Ductility and strength properties of shot peened surfaces by David Kirk

INTRODUCTION

It is an apparent paradox that peening, which requires a large degree of ductility, can readily be applied to high-strength, low-ductility, engineering components. A single indentation may induce plastic deformations of more than 100%. This is illustrated in fig.1 where it is assumed that the depth of the deformed zone is twice that of the indentation itself. A column of length AC has been compressed to half of its height BC. The deformed column therefore has an average compressive plastic deformation **equivalent** to a tensile deformation of 100% (using engineering strain calculation). That deformation varies from 0% at C (the boundary of the plastically-deformed zone) to a maximum at B. Assuming a simple linear variation, that will equate to 200% at B.
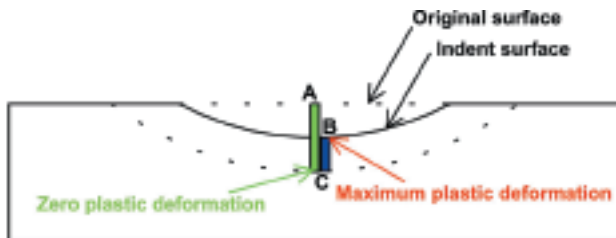

Fig.1 Schematic representation of plastic deformation range in peened surface.

Ductile metals have a **tensile** ductility of about 40% and high-strength alloys generally have a **tensile** ductility of less than 10%. With coverages approaching a nominal 100%, peened surfaces have to have withstood multiple indentations giving plastic deformations of the order of about 1000%! This article is a simple account of the factors that account for the apparent ductility paradox, together with a discussion of the strength changes that accompany ductility changes.

It is obvious that shot peening involves very high deformations. We must, therefore, use appropriate definitions. Fig.2 illustrates the difference between 'engineering strain' and 'true strain' for large tensile extensions. At the very small extensions encountered with **elastic** straining (less than 1%) there is very little difference between engineering strain and true strain. With massive extensions the difference becomes very large. The significance is that we should expect properties to change on the scale of true strain rather than engineering strain. For example we might anticipate a 1000mm extension to increase strength by a factor of two or three – rather than by an order of magnitude.

DUCTILITY

There is a profound difference between the ductility of a material measured in tension and that measured in compression.

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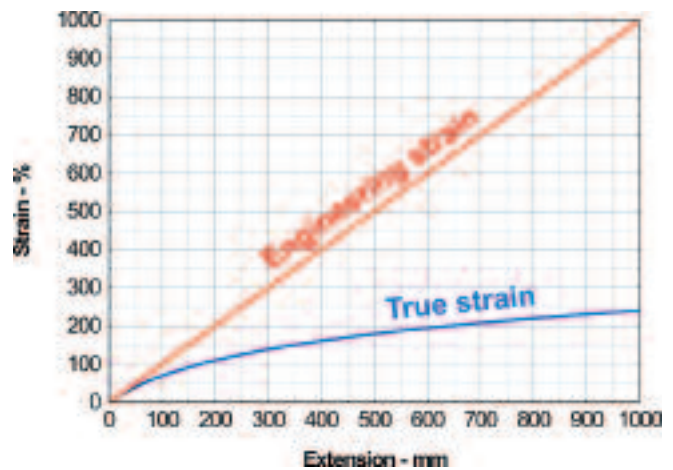
Fig.2 Comparison of engineering and true strains for extensions applied to 100mm long specimen.

As engineers we are generally familiar with **tensile** ductility values for materials – because they are easy to measure and are readily available. Ductility values in compression are not readily available. This is not a problem for most engineering situations as failure is generally related to tensile, rather than compressive, strains. Some materials however, such as gray cast iron, are so brittle in tension that they are best suited to situations involving compressive strains. That is because the ductility in compression is up to twenty times that in tension, see fig.3. Failure occurs in tension at point **T** with a strain of about 0.0035 (0.35%). That contrasts with failure at point **C** in compression at a strain of about –0.07 (7%). The corresponding failure strengths are about +150 and –900MPa respectively. It is worth noting that ductility in compression is an order of magnitude greater than that in tension for virtually all metallic materials.

