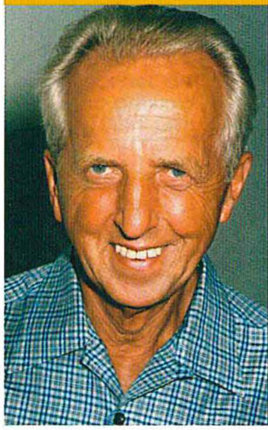

Shot Particle Shapes

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Dr. David Kirk, our "Shot Peening Academic" is a regular contributor to *The Shot Peener*. Since his retirement, Dr. Kirk has been an Honorary Research Fellow at Coventry University and still supervises their Shot Peening and X-ray Stress Analysis laboratories. He is currently writing a book "The Science of Shot Peening". We greatly appreciate his contribution to our publication.

INTRODUCTION

The ideal shape for a shot particle is a sphere, but real shot particles are not perfect spheres. The most commonly employed media are cast steel and iron 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 direct production of near-spherical shapes. Because of the method of manufacture, variations from sphericity are inevitable. This article attempts to analyse the causes and significance of those variations.

CAST MEDIA

Steel, cast iron and glass shot particles are produced by liquefying the material and then dispersing it as fine particles that solidify as they cool. The controlling factor affecting shape in these particles is surface tension. Surface tension is present in both liquid and solid particles, but reveals itself more dramatically for the liquid state. We are made aware of surface tension if we watch a drop of water forming from a faucet (tap) that is not completely closed. A 'spherical cap' forms first, which grows, begins to 'neck' and finally is suspended as if by a thread. When the water droplet breaks free, it immediately assumes a near-spherical shape. The liquid droplet contains two components of energy—internal and surface. The internal energy is independent of the shape of the particle and is directly proportional to its volume.

The surface energy of a particle is given by multiplying its area by the intrinsic surface tension (energy per unit area). A cylinder of unit volume with a diameter equal to its height has a surface area of 5.537. That compares with the surface area of unit volume cubes and spheres of 6.000 and 4.831 respectively. The minimum surface area/volume ratio for any particle is a sphere. Therefore, the total energy for a spherical particle is lower than for any other shape having the same volume. It is a fundamental, inescapable law that any system tries to reduce its energy. Hence, cast liquids sprayed into another fluid - such as water or air - will form near-spherical shapes. It must be noted, however, that the difference in surface area between a near-spherical shape and a perfect sphere is negligible. Consequently, there is insufficient driving force to form a perfect sphere. Real cast shot particles can, therefore, only approximate to perfect spheres.

If, during production, two hot particles encounter each other they will tend to coalesce, see fig.1. That is because the surface area for the merged particles is less than for the two separate particles.

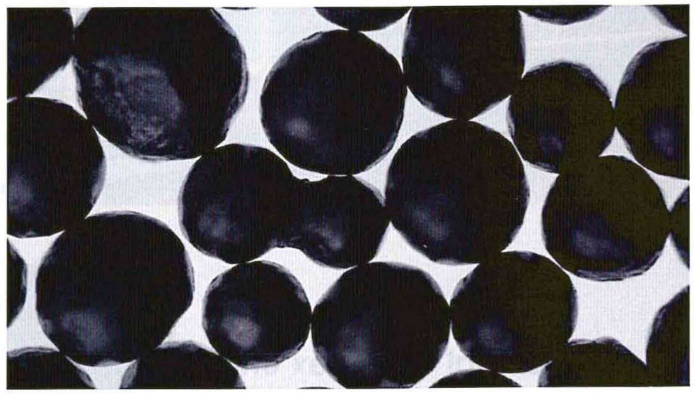

Fig.1 S230 cast steel shot showing, centre, coalescence of particles.

SPHEROIDISED GLASS BEADS

An alternative production route for glass beads is to spheroidise crushed glass ("cullet"). This can be achieved by blowing hot gas through a fluidised bed of the crushed glass particles. As the glass particles become very hot, the surface tension effect becomes active. Each particle reduces its surface area, and therefore its total energy, by changing its shape towards that of a sphere. A major production problem is that the hot glass particles tend to coalesce if they touch one another. This problem can be overcome by coating every particle with 'carbon black'. Finely-divided carbon is very cheap to produce and will adhere readily to surfaces (as every chimney sweep of olden times found out!). The fine coating of carbon prevents coalescence and is subsequently removed, conceivably by oxidation in a fluidised bed at a lower temperature than that which causes coalescence. Again, particles can only achieve near-sphericity.

CUT STEEL WIRE SHOT

This is a very useful medium because the steel used is in the wrought form - hard-drawn wire. It is axiomatic that wrought steel of a given composition has superior strength properties to those of the as-cast form.

There are obvious differences in morphology of cut wire in its commercially-available forms as "as-cut", "conditioned", "double-conditioned" and "spherical-conditioned" shot. In the as-cut state, we have pieces that resemble cylinders having lengths that are almost equal to their diameters. The actual shearing operation is critical, as a perfectly-cylindrical shape of as-cut particle is impossible. Fracture propagation during wire cutting can be inferred from microscopic examination of as-cut wire samples.

