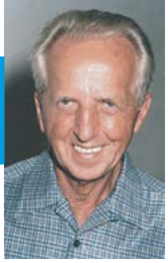

ACADEMIC STUDY
Dr. David Kirk | Coventry University

Back to Basics: Shot Particles

INTRODUCTION

The aim of this mini-series is to cover the basic scientific principles of shot peening. Fundamental principles are presented together with relevant theoretical explanations. Shot particles themselves are an obvious starting point—without them we could not have shot peening.

Shot particles have a set of properties that govern their suitability for specific peening operations. These properties include: shape, size, mass, chemical composition, elasticity, hardness, toughness, wear resistance and structure. Ease of manufacture is also very important for commercial viability.

SHAPE

The ideal shape for a shot particle is a sphere, but real shot particles are not perfect spheres. Deviation from sphericity is important. The most commonly employed media are cast steel shot, cut steel wire shot, glass beads and ceramic beads. These media are manufactured either by spheroidising solid particles (cut steel wire and some glass beads) or by spheroidising liquid material (cast steel shot, some glasses and most ceramics). Because of the methods of manufacture, variations from sphericity are inevitable.

Shot shape is determined from two-dimensional images rather than from spheres. The most important parameters are therefore:

(1) Circularity and
(2) Angularity.

Circularity

Circularity is the measure of how closely the shot's outline resembles a circle.

Quantification of circularity involves calculation—either easy or complicated. The simplest method is the width/length ratio. Fig.1 shows the principle of the width/length parameter when derived from an elliptical shape. Width being the minimum diameter, D_{MIN}, and length being the maximum diameter, D_{MAX} . In fig.1 the ratio works out to be precisely 0.3 because D_{MIN} is 30% of D_{MAX}. The drawback with this method is that it gives the same value for some shapes that are very different in terms of circularity. For example: the width/length ratio for a perfect circle is 1.0 but the ratio is also equal to 1.0 for a square!

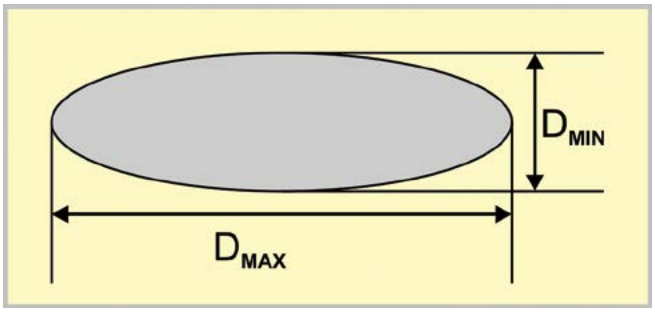

Fig.1. Width/Length ratio shape parameter.

A commonly employed method of quantifying the circularity of an ellipse is to use the parameter $4\pi * A/p^2$ where **A** is the area and **p** is the perimeter of the object. These are indicated in fig.2 which uses the same ellipse as that in fig.1. Solving $4\pi * A/p^2$ for an ellipse is, however, unusually complicated. That is because there is no simple way of determining the perimeter of an ellipse. Fortunately for researchers, relevant computer programs are readily available via the internet. These indicate that $4\pi * A/p^2$ is 0.196 for the ellipse of fig.2, 1 for a circle and 0.785 for a square. This method is more powerful than width/length when applied to ellipses. It is rarely employed in shot peening, possibly because elliptically shaped shot particles are uncommon. Width/length has the great advantage of being universally applicable and simple to measure. Any shot image can be enlarged on a computer's screen allowing minimum width and maximum length to be measured needing only an office ruler.

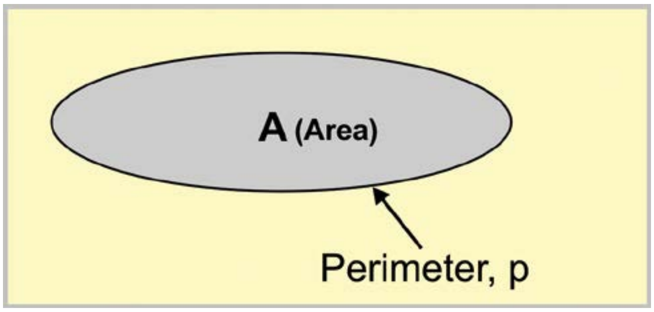

Fig.2. Circularity shape variables for $4\pi * A/p^2$.

