Properties of Carbon Steel Shot

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INTRODUCTION

Most shot peening is carried out using carbon steel shot. This shot is produced either by casting directly to almost spherical shapes or by cutting lengths of wire and pounding the cut lengths into acceptable sphericity. Finished carbon steel shot particles have a tough core with, of necessity, a brittle skin of iron oxide, see fig.1 (where the skin thickness has been deliberately exaggerated).

Fig.1 Section of spherical carbon steel shot particle.

Cast and cut wire carbon steel shot are both produced in "regular hardness" and "high hardness" grades. Table 1 summarizes some of the requirements specified in AMS 2431. The average carbon content of cast steel shot can be seen to be 50% greater than that of cut wire steel shot.

Carbon steel shot is produced in vast numbers. The vastness of scale can be illustrated by 'round number' calculations. A ladle containing 10 cubic meters of molten steel can be cast into shot in a single pouring. One cubic meter of steel has a mass of 7.8 metric tons. If the average shot mass is 1 milligram then 78 billion shot particles will have been produced in a matter of minutes. If the average cross-section of wire is 1 square millimeter then 10 cubic meters of wire would have a length of 10,000 kilometers. Cutting that wire into lengths averaging 1 mm would require 10 billion cuts.

Carbon steel shot has to have several properties that include hardness, shape, size, toughness, wear-resistance and low cost. This article is an account of some of the factors that enable the required properties to be achieved.

BRITTLE IRON OXIDE SKIN

The iron in carbon steel oxidizes when exposed to air. Iron plus oxygen gives iron oxide. Iron oxide is a brittle, ceramic-type, material that fractures very easily on impact. It follows that steel shot impacting a component shatters part of its oxide coating contributing vast numbers of minute iron oxide particles to the 'atmospheric dust' inside the peening cabinet. When iron oxide shatters, the skin is rapidly healed by further oxidation. The net effects are that (a) loss of shot mass is unavoidable and (b) clouds of iron oxide particles are generated that can explode.

Fig.2 (page 26) represents a slice of a carbon steel shot particle. The iron oxide coating has a variable chemical composition – Fe_xO_y. The ratio of y to x varies continuously from 1 at the shot interface to 1.5 at the air interface. A ratio of 1 gives FeO, 1.33 gives Fe_3O_4 and 1.5 gives Fe_2O_3.

When shot is heated in an air furnace the oxide layer grows thicker and thicker. The mechanism is that iron atoms diffuse into the layer at the shot/oxide interface whereas

Table 1. Some Requirements for 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

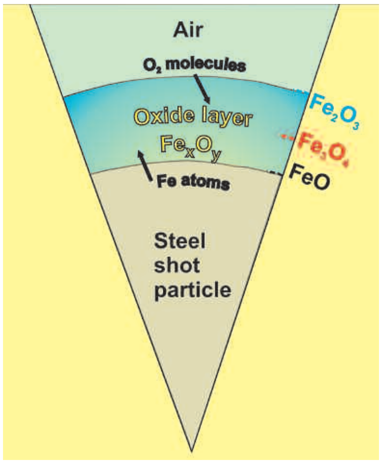

Fig.2 Slice of shot particle showing iron oxide layer of variable chemical composition.

oxygen atoms diffuse into the opposite side of the layer at the oxide/air interface. Hence the outer layer is saturated with oxygen and the inner layer is saturated with iron. Layer thickening can be reduced, even reversed, by controlling the atmosphere in the furnace.

Fragmented oxide particles are minute so that the area to volume ratio is enormous. One cubic centimeter, for example, could have a surface area of 10 square meters. Each particle has regions varying from saturated Fe_2O_3 to pure iron. The oxide layer is, by definition, chemically-bonded to the shot particle so that, on fracture, very tiny areas of steel are torn away with the oxide fragments. Because most of each oxide fragment is unsaturated with oxygen further oxidation is required to give chemical stability. This further oxidation is exothermic (heat is given out) which contributes to the explosive potential of the peening cabinet atmosphere.

HIGH-TEMPERATURE STRUCTURE OF CARBON STEEL SHOT

If carbon steel is heated to an appropriate high temperature, then it adopts a very simple crystalline structure called "austenite." Carbon atoms are free to roam in a face-centered-cubic matrix of iron atoms. At a shot particle's surface they can either emigrate (de-carburization) or immigrate (carburization) – depending on the surrounding atmosphere. Within the particle they are randomly distributed in the holes (interstices) between the iron atoms, moving freely from hole to hole. A key factor is the relationship between carbon content and the "appropriate high temperature." Fig.3 illustrates the relationship.

