



Metals are Alive!

INTRODUCTION

Metallic objects abound in shot peening—steel shot, Almen strips, nozzles, wheels, etc. The metals used are alive! Essentially metals are made up of a regular framework of vibrating, charged, atoms (ions) surrounded by a cloud of high-speed electrons. The pulse rate of the vibrating atoms is about 10 trillion per second—more than that of the Earth's human population combined. The speed of the electrons is difficult to visualize—it is like comparing that of a supersonic bullet with that of a geriatric snail. Electron speeds are of the order of thousands of kilometers per second—enough to go round the Earth in less than a minute.

The aims of this article are twofold. One is to present a different perspective on the properties of metals. The other is to serve as primer in metallurgy for shot peeners. For this article the word “primer” means that it is intended to serve only as an introduction. Metallurgy is important because most of the objects used by shot peeners are metallic. Metallurgical principles underpin the usefulness of those articles.

METAL ION FRAMEWORKS

Almost all of the metals used by shotpeeners have one or other of three metal ion frameworks. These frameworks are called “crystal lattices” and are formed by the three-dimensional repetition of a basic unit cell. The three basic unit cells are body-centered cubic (b.c.c.), body-centered tetragonal (b.c.t.) and face-centered cubic (f.c.c.). Each metal atom is stripped of one or more electrons (which are negatively-charged) thereby becoming a positively-charged ion. The stripped electrons whizz around the lattice at an astronomical speed. There are so many of these moving electrons that they are commonly described as a “Cloud of free electrons”. These free electrons are responsible for the metal's ability to conduct electricity and for the stability of the lattice.

The positively-charged metal ions tend to push each other apart. Conversely, the negatively-charged electrons push the ions together. A balance of forces is thereby achieved. Each metal ion is covered by an impregnable inelastic shield. This means that no external electrons can enter, whatever their velocity.

Fig.1 illustrates the body-centered cubic unit cell which has an ion centered at each of the eight corners of a cube together with one at the cube's center. The length of the cube's side, a , is called its “lattice parameter”. Each of the ions pulsates at an enormous rate—a rate that increases with temperature.

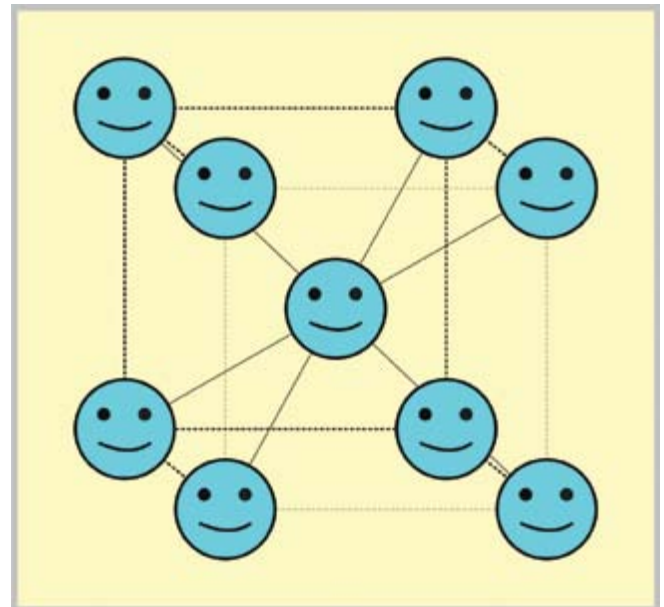


Fig.1. Body-centered-cubic unit cell.

Fig.2 (page 28) illustrates a body-centered-tetragonal unit cell which is similar to the b.c.c. unit cell but with one dimension, c , being larger than the other two a 's. This vertical axis stretching is caused by four carbon atoms acting in unison and exerting forces shown as red arrows. Again the metal ions pulsate at an enormous rate but the carbon atoms are in fixed positions. The metal ions are prepared to put up with the imposed stresses—temporarily.

Fig.3 (page 28) illustrates a face-centered cubic unit cell which has a metal ion centered at each of the eight corners of a cube together with a metal ion centered on each of the six faces of a cube. The center positions of the metal ions are generally shown as black dots. Only the five ions at the center of the front face have been illustrated for simplicity. Again all of the metal ions pulsate at an enormous rate.