Angularity

Angularity is a measure of how much a particle deviates from perfect smoothness.

A square has no smoothness—only four straight sides at 90˚ angles to each other—hence it is regarded as having very high angularity. By way of contrast, an ellipse is a perfectly smooth curve and is regarded as having zero angularity. Cut wire shot particles have many flat surface regions, albeit tiny, even after multiple conditioning. Cast steel shot has very low angularity. Grit differs from shot in that it is, necessarily, very angular.

Angularity is very, very difficult to quantify. Some idea of angularity variation is provided by fig.3. This is a modified version of a chart popularized by Krumbein and Sloss. The chart values are those calculated for roundness. Angularity is the opposite of smoothness so that low smoothness corresponds to high angularity.

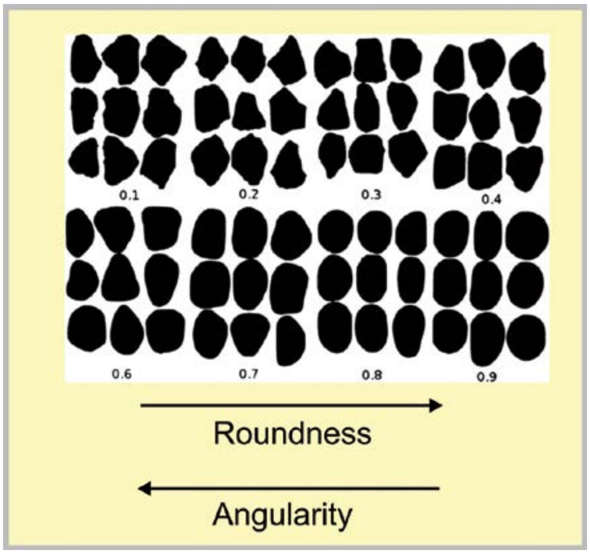

Fig.3. Angularity versus roundness of particles.

SIZE

Size is probably the most important shot property. Any variability of shot size is therefore important. Specifications, such as SAE J444 and AMS 2431, nominate shot size in terms of sieving results. The range of sieve sizes employed leads to a corresponding nominal shot size. Hence we have **nominal shot sizes** based on sieve mesh spacing.

Shot size can also be associated with the diameter of a sphere. That is convenient from a scientific point of view because the geometry of a sphere is well-known. For example: volume is $\pi D^3/6$ where D is the sphere's diameter. 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.

Fig.4 illustrates the difference between nominal size and corresponding equivalent sphere as methods for sizing shot particles. Although not to actual sizes, it allows us to get a mental picture of the huge range of available shot sizes. By way of analogy, the range is similar to that between a shotgun pellet and a cannonball.

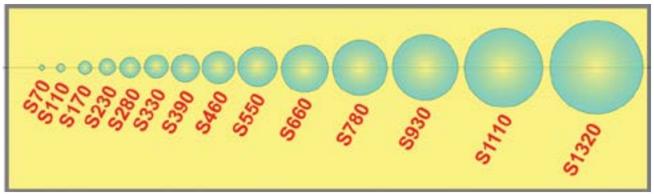

Fig.4. Nominal and equivalent sphere sizes for cast steel shot.

Another way of looking at the huge range of shot sizes is to compare how many particles there are per 100 grams. Table 1 shows the range for cast steel particles.

Table 1. Variation of Size, Mass and Particles per 100 g of Cast Steel Particles

SHOT	DIAMETER		MASS	PARTICLES
	-inch	- mm	- mg	Per 100 g
S70	0.0070	0.1778	0.02313	4322983
S110	0.0110	0.2794	0.08976	1114037
S170	0.0170	0.4318	0.33134	301808
S230	0.0230	0.5842	0.82055	121869
S280	0.0280	0.7112	1.48046	67547
S330	0.0330	0.8382	2.42362	41261
S390	0.0390	0.9906	4.00052	24997
S460	0.0460	1.1684	6.56441	15234
S550	0.0550	1.3970	11.22045	8912
S660	0.0660	1.6764	19.38894	5158
S780	0.0780	1.9812	32.00414	3125
S930	0.0930	2.3622	54.24643	1843
S1110	0.1110	2.8194	92.23404	1084
S1320	0.1320	3.3528	155.11154	645
Ratios				
highest/ lowest	19:1	19:1	6700:1	6700:1

MASS

Mass is volume multiplied by density. If the average mass per particle is small there will be a large number of particles per 100 g. The calculation given in Table 1 indicates that there will be more than four million S70 particles per hundred gram handful!