In the specialized situation of peened surfaces it is the compressive ductility that is relevant – not the tensile ductility. The order-of-magnitude difference in ductility goes a long way to
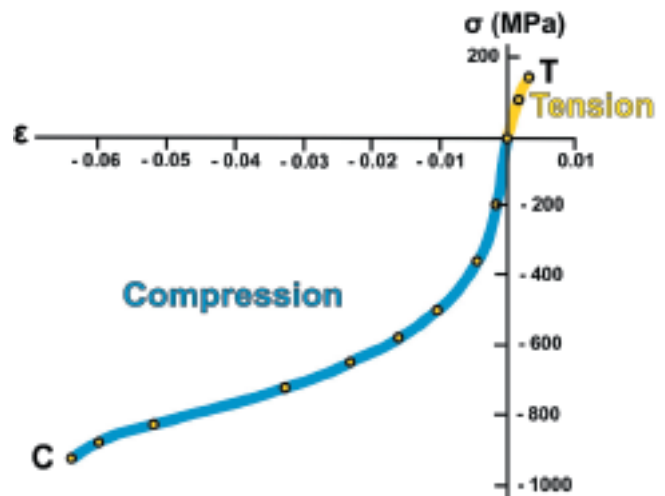

Fig.3 Comparison of stress/strain behavior of gray cast iron in compression and tension.

explaining the ductility paradox. One familiar example of compressive ductility is that of Brinell hardness indentations, which do not induce cracking in either gray cast irons or in other brittle materials.

Compression testing is generally based on squeezing cylinders of material between polished platens – as illustrated in fig.4. A compressive stress, σc, is applied to the end faces of the cylindrical sample. Friction between the end faces and the platens restrains lateral movement so that bulging occurs. Eventually cracking will occur on the walls of the bulged cylinder – as indicated in fig.4. That situation is inhibited by the lateral restraint offered by continuous surfaces – as in shot peening. This restraint adds a hydrodynamic compressive component to the applied stress system. Fig.5 shows a model of the situation where a cylinder of material being compressed under an applied stress, **-c**, is restrained by a surrounding annulus of surface material. The constraining annulus imposes a compressive stress, **-r**, on the deforming cylinder.

Hence we have a stress system that can be expressed as **(-c+r, 0, 0) + (-r, -r, -r)** where **(-r, -r, -r)** is the hydrostatic compressive component. Hydrodynamic compression is the reason why it is possible, for example, to roll to large extensions and to extrude metal cylinders to enormous extensions. It follows that the ductility of peened surfaces is much higher than that predicted by simple compression tests on cylinders of material. The author is not aware of any standard ductility test for peened surfaces.

STRENGTH PROPERTIES

It follows from the massive ductility available during shot peening that work-hardening will raise strength properties by large amounts. Hence the yield strength, for example, may become several times the ultimate tensile strength recorded during tensile testing. That in turn means that surface residual stresses can reach values well in excess of the nominal tensile U.T.S.

An important design problem is to be able to relate applied stress to failure. If a material is ductile, failure is usually defined by the yield strength. A brittle material, on the other hand, is usually defined by its fracture strength. The difference between ductile and brittle materials is illustrated in fig.6 for **tensile** applied stress. With a ductile material the yield strength is well below the fracture strength of the same material. As an applied stress increases we first reach the yield stress so that yielding is induced. After large amounts of work hardening have been applied the yield strength is raised to that of the fracture strength. Fracture can then
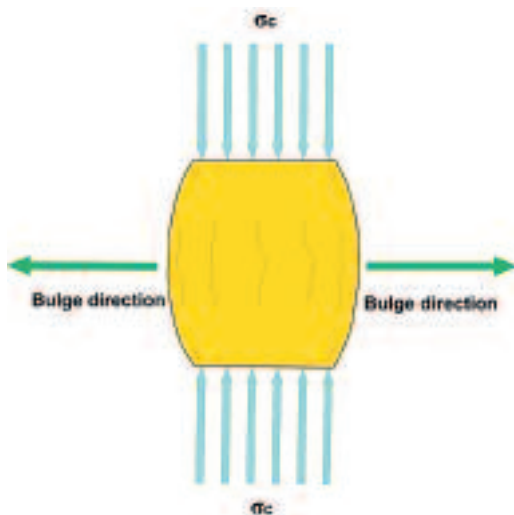
take place. For a brittle material the fracture strength is already very close to the yield strength. With increasing applied stress, yielding (and therefore work hardening) quickly raises the yield strength to that of the fracture strength. No more work hardening can be then be induced because fracture propagation takes over.