For all three types of lattice, crystals are formed by repeating the basic unit cell in three dimensions.

ALLOTROPY

Metal crystals can take collective decisions to change their crystal structure. This phenomenon is called “allotropy”. The classic example of allotropy is that of carbon steels where, depending on prevailing conditions, the crystal structure can exist as face-centered cubic (on heating), body-centered-cubic

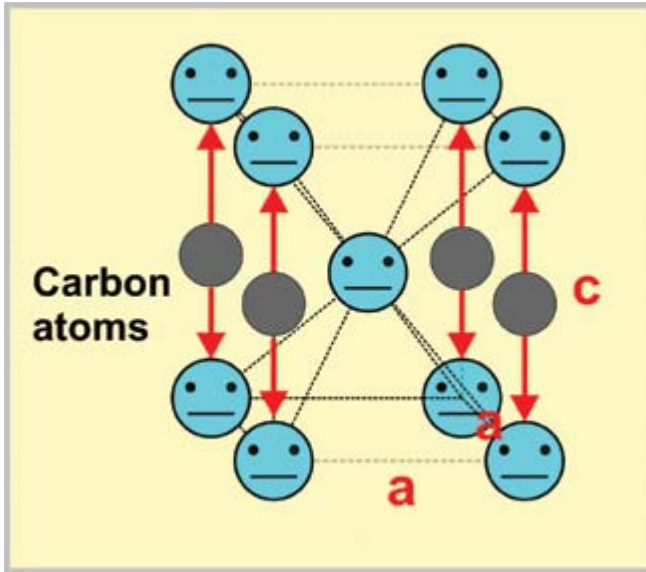


Fig.2. Body-centered-tetragonal unit cell.

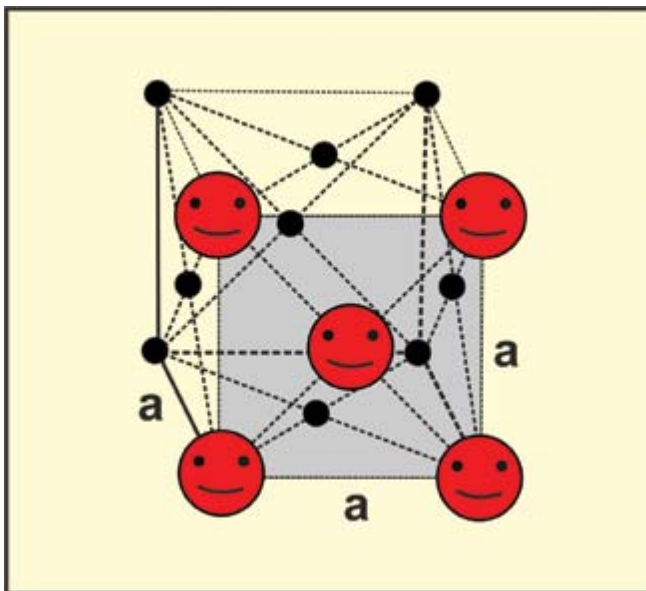


Fig.3. Face-centered-cubic unit cell.

(on slow cooling) or body-centered-tetragonal martensite (on fast cooling). This topic has previously been described in detail (“Properties of Carbon Steel Shot”, TSP, Spring, 2011).

Fig.4 illustrates one important effect of cooling rate on carbon steel crystal structure. Above a certain critical temperature, C.T., iron ions exist happily in a face-centered-cubic arrangement called “Austenite” with much smaller carbon atoms moving around in the spaces between the ions. Below the critical temperature the iron ions cease to tolerate the interloping carbon atoms and collectively take decisive action. During both slow quenching and slow cooling there is time for three iron ions to be assigned to each carbon atom to form an iron carbide molecule Fe_3C . The iron carbide

