is very brittle. Normally, however, the whole output is classified, then austenized and quenched before rough
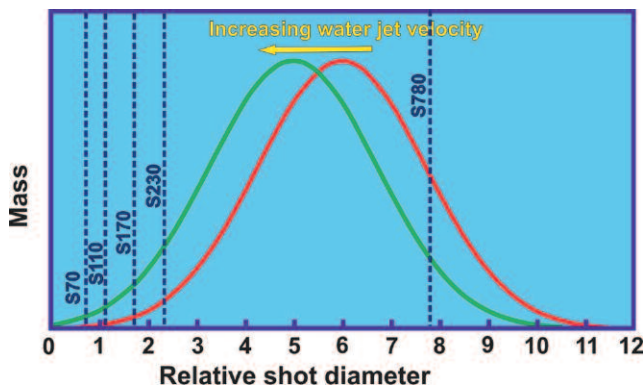

Fig.3. Type of size variability for as-cast steel shot.

screening to separate potential grit and shot fractions. The shot fraction is tempered and fine screened in order to yield different specification sizes of virgin shot.

Fine screening divides the shot fraction into sub-fractions – each of which will satisfy a corresponding standard specification. Precise details of fine screening are kept confidential by manufacturers. Fig.4 represents a possible screening routine designed to satisfy J444. Consider, for example, the S70 fraction - separated by having it pass through a 0·355mm sieve but not passing through a 0·125mm sieve. This would satisfy the J444 requirement of "All pass 0·425mm, 10% max on 0·355mm, 80% min on 0·180mm and 90% min on 0·125mm". The S110, S170 and S270 fractions shown would also satisfy the corresponding J444 requirements.
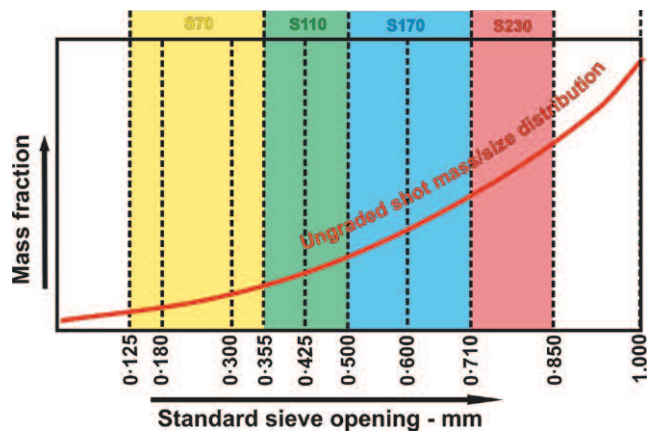

Fig.4 Possible screening system for cast steel shot.

Each nominal size of virgin shot will contain a range of sizes. For S70 produced using the procedure indicated in fig.3 the size range would be from 0·125mm to 0·355mm in diameter. The mass of a shot particle is its volume multiplied by the steel's density. Volume of a sphere is $\pi d^3/6$ (**d** being diameter). Hence the range of mass is the cube of the range of diameters. For the previous S70 example, the range of mass would be $(0·355/0·125)^3$ or 22·9 to 1! Mass ranges would be only 2·8 to 1 for S110, 2·9 to 1 for S170 and 1·7 to 1 for S230 respectively. If the shot manufacturer needed to produce smaller shot than S70 then the lower end of the S70 grade range could be reduced to 0·180mm which would still satisfy J444. The mass range would then be reduced to 7·7 to 1 for the finer-screened S70.

SIZE SPECIFICATION TESTING

A typical size specification test involves taking a 100g sample of a given batch, sieving it with a set of standard sieves and weighing the sieved fractions. This type of test involves several sources of variability. One is the sample itself – which has to be selected from a large batch of shot. Various techniques, such 'splitter boxing', have been developed to ensure that the sample is reasonably representative. Another source of variability is that if we subject the same 100g sample to repeat testing then the weights will vary – albeit slightly. A third, more significant, source of variability is that of the sieves themselves. The individual openings in a given brand-new sieve vary in size – even with the highest quality of sieves. Wear in use exacerbates the variation in opening size - as well as causing the average opening size to drift to larger values. One noteworthy

feature is the very large numbers of particles that are present in a 100g sample – for example, about a million for 100g of S110.