The range of mass for cast steel particles at 6700:1 is the same as the range of particles per 100 grams. This contrasts with the range of only 19:1 for particle diameter due to the fact that the volume of a sphere is $\pi D^3/6$ where D is its diameter. Nineteen cubed is approximately 6700.

CHEMICAL COMPOSITION

The commonest groups of shot particles are steels, ceramics and glasses with each group having a range of chemical compositions.

Steel Shot

Steel shot is generally made from carbon steel as opposed to the much less common stainless steel. Carbon steel is used to make either cast shot or cut wire shot. Cast steel shot has a higher carbon content than does cut-wire shot. Table 2 shows the ranges involved. Cast shot is **hyper-eutectoid** (more than 0.8% C) whereas cut wire shot is **hypo-eutectoid** (less than 0.8% C). Fig.5 reveals the significance of this carbon content difference. Both types of steel have to be heat-treated. Austenitizing is followed by quenching. Quenched hyper-eutectoid steel may contain hard brittle phases. For cast shot this is not a problem as the particles are already in their finished shape. For cut wire shot this would be a big problem as cut particles have to be pounded severely during conditioning. That is why a hypo-eutectic composition is employed. Identical hardness ranges can be achieved for both cast and cut wire shot.

Table 2. Carbon content and hardness properties of carbon steel shot

Cast Shot		Cut-Wire Shot	
Carbon content	0.8 – 1.2 wt.%	Carbon content	0.45 – 0.85 wt.%
Regular hardness	45 – 52 HRC	Regular hardness	45 – 52 HRC
High hardness	55 – 62 HRC	High hardness	55 – 62 HRC

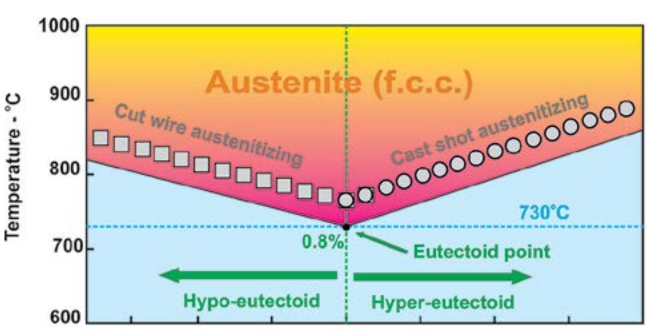

Fig.5. Cut wire versus cast steel shot austenitization.

Ceramic Shot

The composition of the common zirconia/silica/alumina shot is specified in AMS2431/7B and in J1830. Table 3 indicates the permitted composition ranges.

Table 3. Composition ranges for ceramic shot

Zirconia/silica/alumina shot	Content
Zirconium oxide, ZrO_2	60-70%
Silica, SiO_2	28-33%
Alumina, Al_2O_3	10% max
Free iron, Fe	0.1%max
Others	3% max

A disadvantage of zirconia/silica/alumina shot is its relatively low density when compared with that of steel shot —3 versus 8 g/cc. An interesting development is that of "high density ceramic shot." The corresponding AMS Specification is undergoing evolution. Essentially, high density ceramics contain a substantial proportion of a rare earth element, typically cerium. Consider a three-dimensional framework of cerium atoms that is infiltrated by zirconia molecules. As an analogy, imagine that the cerium atoms (ions) act as if they were hungry octopuses that mightily clutch zirconia molecules to themselves. This strong clutching/attraction reduces the volume being occupied hence increasing density to about 6 g/cc.

Glass Shot

AMS 2431/6B states that the composition "Shall be high quality glass of the soda-lime type. Silica content shall be not less than 67% by weight." Pure silica melts at the very high temperature of 1723˚C. Soda (sodium carbonate, Na_2O_3) is therefore added in order to lower the melting point dramatically but, on its own, makes the glass water soluble! Lime (CaO) is therefore added to remove this solubility. Magnesia (MgO), Potassium oxide (K_2O) and alumina (Al_2O_3) may also be added to improve glass shot durability. Table 4, published by a glass shot manufacturer, is an example of the final composition.