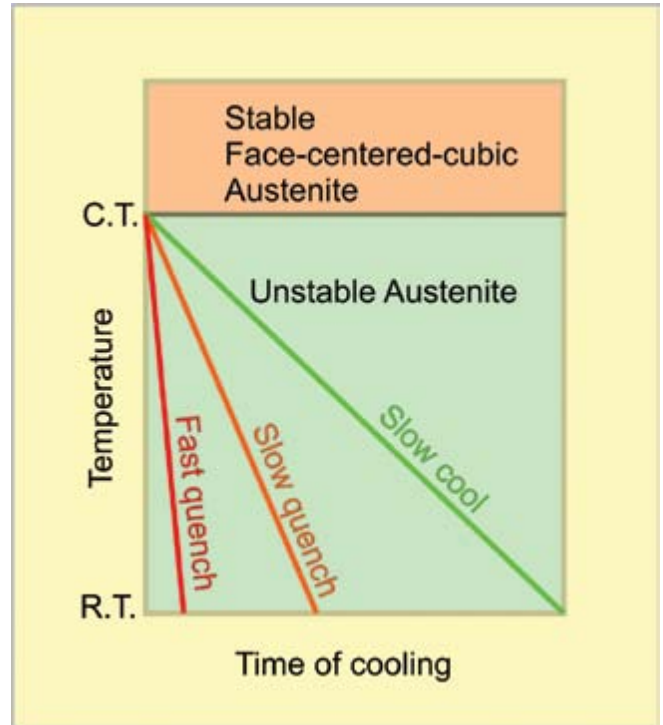


Fig.4. Range of cooling rates applied during heat-treatment of steels.

molecules are then assembled to form a very hard, brittle, material called “Cementite”. The resulting structure at room temperature, R.T., becomes a mixture of relatively pure iron crystals with interspersed colonies of cementite. During fast quenching there is not enough time to form cementite. The face-centered-cubic lattice transforms itself into a body-centered-tetragonal arrangement where the carbon atoms have only to be moved tiny distances. If this cannot be fully achieved in the limited time available then numerous ghettoes remain of untransformed austenite—generally called “Retained austenite”.

VACANCY MIGRATION OF METAL IONS

Metal ions are usually quite happy to remain centered on their own home lattice site. Every lattice does, however, contain a proportion of empty sites called “vacancies”. Metal ions closest to a vacant lattice site feel the urge to migrate into that site, marked V in fig.5 (page 32).

The proportion of vacancies increases with temperature, as does the available energy for metal ion migration. It follows that the rate of vacancy migration also increases with increase of temperature. Interlopers, such as carbon atoms, being relatively small, can slow down migration by occupying some of the vacancies.

WORK-HARDENING

The more we deform metals the more they resist further deformation—a phenomenon called “work-hardening”. A

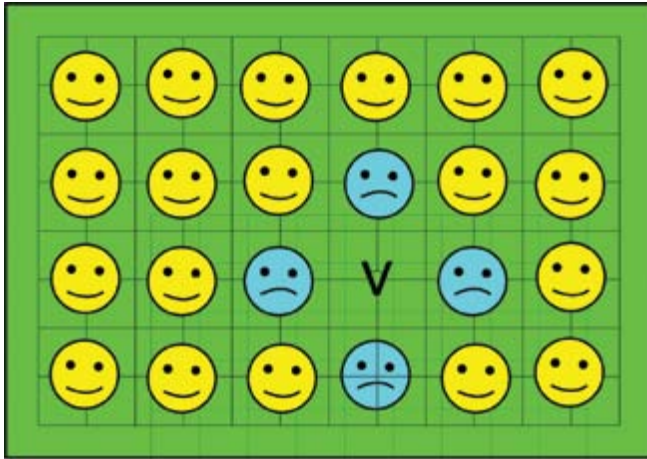


Fig.5. Schematic representation of vacancy condition.

simple demonstration of work-hardening is afforded by a stress-strain curve derived by tensile testing. The maximum stress that can be endured in a tensile stress is called the “U.T.S.” (Ultimate Tensile Strength). It is important for shot peeners to appreciate that the U.T.S. derived from a tensile test is far lower than the maximum stress that can be endured on peening. Fig.6 is from a previous article (“Work-hardening During Peening”, TSP, Summer, 2017). Denting is essentially deformation under conditions of high hydrostatic compression. Cold-rolling has a small hydrostatic compression component but which still allows at least ten times the maximum extension evidenced in a tensile test. Extrusion has a huge hydrostatic compression component that allows a thousand times the tensile test’s maximum extension.

The author well-remembers a client objecting when informed of the magnitude of the maximum compressive residual stress in his shot-peened component. “That’s impossible,” he said. “It would be above the U.T.S.” The reason had to be carefully explained!