With compression failure there is an order of magnitude increase in the **difference** between the yield strength and the fracture strength. The changed situation is illustrated in fig.7.
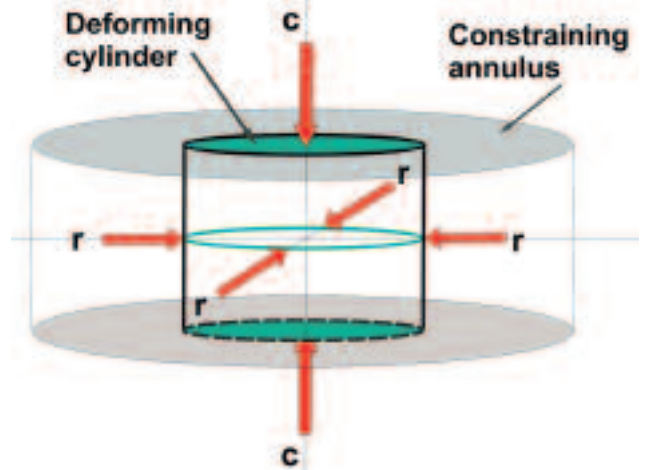

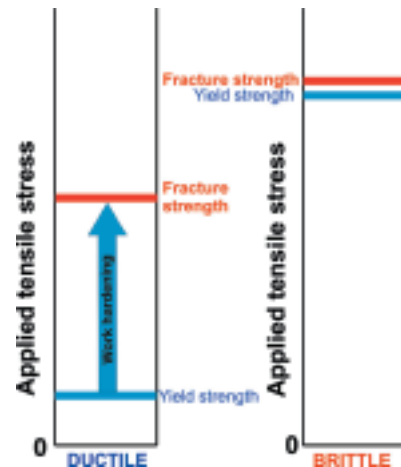*Fig.5 Schematic representation of surface constraint of material being compressed during impact.*

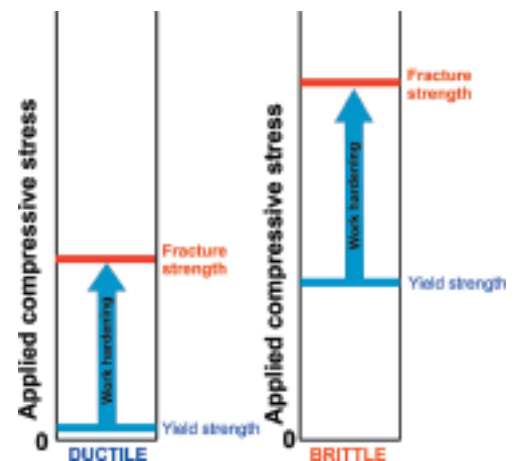*Fig.6 Schematic representation of ductile versus brittle **tensile** failure strengths.*

Fig.4 Schematic representation of a compression test.

*Fig.7. Schematic representation of ductile versus brittle **compressive** failure strengths.*

The elevation of strength properties induced by shot peening the surface can be explained in terms of the corresponding structural changes. Dislocation theory was introduced more than fifty years ago to explain why real crystalline materials had much lower yield strengths than would be predicted for perfect crystals. Dislocations explained the transportation of material along slip planes at observed applied stress levels. A rough, but informative, analogy is the use of automobiles to transport people on a city's grid system of roads. If we have only a handful of automobiles on the roads then travel is virtually unhindered. Imagine, however, if every automobile cloned itself every few metres of travel. Very quickly we would have monumental congestion with pile-ups at every intersection. The 'stress' required for further vehicle movement increases rapidly. When a shot particle strikes the component surface the dislocation content is multiplied by a factor of about one million giving more than one trillion dislocations per square centimetre! Dislocations have 'cloned' themselves millions of times in a microsecond.