The situation as steel wire is being cut is illustrated in fig.2. If a straight-edged blade is used on the circular section wire then

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initial contact is a "high-speed, high stress" situation (analogous to hitting a glass plate with a hammer).

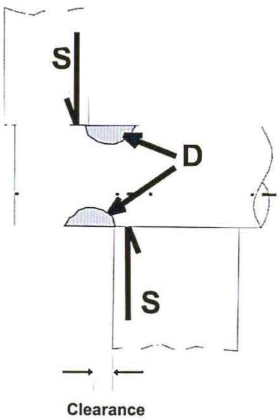

Fig.2 Deformation at D as shearing force, S, is applied to wire.

As the shearing force, S, is applied, it induces a bending moment in the wire with a maximum value on the wire surface. This, in turn, causes plastic deformation to occur in the two zones, D. With work-hardening of these zones the fracture strength is exceeded and cracks are initiated. As soon as a crack is formed, the stress required for it to spread through the section falls rapidly. Complete fracture across the wire section occurs at speeds approaching that of sound. The direction of crack propagation across the wire section will depend upon several factors, including the ratio of blade clearance to wire diameter, the ductility of the wire and the direction of maximum shear stress. These factors, together with inhomogeneities in the wire, ensure that a perfect 90° "slicing" is not possible. Blade clearances for shearing operations usually range between 2% and 10% of the wire diameter. The smaller the clearance the "cleaner" the cut, but at the expense of high blade wear and increased shear forces.

As-cut steel wire is more appropriate for blasting than for peening, due to the sharp edges that are present, see fig.3.

Fig. 3 As-cut steel wire, grade CW14.

The as-cut steel wire particles are fired at high velocities against a very hard surface to produce relatively-spherical shot. With multiple impacting, the sharp edges are worn away and the "conditioned" particles assume shapes that tend towards the spherical. The attrition of angular particles to produce rounded particles is apparent on any pebble beach. Fig.4 gives examples of the different stages of conditioning. It can be seen that even the "spherical conditioning" state does not produce the near-sphericity of cast media particles. Quantitative image analysis on three of the particles in each image gave average "circularity" values of 0·487, 0·760, 0·793 and 0·893 for the four progressive stages of conditioning. For the much finer CW14 shown in fig.3, circularity values of less than 0.290 were obtained for some particles.

An expensive alternative to conditioning is to die-form the cut cylinders, followed by grinding in a groove between counter-

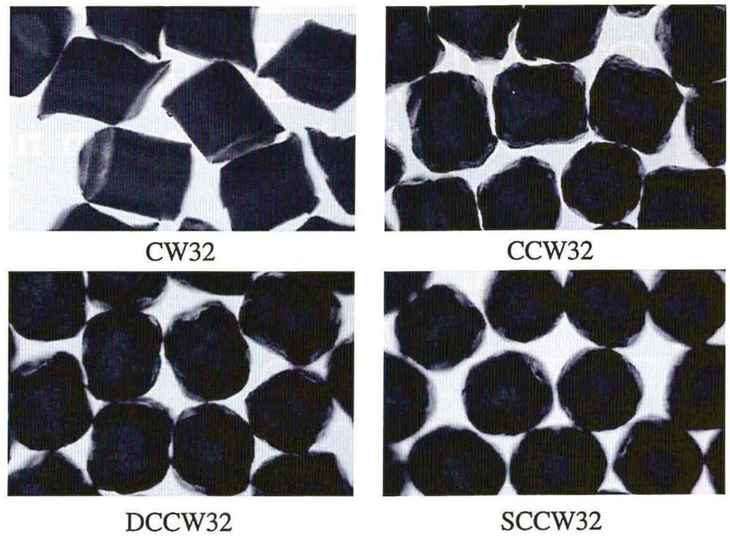

Fig.4 Grade 32 wire shot in the four commercial grades of CW, CCW, DCCW and SCCW.

rotating plates to form near-perfect spheres. That process is similar to the one used in ball-bearing manufacture and is used to produce ballistic-grade steel shot.

CERAMIC BEADS

Glasses are amorphous (non-crystalline) materials, whereas the ceramics used for beads contain a mixture of crystalline and amorphous phases. Both materials are based on mixtures of stable oxides (silica, alumina, sodium oxide, zirconium oxide, etc.). As a mixture, they have much lower melting points than the constituent oxides. It is possible to produce ceramic beads by cold- or hot-pressing of powder mixtures followed by sintering at high temperatures. The general route, however, is similar to that for cast glass beads. Mixtures are used that have sufficient fluidity to be "atomised" as particles directly from the liquid state. These are then cooled in air or gas streams to produce the solid-state beads, see fig.5. For this size of bead, the average circularity was measured as being 0·83. Coalescence is fairly common with ceramic beads with fusion of both similar sized beads and also "large-with-small" beads.