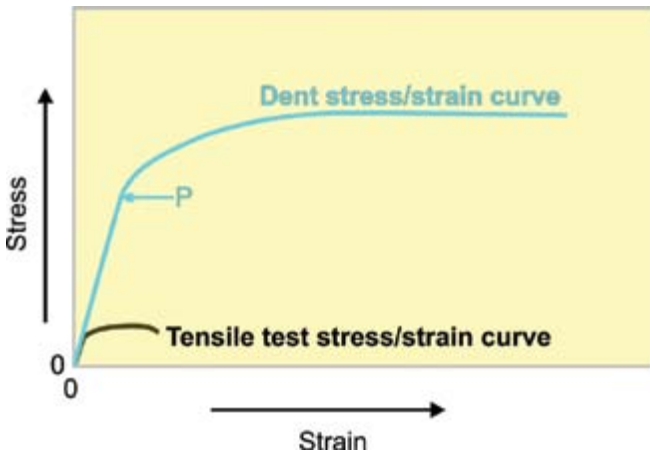


Fig.6. Stress-strain curves for tensile test versus denting.

When plastic deformation is imposed on a crystal of annealed pure metal, its behavior is analogous to it being a three-dimensional skating ring. Deformation is achieved by using crystal defects called “Dislocations”. Fig.7 attempts to illustrate the main features of an edge dislocation. The term “edge dislocation” was originally coined because its structure, as shown, is analogous to the bottom edge of an extra sheet of ions appearing at X. If a shear stress is applied that just exceeds the shear strength the dislocation moves—analogue to the hump of a caterpillar moving towards its head. Note that for a caterpillar all of its remaining legs stay in position until the hump reaches its head. Similarly, for a metal crystal, it is only the position of the extra sheet that is moving, initially from X to X’.

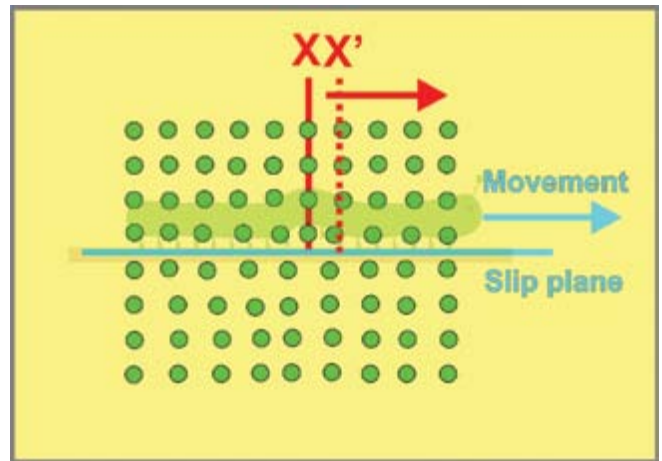


Fig.7. Structure and movement of an “edge dislocation”.

Once a dislocation starts to move, it accelerates to the speed of sound! It then starts to replicate itself at a rate that is astronomical. An annealed crystal containing 10^6 dislocations per cubic centimeter may contain 10^{12} when deformed by an impacting shot particle. A million-fold increase in less than a thousandth of a second! This feature of annealed metal crystals being relatively-free of dislocations (when compared with cold-worked crystals) is the key to understanding work-hardening. A reasonable analogy is that of traffic on a city’s streets. Imagine the streets being almost empty. Traffic can then move freely and fast. If, however, the number of moving vehicles suddenly multiplies a thousand-fold chaos would reign. Vehicles would crash into each other causing multiple pile-ups. Movement would then become very difficult. With deformation of metal crystals multiplying dislocations, travelling at the speed of sound, pile-up at crystal boundaries (and elsewhere), creating a back-pressure that slows down further deformation.

