



Shot Peening Materials Science

INTRODUCTION

The most important question in the Universe is probably “Why?” For shot peening it applies to the several materials that are at the heart of the process. For example, “Why is steel shot so commonly used?”. Materials science covers all of the materials used in shot peening—metals, ceramics and polymers. This article attempts to provide answers to why particular materials are selected for shot peening applications.

SHOT PARTICLES

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 spheroidizing 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.

Cast Shot

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 therefore a sphere. 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. “Roundness” and “Angularity” are the two parameters relating this approximation (see fig.1).

The controlling factor affecting cast steel shot size is the velocity of the water jet stream as illustrated by fig.2.

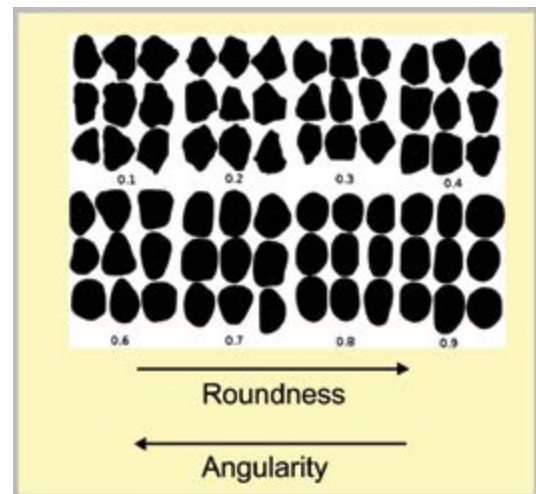


Fig.1. “Roundness” on a scale of 0.1 to 0.9.

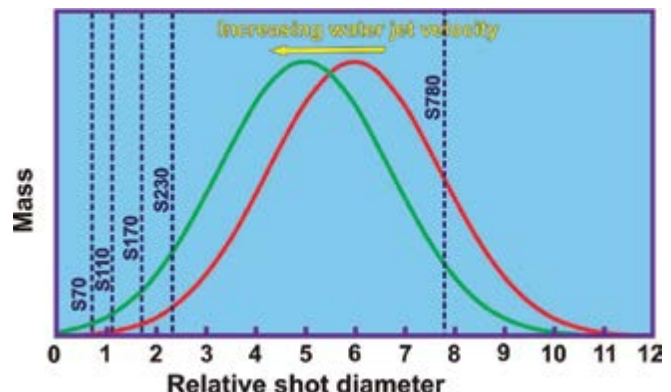


Fig.2. Effect of water jet velocity on cast steel shot size ranges.

Spheroidized Glass Beads

An alternative production route for glass beads is to spheroidize crushed glass (“cullet”). This can be achieved by blowing hot gas through a fluidized 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 fluidized 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. A detailed account of cut steel wire shot production was given in a previous *The Shot Peener* article (Fall, 2003).

A feature of cut steel wire shot is that its size distribution is much smaller than that for cast steel shot. Size distribution is commonly represented using “Normal Distribution Curves”. Fig.3 is a simple example of Normal Distributions. Curve A is much sharper than Curve B, indicating a difference in one or more properties.

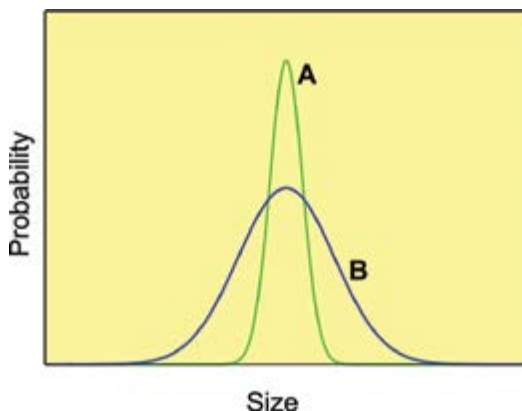


Fig.3. Normal Distribution Curves.