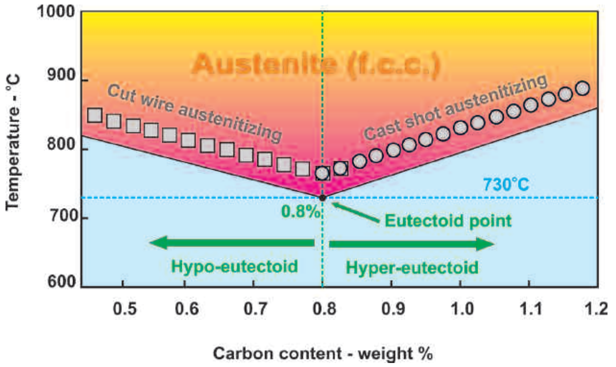

Fig.3 Schematic representation of carbon steel shot austenitizing.

The minimum temperature above which carbon steel austenetizes is about 730˚C for a 0.8% carbon steel. This is the so-called "eutectoid point." Lower and higher carbon contents than 0.8% require higher temperatures than 730˚C. Lower carbon content steels are called "hypo-eutectoid" and higher carbon content steels are called "hyper-eutectoid." These words derive from the Greek word "eutectos." The values of 730˚C and 0.8% carbon vary slightly with the presence of minor alloying elements. The appropriate austenitizing temperature for cut wire shot varies from about 780˚C to about 870˚C depending on its carbon content – as shown in fig.3. Cast steel shot can be austenitized at temperatures between 780˚C and 900˚C – again depending on the carbon content. Austenitization temperatures should not greatly exceed the minimum - in order to avoid coarsening of the austenite grains (which results in a lowering of eventual properties).

Austenitizing is a vital part of carbon steel shot manufacture. Only one austenitization is required for cast steel shot. The as-quenched shot particles are normally austenitized before hardening by quenching and subsequent tempering. Production of the wire for cut wire shot requires several austenitizations. Molten steel can be continually cast into round billet shape having a cross-section of about 10000 mm^2. Billets are then hot-rolled in a multiplicity of reductions to rod of about 100 mm^2 cross-section. That corresponds to an elongation of 10000% - only achievable because hot austenite self-anneals after every reduction. Hot-rolled steel rod is subsequently cold-drawn to the required wire diameter. Rod with a 100 mm^2 cross-section cold-drawn down to a 1 mm^2 cross-section (in multiple pulls) is being elongated by another 10000%. The wire has to be austenitized several times during cold-drawing in order to restore its ductility.

A consequence of the foregoing factors is that a carbon steel of close to the eutectoid temperature is very popular for converting into shot. Such steels require the lowest temperature of re-heating in order to be austenitized. Heating to these lower temperatures is quicker and cheaper than heating to higher temperatures. A very important additional benefit is the reduced amount of oxidization that occurs at lower austenitization temperatures. The thickness of oxide skin layer can therefore be minimized.

LOW-TEMPERATURE STRUCTURE OF CARBON STEEL SHOT

At high temperatures iron and carbon atoms co-exist happily as austenite. At low temperatures the opposite is true. Carbon atoms are forced to migrate - forming structures that depend on the rate of cooling from the austenitic state.

Slow Cooling

If austenite is cooled relatively slowly then there is time for the carbon atoms to be migrated as an extreme act of segregation. Most of the iron atoms then form themselves into "ferrite" which is virtually pure body-centered-cubic iron. The remaining iron atoms bind themselves to the carbon atoms in a highly regimented format – three atoms of iron for every carbon atom. This three-to-one ratio leads to its chemical formula of Fe_3C – a brittle ceramic substance called "cementite." Layers of cementite alternate with layers of ferrite to form crystals of "pearlite," shown in fig.4. Pearlite consists of seven parts of soft, ductile, ferrite to one part of hard, brittle, cementite. As a combination, this structure has sufficient ductility to allow the huge amounts of cold working needed for wire production.