The distribution of the vast number of dislocations in a work-hardened metal can only be described loosely. Fig.8 (page 34) is a schematic representation of its most important feature—each crystal develops a substructure. Overall the

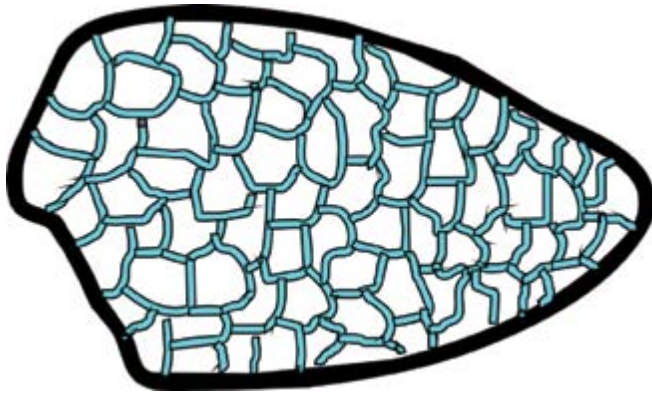


Fig.8. Schematic representation of sub-grains within a work-hardened crystal.

crystal has been divided up into millions of sub-grains. Each sub-grain is a region of relatively-low dislocation intensity whereas each sub-grain boundary is a region of very high dislocation intensity. Each metal crystal is not at all happy with this state of affairs and will take every opportunity to make life more comfortable.

ALLOY HARDENING

There are two main types of alloy hardening: “Solid solution hardening” and “Precipitation hardening”.

(1) Solid solution hardening

Alloying element atoms dissolved into a crystal’s matrix will be either larger or smaller than those of the matrix. This is analogous to myriads of tiny bumps on a skating rink’s surface. Fig.9 illustrates this bumping effect in cross-section. A moving dislocation line is analogous to a line of linked skaters moving across a rink. As individual skaters encounter a bump in the ice their progress is retarded.

(2) Precipitation hardening

Precipitation hardening is analogous to scattering grit on a skating rink. Dislocation lines can either slide over the precipitate particles or crash through them or even loop

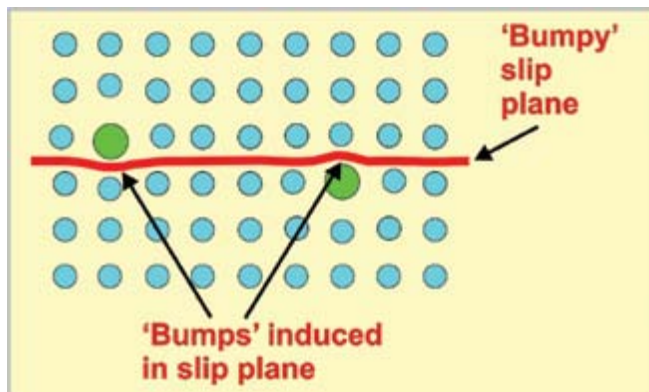


Fig.9. “Bumps” in a slip plane caused by solid solution atom.

around them, multiplying as they do so. The effect is to increase the resistance to further deformation and hence increase hardness. Precipitation hardening is particularly effective when used for soft metals such as aluminum.

Precipitation occurs when unwelcome atoms are encouraged to leave the matrix of a crystal and form particles. Aluminum is commonly alloyed with a small percentage of copper to form hardenable alloys. At a high enough temperature, the copper atoms are dissolved in the matrix to form a solid solution. At a lower temperature, intolerance sets in and the copper atoms are made to combine with aluminum atoms to form particles of $CuAl_2$.

CRYSTAL BOUNDARIES

Crystal boundaries, also known as “grain boundaries,” are important. The rules that are obeyed by metal ions within each crystal no longer apply at its boundaries. Just as a farmer might resent the loss of land caused by hedgerows, so the crystals resent the presence of boundaries. There is a natural tendency for the larger crystals to swallow up the smaller crystals leading to what is known as “grain growth”. This process is accelerated by any rise in temperature. Steels austenitized at too high a temperature develop a very large crystal size. This has a deleterious effect on the properties of quenched steels.

Grain boundaries do not have the same regular structure that exists within each crystal. The metal ions at grain boundaries are not as closely packed as they are within the body of the crystal. Alloying element atoms can migrate at a relatively huge rate as compared with that allowed within crystals. This is exemplified by the process known as “decarburization”. It was described in a recent article titled “Decarburization”, TSP Winter, 2018. Pesky carbon atoms can be shunted rapidly along grain boundaries and made to join up with oxygen atoms at the metal’s surface. This migration also allows for ferrite (b.c.c. iron) to form at the crystal boundaries as illustrated by fig.10.