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 “atomized” as particles directly from the liquid state. These are then cooled in air or gas streams to produce the solid-state beads. One problem is that the fluidity (inverse of viscosity) is still marginal for spheroidization. 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 by the skin to achieve a given amount of shape change. Major improvements have been made by making 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.

CARBON STEEL SHOT

Most shot peening is carried out using plain carbon steel shot. Finished carbon steel shot particles have a tough core with, of necessity, a brittle skin of iron oxide (see fig.4 where the skin thickness has been deliberately exaggerated).



Fig.4. Section of spherical carbon steel shot particle.

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 on the shot particle is rapidly healed by further oxidation. The net effects are that (a) a small loss of shot mass on impact is unavoidable and (b) clouds of iron oxide particles are generated that can explode.

Fig.5 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 .

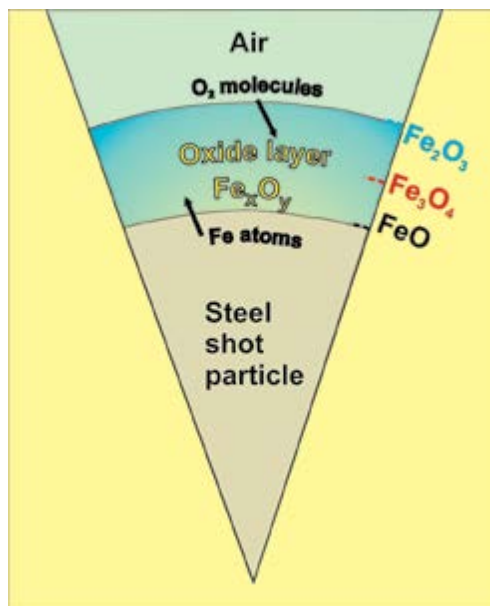


Fig.5. Slice of shot particle showing iron oxide layer of variable chemical composition.

When carbon steel 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 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.

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 within 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.6 illustrates the relationship.

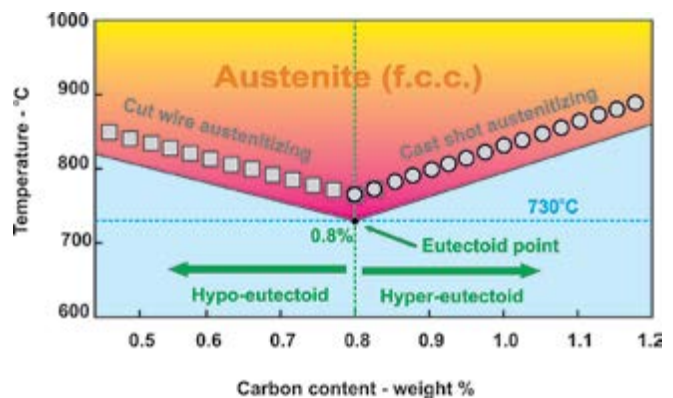


Fig.6. Schematic representation of carbon steel shot austenitizing.

The minimum temperature above which carbon steel austenitizes 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.6. 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 necessary 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.

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.

Occasional use is made of steel shot that has a carburized skin imposed on a lower-carbon core. The skin is much harder and wear-resistant than the core which itself is relatively tough.

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.7. 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 (less than 0.8%) 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 (more than 0.8%) 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.

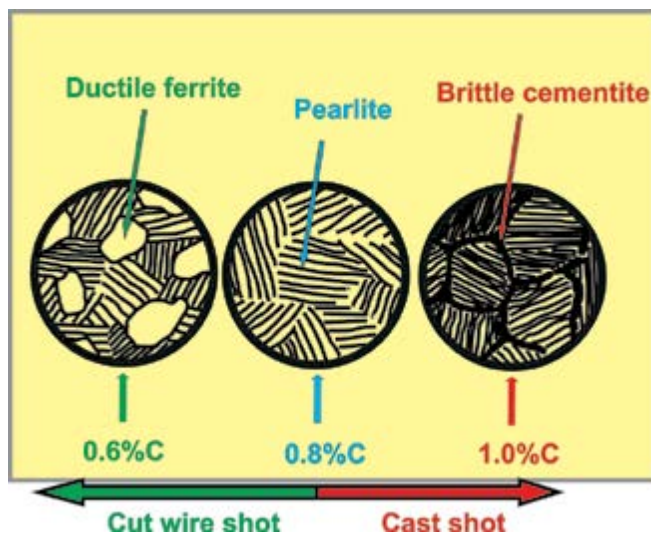


Fig.7. Schematic representation of slow-cooled carbon steel structures.