The microstructure of slowly cooled carbon steel depends on its carbon content. Fig.5 illustrates the relationship. For hypo-eutectoid steel compositions, cut wire, the slow-cooled structure consists of pearlite with some ductile ferrite – the amount of ferrite increasing as the carbon content reduces. For hyper-eutectoid steel compositions, cast shot, the slow-cooled structure is pearlite with some brittle primary cementite – the amount of brittle primary cementite increases as the carbon content increases. Fortunately, cast steel shot does not need to be slow-cooled at any stage of its manufacture.

Fig.4 Schematic representation of "Pearlite" structure.

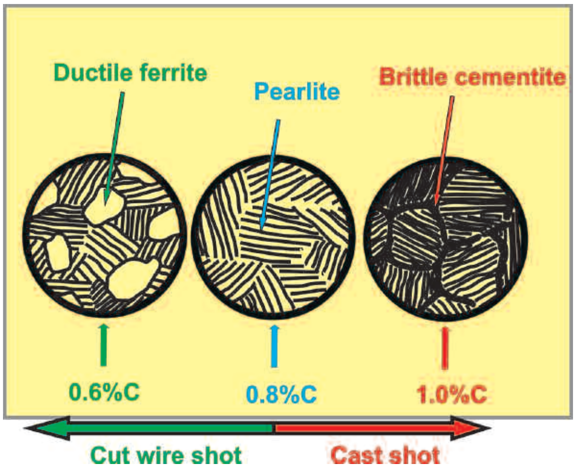

Fig.5 Schematic representation of slow-cooled carbon steel structures.

Rapid Cooling

If austenite is cooled rapidly there is insufficient time for the carbon atoms to migrate through the lattice to form either pearlite or cementite.

Quenching to far below the critical temperature of 730˚C (see fig.3) induces a truly cataclysmic change in structure. At room temperature, austenitic carbon steel has so much pent up energy that it 'explodes' into a structure called "martensite." Needles of martensite nucleate and then propagate, at almost the speed of sound, in any one of twenty-four directions within each austenite grain. Enormous micro-stresses are generated as the growing needles crash into each other and become locked together. The enmeshed martensitic structure is very difficult to deform – hence its high hardness. The corresponding brittleness can be alleviated by post-quench heating – "tempering." Heating to a few hundred degrees Celsius allows a very limited amount of carbon atom migration – to more comfortable locations - and reduces the micro-stress levels. The resulting structure is called "tempered martensite." Tempering increases toughness and deformability.

The crystal structure of martensite is almost identical to that of ferrite (which is body-centered-cubic). A cube has three edges of identical length. Carbon atoms in quenched austenite do a 'shimmy' towards just one of three edges, see fig.6, at the same time as the face-centered- cubic austenite transforms itself into a body-centered cubic arrangement of iron atoms. The carbon atoms are smaller than the iron atoms but still have to push them apart to fit into the available space. This type of crystal structure is called "body-centered-tetragonal." Because the carbon atoms are pushing the iron atoms apart in just one of three possible directions then that direction, "c", becomes larger than that of the other two directions, "a".

The ratio of "c" to "a", tetragonality, increases with carbon content, as illustrated in fig.7. Hardness increases as tetragonality increases.

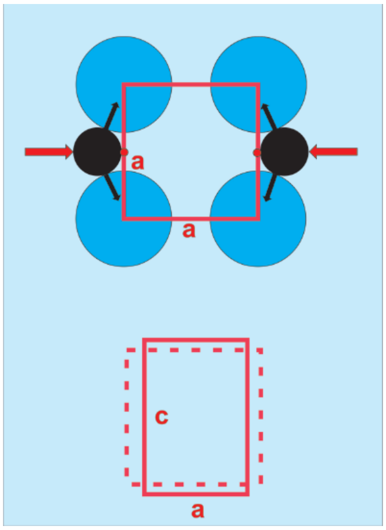

Fig.6 Carbon atoms distorting cubic arrangement of iron atoms.

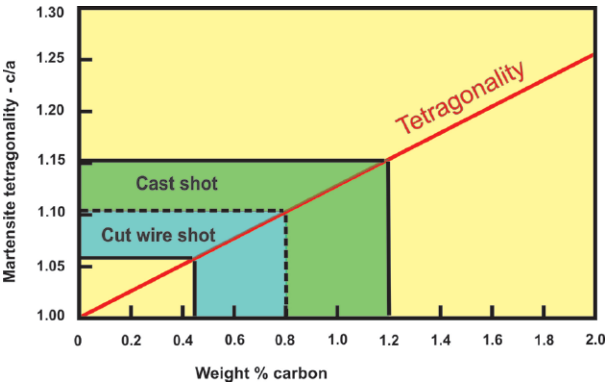

Fig.7 Increase of martensite tetragonality with increase of carbon content.