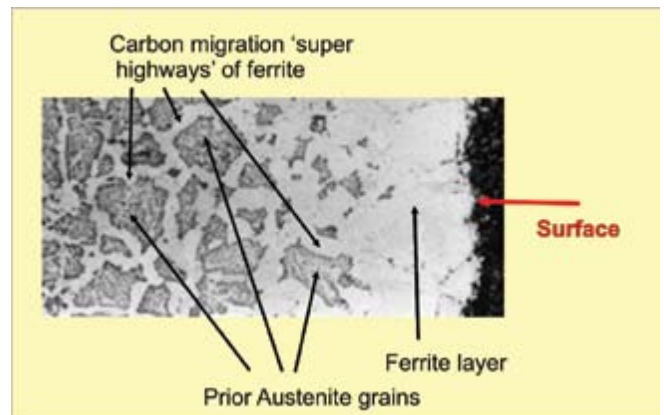


Fig.10. Carbon migration in carbon steels.

Another example of the importance of crystal boundaries is a phenomenon exhibited by stainless steels. Carbon atoms at high temperatures much prefer a close association with chromium atoms to being accommodated within a crystal's f.c.c. structure. Precipitation of chromium carbide therefore occurs at crystal boundaries as illustrated schematically in fig.11. The chromium carbide particles have the chemical composition $Cr_{23}C_6$. Chromium is the principal element that confers corrosion resistance to stainless steels. The gross lowering of chromium content therefore makes the steel much more sensitive to corrosion. Hence, the phenomenon is called "Sensitization". The crystal boundaries have become preferred corrosion attack zones.

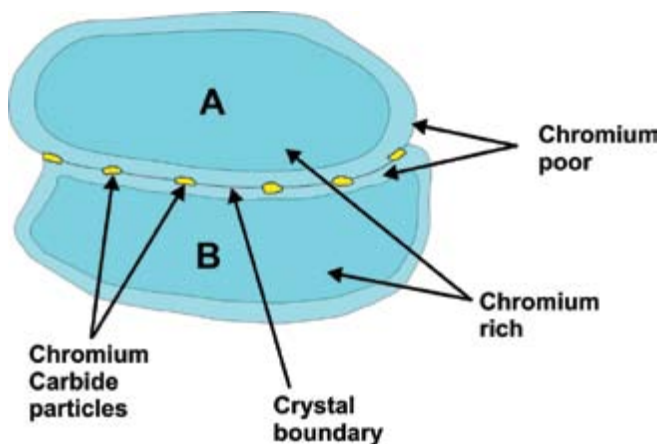


Fig.11. Chromium carbide precipitation at crystal boundaries.

If high tensile stresses are imposed on a metallic component at high temperatures, then a phenomenon called "Creep" occurs. The crystal boundaries behave as if they have been lubricated. Crystals slide over one another, keeping their integrity intact. Creep is so important for aircraft blades that many are fabricated as one huge crystal.

THERMAL EFFECTS

Deformed metals resent the carnage that deformation causes to their otherwise pristine, lightly-stressed, lattice arrangements. They will strive to restore order out of chaos. Restoration depends upon the crystal's metal ions having enough energy. Available energy depends upon the prevailing temperature. The higher the melting-point of a particular metal the greater is the temperature rise needed to supply the requisite energy.

Raising the metal's temperature and then keeping it there for different times is called "Isothermal annealing". Raising the temperature to a different temperature but keeping it there for a fixed length of time is called "Isochronal annealing". Both annealing processes are useful for analyzing property changes brought about by ion activity.