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.6) 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.8, 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”.

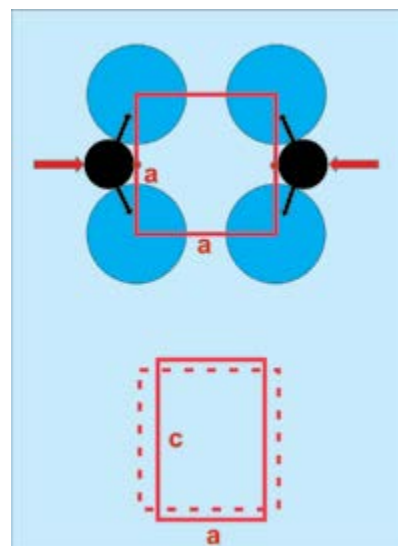


Fig.8. Carbon atoms distorting cubic arrangement of iron atoms.

The ratio of **c** to **a**, “tetragonality”, increases with carbon content as does hardness.

Cold-Working of Carbon Steel

Cold-working of carbon steel increases its hardness but decreases its ductility. A maximum hardness is reached beyond which the hardness starts to fall—a phenomenon called “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 even 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.

WORK-HARDENING OF COMPONENTS

Shot peening induces two very important changes in the surface layers of components. These are work-hardening and compressive residual stress, both of which improve fatigue strength. Fig.9 illustrates their contributions to fatigue strength. Work-hardened material has a greater fatigue strength than does un-peened material. The induced compressive surface residual stress is the “icing on the cake”, making an additional contribution.

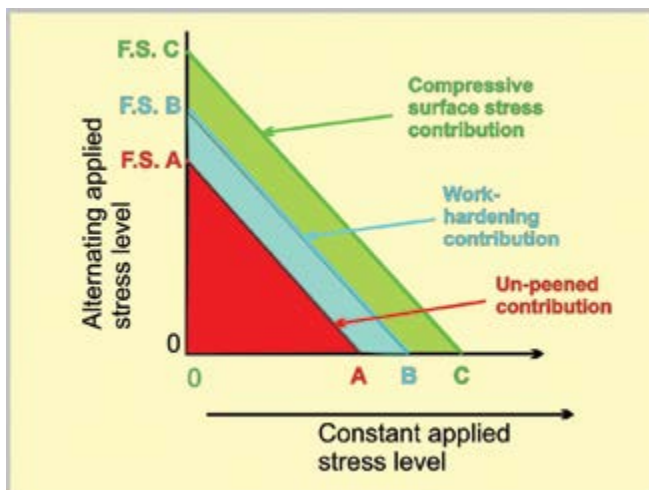


Fig.9. Contributions of Work-Hardening and Compressive Surface Residual Stress.

Surface work-hardening of peened components is quite different from that which occurs during a tensile test. Fig.10 illustrates the difference in behavior.

(1) The quoted yield strength values derived using tensile testing are not the same as the values required to indent when using flying shot particles. That is because yield strength increases with strain rate. The very high strain rates occurring during denting mean that the yield strength is several times greater than that predicted by a slow tensile test.

(2) Relatively-massive amounts of strain occur during shot peening. That is because a compressive stress system is set up, as described in a previous article (*The Shot Peener*, Spring, 2013, “Peening Impressions (Dents)”).