The structure of the cold-worked peened surface is quite different from that of textbook pictures of crystalline materials. Peened material has a structure that can be described as "regions of very high dislocation density surrounding sub-grains which have a high dislocation density". The sub-grain size becomes smaller with increased amounts of cold work. Eventually the stress required to force dislocation movement is less than that for crack generation so that the fracture strength is reached.

DUCTILITY AND STRENGTH PROPERTY ASSESSMENT

The ultimate test of peening effectiveness is the improvement induced in properties such as fatigue strength. This test is well established and will not be discussed here.

Compression testing gives the best available guide to potential ductility on peening. One simple procedure that accommodates the high strain rates of shot peening is to employ drop forging. Cylinders cut from turned bar material are placed on an anvil and subjected to impact by a tup dropped from different heights. The maximum strain that can be withstood without side cracking gives us a measure of compressive ductility. Measured ductility levels should, however, be regarded as under-estimates - given the hydrodynamic constraint imposed by a continuous surface during shot peening.

The yield strength of material subjected to large amounts of plastic strain cannot be assessed using conventional tensile testing. One classic modification involves carrying out tensile tests on strip material that has been previously subjected to known amounts of extension by cold rolling. This 'envelope' technique invokes the fact that rolling has a substantial hydrostatic compression component and can therefore impart extensions an order of magnitude greater than those obtained in simple tension. Fig.8 illustrates the principles of the 'envelope' technique. With this example six tensile tests have been carried out. Test 1 corresponds to the 'as-received' state of the material. Tests 2 to 6 correspond to material that has been cold rolled to extensions of 20, 40, 60 100 and 150% respectively before tensile testing. The green line is the envelope representing the change of strength up to large amounts of plastic deformation. For this example the yield strength at 150% prior elongation is some three times that of the U.T.S. for the as-received material. Rolling extensions can be applied at 10% per pass through high-speed four-high rolls to give strain rates approaching those obtained with shot peening.

The level of strengthening induced into peened surfaces can be assessed indirectly. X-ray line broadening and micro-hardness
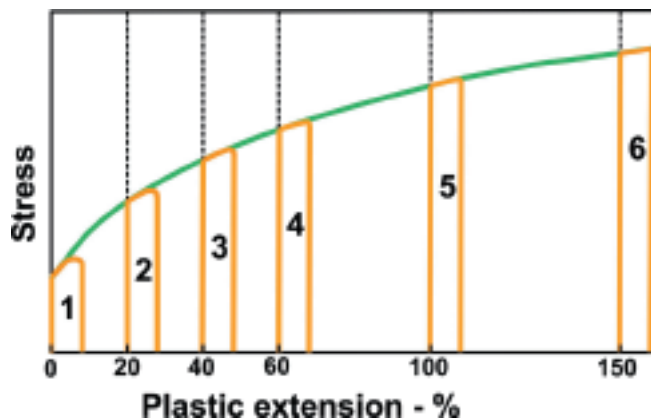

Fig.8 The 'envelope method' of determining high-strain strength.

are commonly-applied indirect methods. X-ray line breadth and micro-hardness increase with cold working (and hence yield strength). Both methods can and should be calibrated using material that contains known large amounts of plastic strain (induced by cold rolling, compression or extrusion).

DISCUSSION

Assessment of ductility and strength changes during peening requires the use of techniques other than conventional tensile tests. The large values involved mean that true stress and true strain definitions should be employed. Strength changes can be measured indirectly by using procedures such as X-ray line broadening and micro-hardness testing. Those procedures can be calibrated against heavily cold-worked reference specimens. Ductility changes during peening are difficult to assess. The author uses a simple technique to test for the onset of cracking. This involves dropping a carbide cylinder having a hemispherical nose from different heights. With relatively brittle materials cracking is induced above a critical drop height.

The essence of this account is that very large ductilities reign during shot peening with corresponding large increases in yield strength properties. These very large ductilities are due to a combination of the compressive nature of the deformation and the hydrostatic compressive element that is present. As a consequence of the large yield point increases imposed by shot peening it is possible to sustain residual stresses that are greater than the unpeened U.T.S. The ready availability of ductility should not, however, be abused because high levels of cold work equate to high levels of stored energy. This stored energy becomes a driving force for thermally-activated changes - such as stress-relief. ●