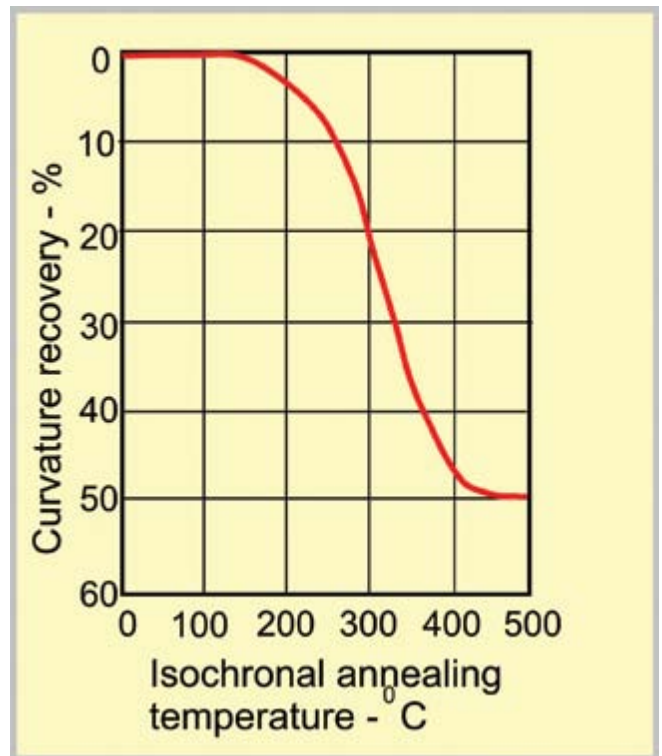


Fig.12. Effect of isochronal annealing on curvature of peened Almen strips.

Fig.12 illustrates how isochronal annealing reduces the curvature of peened Almen strips. Each strip was annealed for one hour. At temperatures above about 1500°C, the curvature of peened Almen strips began to be reduced. The rate of change of curvature subsequently increased to a maximum followed by a slowing down. Eventually no further change occurs. Mathematically speaking, the shape of this curve is dubbed "Sigmoidal". The inference from fig.12 is that the curvature induced by peening has two components. One is permanent, whereas the second is temporary. The temporary component of strip curvature is largely due to residual macro-stresses which are removed by annealing. Specifications rightly restrict the operating temperature for shot-peened components in order to combat stress-relief.

The increase of temperature during annealing gives the metal ions sufficient energy to carry out "disaster relief". Several processes can then be employed depending upon the magnitude of the annealing temperature. At low annealing temperatures so-called "Recovery processes" predominate. These are analogous to tidying-up a house and involve unwelcome dislocations being moved only short distances within the sub-grains—a process termed "Polygonization". At higher temperatures, large-scale rebuilding takes place with new grains being nucleated by polygonized sub-grains. This is "Recrystallization" with new grains absorbing pre-deformed material.

Less recognized, but universally present, is the surface temperature rise induced by the energy transferred from the impacting shot particles. Some 90% of the work required to create each dent is transformed into heat energy. Surface temperature rises can vary between a few degrees to over a thousand degrees Centigrade. These temperature rises are, however, temporary as heat is made to diffuse away from the surface.

Electrical conductivity of metals decreases with increase of temperature. This is because the metals ions then have greater vibration amplitude thereby interfering with the motion of the whizzing electrons (which are the ones enabling conduction). At very low temperatures the metal ions effectively go to sleep hence allowing, for some alloys, superconductivity.

RESIDUAL STRESS

Very important, for shot peeners, is the ability of metal lattices to store residual stresses. Metal lattices are elastic in the sense that planes of atoms can be either pushed closer together or pulled further apart, depending on the sign of the residual stress. Compressive residual stress will cause a decrease in spacing, as illustrated by fig.13. The consequent change in the lattice spacing, d , can be detected by x-ray diffraction.

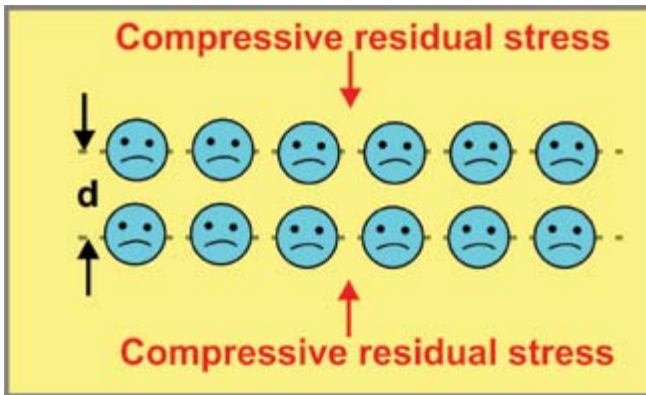


Fig.13. Compressive stress reducing interplanar spacing.

CONCLUSIONS

This article was written as a simple primer in metallurgy that would be palatable for the majority who has little interest in detailed aspects of the subject. Treating metals as if they were alive provides coherence. We can then imagine a metal ion lamenting, "Using thermal-imaging cameras, humans have started to film the misery imparted on a metal's surface." There are also numerous parallels that can be drawn between the reaction of metal ions and humans to outside influences. ●



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