Table 4. Typical Glass Bead Composition

Silica, SiO_2	72%
Sodium oxide, Na_2O	13%
Lime, CaO	5%
Magnesia, MgO	4%
Potassium oxide, K_2O	3%
Alumina, Al_2O_3	1%

SURFACE STRUCTURE AND COMPOSITION

An important feature of chemical composition is its effect on the surface of the shot particles. Ceramic and glass shot are composed of stable oxides so that they do not react with air during shot peening. Surface and core structure and composition are the same. Metal shot particles, on the other hand, become coated with a brittle layer of metal oxide when in contact with air. Fig.6 (fig.1 of *The Shot Peener*, Spring, 2011) illustrates this phenomenon. The iron oxide coating has a variable chemical composition of Fe_xO_y. The value of y to x varies continuously from 1 at the shot interface to 1.5 at the air interface. A value of 1 gives FeO, 1.33 gives Fe_3O_4 and 1.5 gives Fe_2O_3. The ratio of oxygen to iron atoms is lowest at the skin/core interface and highest next to the surrounding air as would be expected.

Fig.6. Iron oxide skin on carbon steel core.

The skin on stainless steel shot particles is chromium oxide (Cr_2O_3) which is so thin as to be transparent but it is also fairly brittle. If damaged on impact, self-repair occurs very quickly—chromium atoms combining with oxygen atoms—hence the term "stainless."

ELASTICITY

Elasticity is probably the most significant of a shot particle's properties, but doesn't rate a mention in specifications! Rubber, which is very elastic, is obviously not useful for shot peening. Steel, being much less elastic, is useful. Quantifying the difference in elasticity is not helped (for beginners) by the fact that Young's modulus, E, is a measure of stiffness rather than of elasticity. Table 5 lists approximate Young's modulus values for shot materials and for rubber.

Imagine dropping a rubber ball onto a steel plate. Any effects would be purely elastic—and a waste of effort from a shot peener's point of view. A steel ball, on the other hand, will induce plastic deformation because of its relative stiffness.

HARDNESS

Hardness is a measure of a material's resistance to plastic deformation. It is therefore an important property of shot particles—we don't want flats to appear on impact. Hardness values appear regularly in specifications. Table 6 lists some of these values.

The values shown in Table 6 indicate that there is a fairly narrow range of hardnesses for commonly used particles.

Table 5. Approximate Stiffness Values

Material	Young's Modulus, E, - GPa
Ceramic	200 - 400
Steel	200
Glass	60 - 80
Rubber	0.01 – 0.1

Table 6. Typical Specified Hardness Values for Shot Particles

Material	Condition	Hardness - HRC
Steel	Cast	45 - 52
Hard Steel	Cast	55 - 62
Steel	Cut wire	45 - 52
Steel	Carburized	57 - 62
Stainless Steel	Cut wire	45 min
Glass	-	48 - 52
Ceramic	-	58 - 63

TOUGHNESS

Another very important property of shot is its ability to resist fractures, that is, its toughness. Toughness values do not, however, appear in specifications. This may be due to the fact that there is currently no appropriate test procedure for shot toughness. Izod and Charpy tests have a long history of use for assessing resistance to fracture propagation, but employ large, notched specimens.

In view of its significance, a simple fracture resistance test is outlined as follows.

Shot Fracture Resistance Test

A familiar test of glass sheet toughness is to strike it with a hammer. Velocity and mass of the hammer are then the controlling factors. These parameters can be simulated for a shot particle by artificially increasing its mass using a striker as indicated in fig.7. Velocity can be varied by dropping the striker from different heights down a tube. In essence, the effective kinetic energy, $½mv^2$, is being controlled. Relevant theory is contained in the author's TSP. Spring, 2004, article titled "Actual and Predicted Shot Peening Indentations."

Fig. 7(a) shows a schematic representation of the overall device and fig.7(b) shows an enlargement of the striker's head.

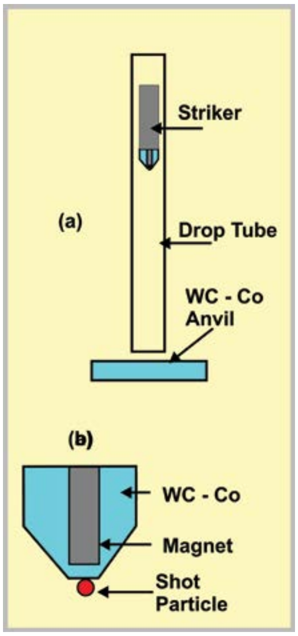

Fig.7. Schematic representation of shot fracture resistance tester.