One problem is that the fluidity (inverse of viscosity) is still marginal for spheroidisation. Work has to be done by the "skin" to change the shape of the liquid particle. The greater the fluidity the less work has to be done for a given amount of shape change. Major improvements have been made by making (patented) additions of oxides such as cerium oxide or hafnium oxide to a basic zirconium oxide/silica mixture. The surface tension effect is then sufficiently powerful to pull the liquid droplets into near-spherical shapes.

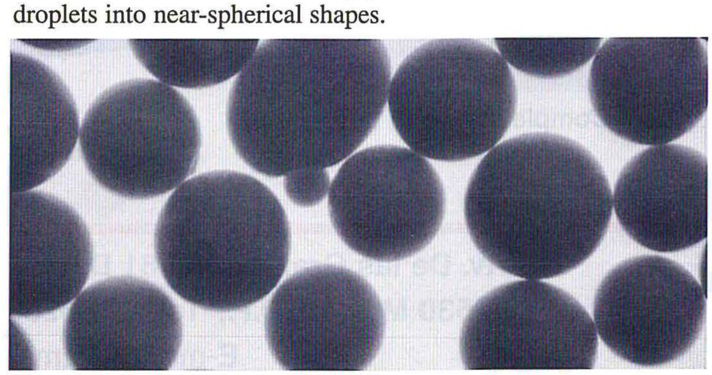

Fig.5 Zirconia shot beads, size 600

QUANTIFICATION OF SHAPE FOR SHOT PARTICLES

Various specifications govern the acceptability of shape for shot particles. These contain a major subjective element factor - visual comparisons with published sketches. In the author's opinion, more use should be made of quantitative image analysis and physical analysis principles.

Quantitative Image Analysis

One standard parameter that is easily measured is "circularity" - the ratio of minimum to maximum diameter. A perfect cylinder of as-cut wire on its side presents itself as a square image on a microscope screen. Spheres present themselves as circles. The circularity of a square is 0·707 whereas that for a circle is 1·000. Smoothness of particle surface can be quantified by measuring the ratio of perimeter-to-area for the projected image.

Quantitative Physical Analysis

The quantitative physical analysis of shape can employ the measurement of a dynamic property. Dynamic properties are directly related to the shape of the shot particles. One familiar industrial example of using dynamic properties is found in media classifiers. Used shot is classified according to its ability to stick, roll or slide. When a shot particle is placed on an slope, depending on the angle of inclination of the slope, one of four effects will occur: sticking, rolling, rolling with some sliding and finally pure sliding. The steeper the slope the greater is the tendency for pure sliding to occur. The time taken for a rolling shot particle to reach the bottom of a gentle slope is directly related to its shape. That is because the rolling particle has to develop both rotational and forward velocities. The work being done, by gravity, on the particles has to be shared between rotation and forward motion. This phenomenon is used by the author on a laboratory scale to (a) quantitatively separate broken shot particles from used shot and (b) quantitatively analyse the shape of the unbroken shot particles. As procedures, they are simple, objective and accurate.

For procedure (a), precisely 100.00g of shot sample are spread along one, curved, edge of a 1000 by 1000 mm plate when it is in a "reverse slope" position. The plate is raised slowly to an angle of 10°, which causes most of the sample to roll into a container - the broken shot sticking to the plate. The collected shot is then weighed and the "loss" gives the percentage of broken shot.

Procedure (b) involves taking the unbroken shot fraction and measuring the time taken for each shot particle to roll down a 1000 mm long tube inclined at 10°. In general, for rolling bodies, we have that the acceleration, a, is given by:

$$\mathbf{a = S.g.\sin}\,\alpha \qquad (1)$$

where **S** is a "shape factor" for the rolling body, having a value of 5/7 for a perfect sphere and lower values for any other shape, **g** is the acceleration due to gravity and α is the angle of inclination of the slope.

Because **g** and α are constant, any variation in **S** is gives a change in **a**. The acceleration, **a**, is given by:

$$\mathbf{a = 2.D/t^2} \qquad (2)$$

where **D** is the distance that a particle rolls from rest taking a time, **t**.

With **D** equal to 2.000m and **g** equal to 9·8ms^{-2}, a perfect sphere will take 2·725s and a perfect cylinder will take 2·768s to roll down the slope. Irregular shapes have been found to take substantially longer times. Electronic timing is used to classify individual particles. Class divisions can be created by simply using a fine blade placed away from the end of the tube. Exiting shot particles fall under the action of gravity. Spherical particles have the highest velocity. They are therefore propelled over the blade edge. Less spherical particles are slower and drop below the blade edge.

CONCLUSIONS

There is a wide range of shapes present in different types of shot media. Near-sphericity is most readily achieved by atomisation from the liquid state. Surface tension is the driving force for sphericity during both atomisation and subsequent cooling.

Cut steel wire exhibits a wide range of circularity for the common production grades. The cutting process for the wire can induce very irregular shapes.

Quantitative image analysis and physical property analysis are relatively objective when compared with existing specified shape examination procedures. The dynamic properties of shot particles can be employed as the basis for quantitative shot classification procedures.

Manufacturers are, understandably, reticent in giving out information about production processes and tend to exaggerate the properties of their products. Every effort has been made in this article to present an unbiased report of shape variations.