Size specification gives only a limited amount of information about size variation – see fig.5. Rather more information is available for shot sieved according to AMS 2431 which has either five or four sieve sizes per grade (depending on shot size) as compared to the four or three for J444 shot.
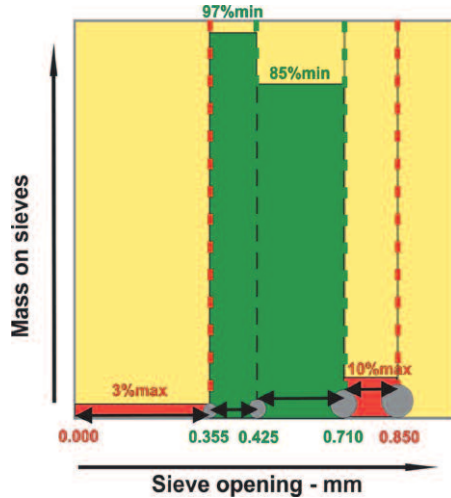

Fig.5. J444 specification limits for S170 cast steel shot.

Actual tests on 100g samples will give different weights depending on the sample. Size variation will be greatest for the 'worst case scenario' (i.e., one that only just meets the specification limits). Fig.6 illustrates this worst case scenario where 10g remained on the 0.850mm, 75g on the 0.710mm, 12g on the 0.355mm sieve and 3g passed through the 0.355mm sieve.
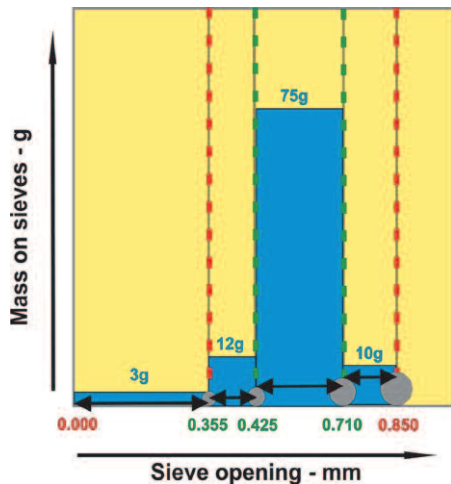

Fig.6. 'Worst case scenario' for S170 sieve test.

The nominal size for S170 corresponds to a sphere diameter of 0.425mm. An important question is "What is the average size of the shot samples sieved as shown in figs.6?" The correct answer is "We do not know – there isn't enough information." If we assumed that the average size of shot in each of the fractions was the average of the fraction limits then we can make an estimate. On the basis of that assumption we have 3g of 0.1725mm, 12g of 0.390mm, 75g of 0.5675mm and 10g 0.780mm particles so

that the average shot size is 0.352mm! That estimate comes from mass-to-volume translations. These show that the 3g fraction is 48% by number of particles, 17% for the 12g, 33% for the 75g and just 2% for the 10g fraction.

The previous estimate highlights the central problem of size assessment – **sieve size relates to diameter whereas mass is proportional to volume.**

A 'best case scenario' for S170 would be one of virgin shot that only had one fraction – all 100g passing the 0.710mm sieve and being caught on the 0.425mm sieve. Even then we would not know precisely the average diameter.

INDIVIDUAL SIZE MEASUREMENT
We can only assess size variation if we can measure individual particles. Measurement of individual particle size can be attempted in several ways. The most commonly-used methods are **precision weighing** and **image analysis.** Each method has its pros and cons. Sample size is important. A range of 10 to 1000 particles represents practical sample sizes. Less than 10 measurements are insufficient to detect variation with meaningful accuracy. More than 1000 measurements are probably too time-consuming. Weighing is independent of shape. Image analysis measurements, on the other hand, are affected by the shape of individual particles and are relatively subjective.

Weighing
Weight measurements are objective and accuracy can be assured for a given weighing instrument. The major drawback is that individual particles have to be manipulated onto and off a balance pan. This is facilitated by using a piece of nylon mesh to assemble the original sample (as in fig.1) and then transferring individual particles by means of a magnetic needle. Modern electronic balances can transfer mass values directly to an Excel spreadsheet.

Image Analysis
This requires the use of a camera microscope to obtain an image, followed by the application of an image analysis computer program. The initial problem is that programs cannot, of themselves, separate touching particles into discrete objects. As with weighing, a nylon mesh separating individual particles is therefore useful. Alternatively, images have to be 'computer-processed'. Computer processing involves progressive 'binary shrinking' (peeling of particle layers until none of the particles is touching) followed by 'binary expansion' that artificially prevents particles from touching one another. This results in an image of the shot particles that the computer can now treat as separate objects.