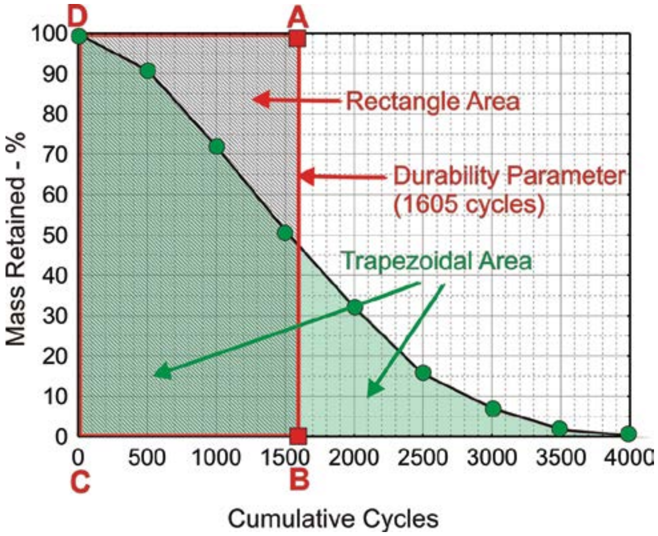

Fig.8. Modified version of J445's fig.1.

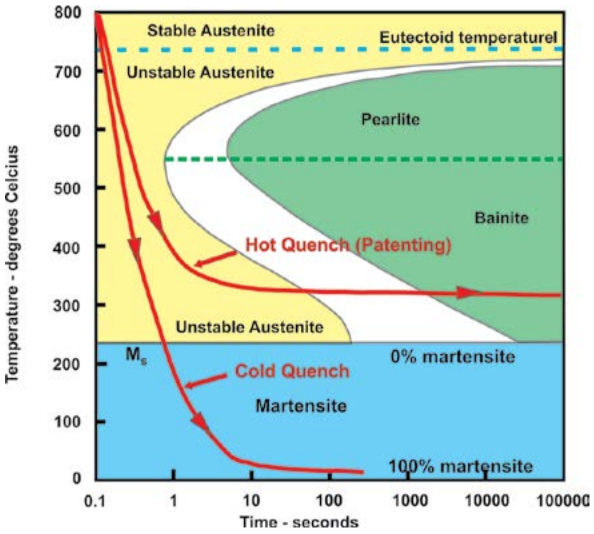

Fig.9. Basic structures obtained by quenching carbon steel shot.

SHOT WEAR RESISTANCE

All available types of shot wear away during use but at different rates. They can therefore be classed as an essential consumable. The most obvious effect of wear is a progressive reduction in the average diameter of the shot particles.

Shot wear mechanisms are based on either oxide layer breakdown and/or adhesive interaction with components. There are no standard tests or specifications that relate directly to shot wear. J445 Metallic Shot and Grit Mechanical Testing, is commonly used in conjunction with an Ervin Tester to estimate the durability of shot samples. It has the considerable advantage of only requiring about 100 g of shot. It does not, however, measure wear rate directly.

Wear resistance is dealt with in a previous article, "Wear and its Reduction", *The Shot Peener*, Winter, 2016. Relevant parts of the excellent J445 are described there in some detail. Fig.8 is fig.7 from that article. Durability is indicated by the loss of mass after different numbers of use cycles. Durability in terms of cycles is shown as **B** which is the point where the rectangle's area is the same as the trapezoidal area. The J445 durability test can, however, be modified to give a direct indication of shot wear rate.

STRUCTURE

Modification of structure is mainly confined to steel shot. This involves heat treating the shot to obtain the correct balance of hardness and toughness. Shot is first austenitized followed by quenching and tempering. The structural changes involved vary with carbon content—hypo-eutectoid cut wire shot behaving differently from hyper-eutectoid cast shot.

A previous article in this series ("Properties of Carbon Steel Shot," *The Shot Peener*, Spring, 2011) gives a general account of the ways in which steel shot structure evolves. Fig.9 from that article summarizes the structures obtained by quenching austenitized carbon steel shot. Cold quenching is normally preferred, with the martensitic structure subsequently being modified by tempering. Tempering substantially increases the toughness of a martensitic structure which is inherently brittle.

DISCUSSION

This article has presented the individual basic properties of shot particles. It is, however, the sum of the individual properties that prescribes the limited range of commonly used materials. Selection from this available range is normally determined by the user rather than by the shot peener. Often the choice depends on possible chemical interactions between the shot particles and the component. The available range of useful shot particles is being steadily widened due to competition between manufacturers.