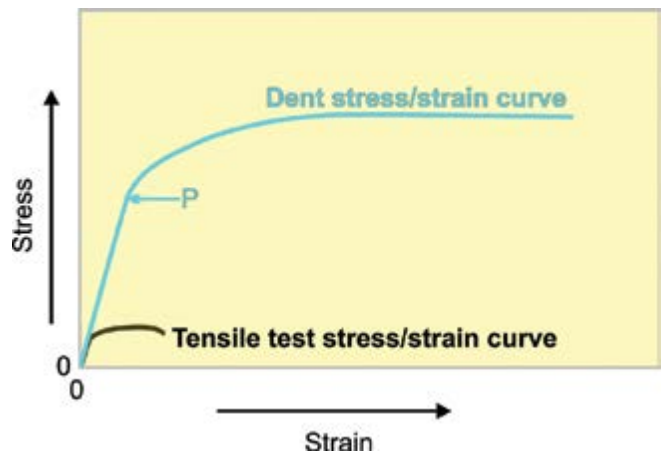


Fig.10. Schematic comparison of tensile test and dent stress/strain curves.

Fig.11 shows the zone of work-hardening (cross-hatched) that accompanies dent formation. An important feature is that the work-hardening is not uniform. As the moving shot particle reaches its maximum depth the deformation zone has two strain boundaries. Maximum plastic strain occurs at the contact area between particle and dent—marked as a red line. Zero plastic strain occurs where the applied stress only equals the proportionality limit stress, **P**, and is marked as a blue line. Below that line the component is only elastically stressed.

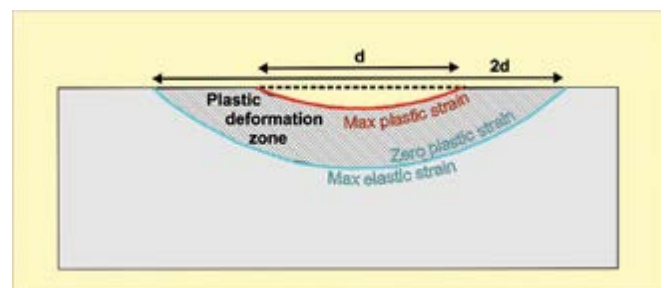


Fig.11. Plastic deformation zone beneath a peening dent.

EFFECT OF MULTIPLE DENTING

As coverage increases, the peened surface is subjected to multiple impacts. Progressively, a continuous work-hardened surface layer is produced. The amount of plastic deformation

is far higher than that encountered in a tensile test. A pertinent question is “Why doesn’t cracking occur during peening?” The answer lies in the different type of stress system that is being applied. It is because a three-dimensional compressive stress system is operating. In effect, the metal is being squeezed together three-dimensionally during deformation.

This is similar to what happens when we make snowballs. Squeezing using cupped hands applies a three-dimensional stress system. Compare that with what would happen if we press using flat hands.

During tensile testing we are simply trying to pull the metal apart. Cold-rolling involves an element of three-dimensional squeezing. Steel that cracks apart at, say, 10% elongation, can easily be cold-rolled to hundreds of percentage elongation without cracking. Extrusion has the largest three-dimensional compressive component of any metalworking operation. The same steel can be extruded, without cracking, to thousands of percentage elongation.

DISCUSSION

This article has attempted to cover the most significant materials science features that influence shot peening. This coverage has been simplified for the sake of brevity. Expanded accounts are, however, available in other *Shot Peener* articles.

Steel shot remains the most popular medium for shot peening. It has been available for hundreds of years and is reasonably inexpensive and easy to manufacture. Materials science does allow us to understand shot behavior and its limitations.

Great strides have been made in progressing many aspects of actual peening. Shot composition remains, however, relatively static. One avenue could be to test the viability of high-manganese steels. Several high-manganese steels are available in a tough austenitic form which cold-working transforms to hard wear-resistant martensite. This would allow shot to be manufactured that developed a self-healing wear-resistant surface layer. ●

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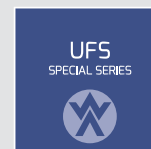
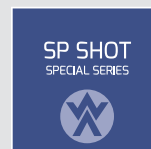
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