The mean of either image analysis or weight measurements will yield values for **average size**.

AVERAGE DIAMETER/MASS MONOLAYER MEASUREMENT
In order to measure the average particle size for a sample we can, as mentioned previously, measure a known number of particles individually and take the average. An alternative approach is to measure the total mass of a sample that, as a monolayer, occupies a fixed area. This approach is based on the fact that there is a direct relationship between average particle diameter, **d**, and mass, **M**, of a monolayer of area, **A**.

For 'square-packed' spheres the number of particles, **n**, occupying an area, **A**, is given by **n = A/d²**. The mass, **m**, of one particle is given by **ρ*π*d³/6**. The mass, **M**, of the **n** particles occupying the area, **A**, is therefore given by: **M = A/d²*ρ*π*d³/6** which simplifies to equation (1).

$$d = 6M/A*\rho*\pi \tag{1}$$

where **ρ = density**.

Fig.7 serves to illustrate equation (1), using identical 'square-packed' spherical particles.

The principle embodied in equation (1) can be applied by spreading a shot sample over a fixed area. The sample size will normally contain a very large number of particles. 10g of S110, for example, would contain more than 100,000 particles. Imagine, as a hypothetical example, a sample of S110 shot that has an average diameter that is exactly 0·0110" and, when spread over a fixed area, has a mass of precisely 10·00g. A 1% increase in sample diameter, other things being equal, would raise the mass to 10·10g.

Such a mass change is readily detected using the scales required for standard sieve tests.

Shot particles simply poured into a circular dish do not readily form a true monolayer. Fig.8 shows a number of 'second layer' particles together with 'vacant particle sites' (black dots versus white areas). Layers equivalent to monolayers can be produced in a few seconds by equating the numbers of 'second layer' and 'vacant particle sites'. Reproducibility of layer mass is then excellent – better than 0·1g for samples of about 10g. True monolayer production requires more sophisticated techniques than simple pouring. Gaging approach to true monolayer achievement is facilitated by projecting a magnified image from a digital camera onto a computer/TV screen.
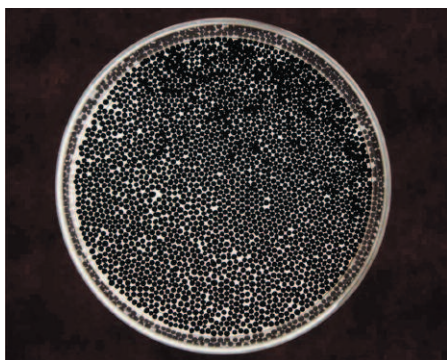

Fig.7. Effect of sphere diameter on number of particles per unit area.

Fig.8 SLR camera image of S330 shot sample viewed through a light box.

SIZE VARIATION ANALYSIS

The two most useful procedures for representing size variation are:

HISTOGRAMS and BOXPLOTS.

Histograms

Histograms are based on dividing measurements into 'bins' – each bin containing all of the measurements that lie within a defined range. Figs.9 and 10 are histograms of 'number of particles in a given bin for 69 weighed particles of S780 shot. The mass measurements plotted in fig.9 were converted into diameters of 'equivalent spheres' for plotting as fig.10.

There are pros and cons attached to the use of histograms – some of which are indicated in figs. 9 and 10. Different types of distribution result from plotting different parameters. Mass variation appears to be skewed towards lower values whereas diameter variation appears to be bi-modal. The test sample originated from shot that had been segregated (by sieving) according to diameter. It is possible that the sample is a mixture of two sievings – each being normally-distributed about a different mean. Bin size, parameter and range strongly affect implied types of distribution.

Histograms do not yield quantitative parameters of distribution. Their strongest feature is that they present a familiar type of visual image. Data acquired for histogram analysis can be used to determine complementary parameters such as range, mean and standard deviation.
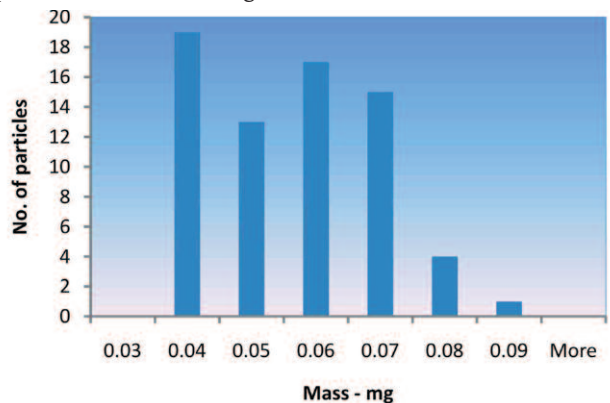