Rapid Cooling to Tempering Temperatures

Quenching austenitic carbon steel into molten lead or salt generates a structure that is intermediate between martensite and pearlite – called "bainite." A significant amount of carbon migration can now occur so that minute particles of cementite are formed within a matrix of ferrite. Quenching of austenitized wire into molten lead prior to cutting is employed by at least one major producer of cut wire shot. Fig.8 illustrates the difference between conventional "cold quenching" and "hot quenching."

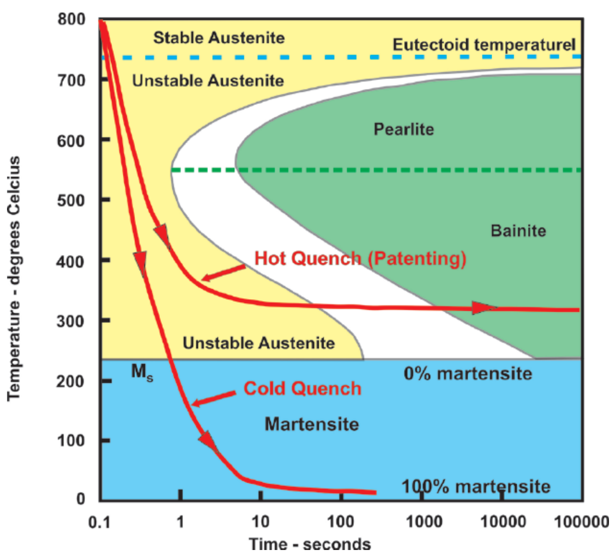

Fig.8 Transformation of austenite by either Cold Quenching or Hot Quenching.

Cold-Working

Cold-working of carbon steel increases its hardness but decreases its ductility. A maximum hardness is reached beyond which the hardness starts to fall – "work softening." Cast steel shot is not cold-worked prior to use. Cut wire shot, on the other hand, suffers very considerable cold-working as a necessary part of both wire drawing and conditioning. Drawn wire must have its ductility restored at intervals of drawing. Cutting of the drawn wire into cylindrical pieces involves massive plastic deformation at the sheared interface. This induces localized work-hardening and can also induce phase transformation.

Several specifications require that shot is produced to two levels of hardness. High-hardness cut wire shot can be produced by controlling the carbon content, work-hardening and heat-treatment hardening contributions. The hardness of cast shot can be controlled by the carbon content and the level of tempering.

SHAPE GENERATION

Near spherical shapes arise when liquid steel is atomized into shot particles. Spheres have the smallest ratio of surface area-to-volume. Hence surface energy is minimized by the liquid droplets if the droplets are spherical.

Shape generation from cut wire cylinders is much more complicated. Conditioning is used to convert cylindrically shaped pieces into near spherical shapes. Shape change is effected by a combination of plastic deformation and erosion as cut wire particles are fired against hard surfaces.

Specification SAE J441 requires that a designated cut wire shot size is to be produced using wire of the same diameter. For example, SCW/CW-41 is to be produced using wire having a diameter of 41 thousandths of an inch. 41 thousandths of an inch corresponds to 1.0 mm. If a 1 mm diameter, 1 mm long, cylinder is converted into a perfect sphere entirely by plastic deformation then it would have a diameter of 1.144 mm. This shape change is illustrated in fig.9.

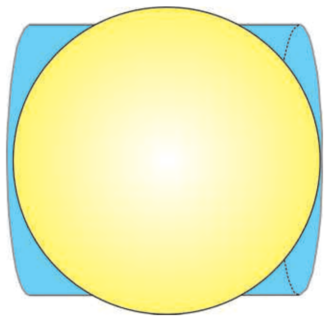

Fig.9 Shape change from unit cylinder to sphere.

In practice, cut wire conditioning is dominated by plastic deformation but has a minor erosion element. The total amount of both elements will increase with the degree of conditioning. Three grades of conditioning are generally recognized: "Conditioned," "Double Conditioned" and "Spherical Conditioned." Both plastic deformation and erosion elements of shape change will increase as sphericity is approached. The ratio of the two elements will be affected, to some extent, by the metallurgical properties of the cut wire. Erosion can be measured by weighing equal numbers of cut wire particles at each stage of conditioning. No definitive information is available to the author at this instant. Such information as is available indicates that the mass loss is only approximately 1 – 2% for "Conditioned," 2 - 3% for "Double Conditioned" and 3 – 5% for "Spherical Conditioned" grades.

SIZE DISTRIBUTIONS OF CAST AND CUT WIRE SHOT

In a perfect world wire could be cut into identical cylinders every one of which would receive identical conditioning and end up as having identical sizes. In the real world there is a 'normal distribution' of size for cut wire shot batches. Nevertheless the standard distribution is usually small, so that almost every cut wire particle has a very similar size. Cast shot variability has been discussed in detail in another article in this series. A complete cast of shot has a size variation similar to that of a 'normal distribution.' Subsequent sieving, however, divides the cast into size categories. Within a given category of cast shot the size distribution is approximately linear.

New Shot

The relative uniformity of cut wire shot size is often claimed to be an advantage when compared with the variable size of a sieved batch of cast shot. Fig.10 (page 32) illustrates, schematically, idealized differences in size distributions between new cut wire and new cast shot.

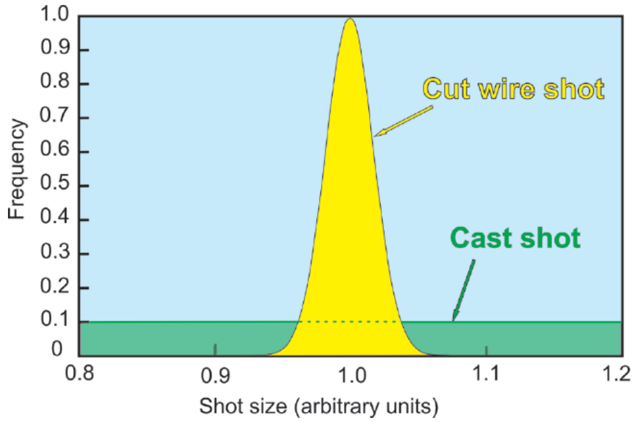

Fig. 10 Schematic representation of difference between cast and cut wire size distributions.

Cast shot is shown as having a uniform linear size distribution. Real distributions may have either a positive or negative slope with some curvature.

Used Shot

As soon as a shot particle is used to strike an object, it must lose some of its mass, The size distribution therefore changes. It is standard practice to replenish the shot charge to compensate for size mass reduction together with the loss due to fracturing of some particles. Replenishment changes the size distribution.

As a simple model, consider a charge of cut wire shot that has lost 10% of its size uniformly due to wear and has been replenished with 10% of new shot from the same original batch. We now have a 'bi-modal' shot size distribution, as shown in fig.11. This is the addition of the normal distributions of the used shot (mean size reduced to 0.9) and new shot (mean size of 1.0).

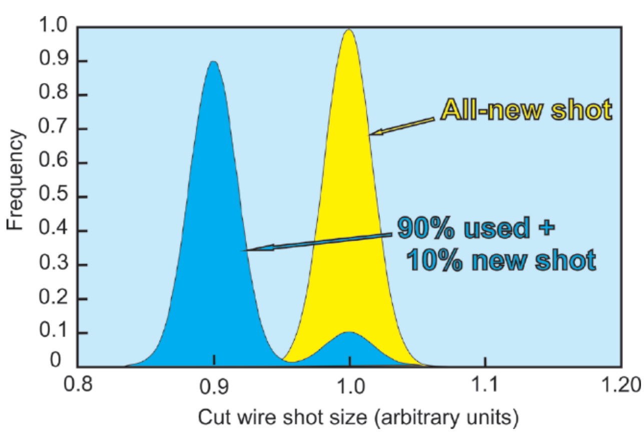

Fig.11 Representation of size distributions for new and used-plus-new cut wire shot batches.

Repeated additions of new cut wire shot will generate a broader, 'multi-modal,' size distribution. If no other peening parameters are changed then the cut wire shot charge will progressively produce higher coverage rates and lower peening intensities.