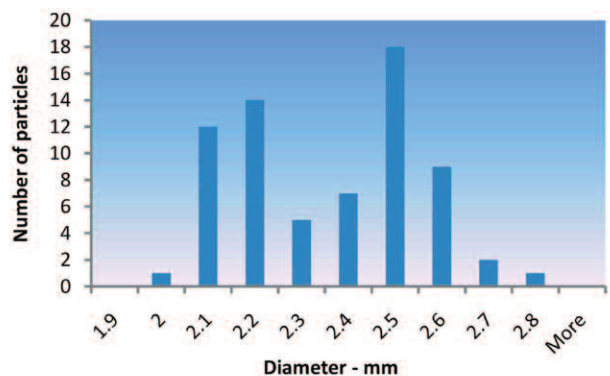*Fig.9 Histogram of S780 weighed particles – mass versus number per bin.*

Fig.10 Histogram of S780 weighed particles – diameter versus number per bin.

Boxplots

Boxplots depict, graphically, a summary of five parameters obtained from a set of measurements. The five parameters are: **Minimum value, Maximum value, Lower quartile (Q1), Median** and **Upper quartile (Q3)**. "Median" is the middle value of a set of measurements – hence half of the measurements are larger than that of the median and half are smaller. "Quartile" is a quarter of the total number of measurements. It follows that the 'box' contains half of the measurements whilst a quarter are 'above' and the remaining quarter are below the box. Excel uses its own system for determining quartiles – together with minimum, maximum and median values.

Fig.11 shows a set of three Boxplots derived from hypothetical data using Excel. This illustrates how we can readily compare, quantitatively, the most important size parameters of shot in terms of difference.

Unlike histograms, Boxplots are completely objective in the sense that they are independent of plotting variables (such as bin size, number of bins etc.). That feature is particularly useful when it comes to possible specification considerations.

Interpretation of Boxplots gets easier with practice. This particularly applies to the very useful 'position of median within the box'.
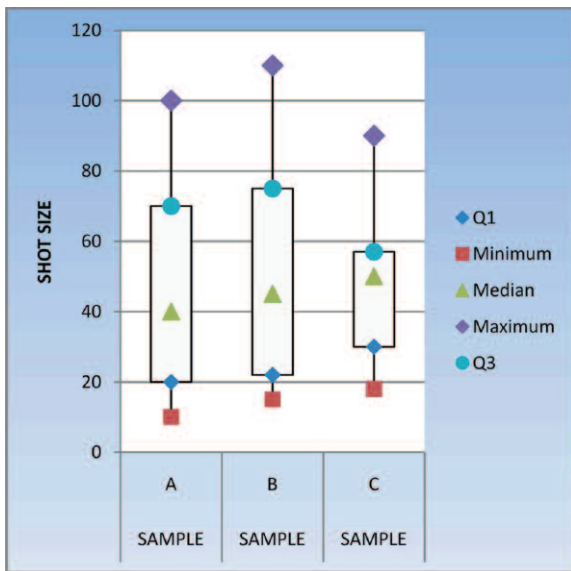

Fig.11. Boxplot comparison of three hypothetical samples.

DISCUSSION AND CONCLUSIONS

This article has considered only cast steel shot – rather than the full range of types and materials that are commercially available for peening. That is in order to contain the article within a reasonable size whilst avoiding superficiality. The principles described using J444 can easily be extended to AMS 2431 shot specification.

The origin of variability lies with the casting process. Subsequent sieving operations are used to produce specified size grades. Size testing based on standard sieve tests on 100g samples yields restricted amounts of information in terms of size distribution and none on actual average size. Image analysis is now readily available and offers a way of obtaining much more detailed information. Care

must be taken to ensure that the image analysis procedure used on samples gives repeatable, consistent, results.

100g samples used for sieve testing are much larger than those used for image analysis. Even greater care must therefore be taken to ensure that image analysis samples are representative.

Analysis of size variation based on either image analysis or weight measurements can be carried out using either histograms or Boxplots. It is suggested that Boxplots are much more suitable than histograms as a basis for both specifications and quality control.

It has been proposed in this article that average size measurements can be made by weighing monolayers of known area. Preliminary results are very encouraging and techniques are being developed to facilitate monolayer production. ●