Wear and breakage of cast shot will produce a corresponding change in the size distribution for a fixed charge (of shot into the equipment). This change can be illustrated using the following grossly-simplified model. Assume (a) that a particular charge of cast shot has a uniform, linear, size distribution with minimum and maximum limits of 0.8 and 1.2 arbitrary units and (b) that there is a uniform 10% loss of size that is replenished with 10% of new shot from the same original batch of shot. The size distribution changes on replenishment. The largest shot fraction (1.16 to 2.0) wears down by 10% so that this size fraction now has zero frequency. The worn fraction replaces the next largest fraction which, in turn, replaces a smaller size fraction. Fig.12 represents the net result of wear as giving a uniform, linear, distribution between limits of 1.16 and 0.8. Shot originally just above 0.8 is assumed to be removed by sieving as it is worn below a size of 0.8.

For the idealized model shown in fig.12 the new cast shot average size is 1.0 which falls to 0.98 after 10% wear (and before replenishment). That is only a 2% reduction - which will have only a marginal effect on coverage rate and peening intensity. The effect of a single replenishment with 10% of uniform shot from the original batch is modeled in fig.13. Size distribution is then no longer uniform. The replenished mixture has an average size of 0.982 so

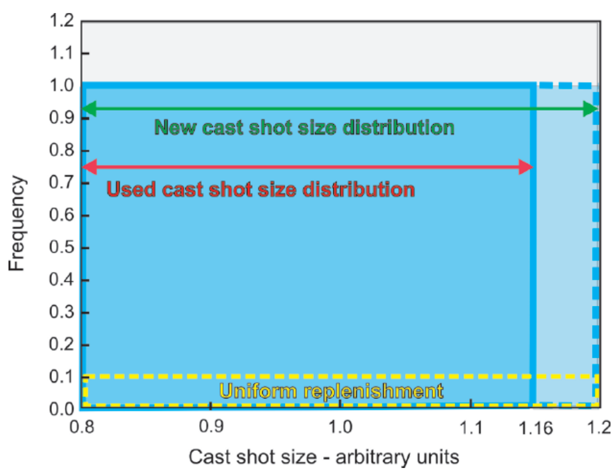

Fig.12 Idealized change of size distribution as charge of cast shot wears down in size.

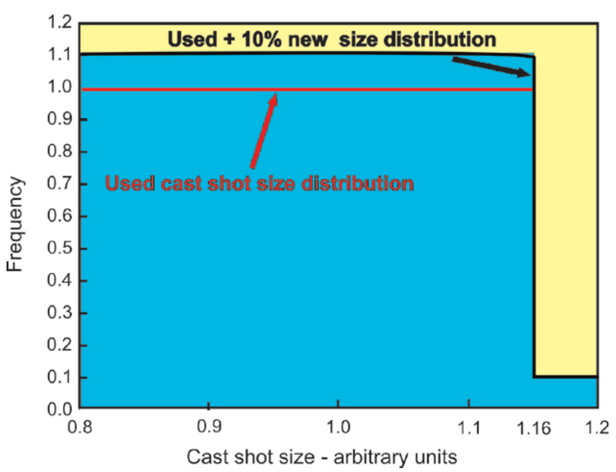

Fig.13 Size distribution after 10% addition of new shot to a used batch of uniformly sized shot.

that coverage rates and peening intensity will be only slightly affected. Multiple replenishments would predict a steady shift to lower and lower average sizes when the effects would become significant. One way to remove/reduce this size reduction effect would be to replenish the used shot with new shot that has a mean size equal to that of the largest original fraction (i.e., 1.18).

DISCUSSION

Carbon steel shot is remarkably efficient as a bulk peening medium. The required combination of hardness, toughness, durability, near-spherical shape and low cost is achieved by controlling chemical composition, heat-treatment and fabrication technique. It is perhaps surprising that the same objective is realized using two radically different production techniques – casting versus conditioning of cut wire.

Cast shot differs from conditioned cut wire shot in almost every respect: carbon content, shape production, size distribution and metallurgical structure. Malleability is essential if cut wire cylinders are to be pounded into near-spherical shapes. This requires the use of hypo-eutectoid compositions. Cast structures are traditionally weaker than wrought structures of the same chemical composition, hence hyper-eutectoid steels are used for cast shot because they are potentially harder than hypo-eutectoid steels.

The models used here for assessing size distributions are very simple and must, therefore, be interpreted with caution. Nevertheless, they serve to highlight potential differences in properties such as peening intensity and coverage generation.