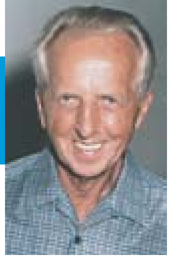

ACADEMIC STUDY

by Prof. Dr. David Kirk | Coventry University, U.K.

'Peenability' of Steel Components

INTRODUCTION

Component designers can assess whether or not their components have the capability for service improvement by shot peening. The extent of such improvement can be termed component 'peenability'. More than 90% of moving engineering components are made of steel.

The 'peenability' of steel components depends mainly on two factors:

(1) **Service Conditions** and

(2) **Steel Composition**.

Fatigue resistance is the most important service condition and steel is the most important component material. There is, however, a large variety of service conditions and steel compositions that are involved. Service conditions and steel composition often interact with one another. Mild steels generally have the lowest peenability whereas high manganese steels have the highest peenability.

Components that are seriously over-engineered will have zero 'peenability'. Their dimensions (and hence weight) are such that imposed stress levels are well below the component's fatigue strength. Shot peening is mainly applied to what would otherwise be under-engineered components. With under-engineered components there are two alternatives to shot peening: either to increase the dimensions of the component to match the gain achieved by shot peening or to use an inherently stronger, probably more expensive, steel. The greater the possible weight reduction (which can be either direct or indirect), the greater will be the component's peenability.

When service performance is improved we have positive 'peenability'. On the rare occasions when performance is lessened, 'peenability' is negative.

This article describes the basic relationships that exist between service conditions, steel composition and 'peenability'. The subject area is huge so that, of necessity, selected examples are used to illustrate these relationships.

FATIGUE RESISTANCE

Fatigue resistance is the most important service property that can be enhanced by shot peening. Fatigue strength and fatigue limit are terms commonly used to describe fatigue resistance. The ASTM defines **fatigue strength** as: the value of stress at which failure occurs after **N** cycles, and **fatigue limit** as: the limiting value of stress at which failure occurs as **N** becomes very large. Steel composition has a primary effect on fatigue resistance.

Carbon/low-alloy steels exhibit a definable fatigue limit. Virtually all other steels exhibit definable fatigue strength. The difference is illustrated by the hypothetical fatigue curves shown in fig.1, where stress levels are in arbitrary units.

Fig.2 illustrates the general benefit that peening can give to carbon/low-alloy components. The 'peenability' of carbon/low-alloy steel components depends on the level of fatigue

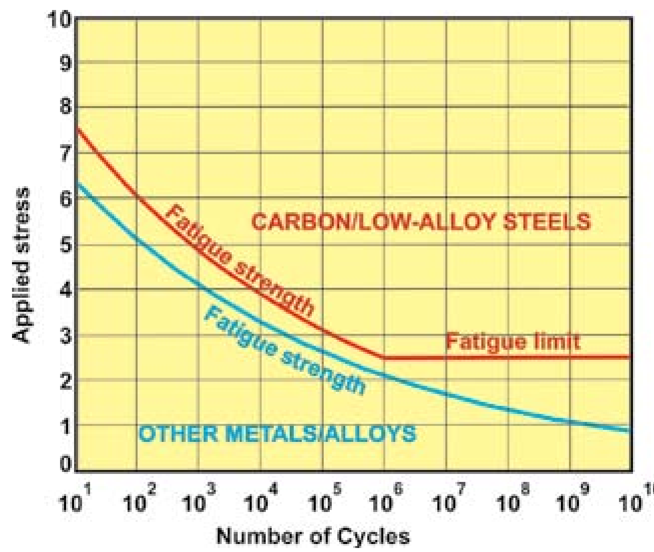

Fig.1 Hypothetical fatigue curves.

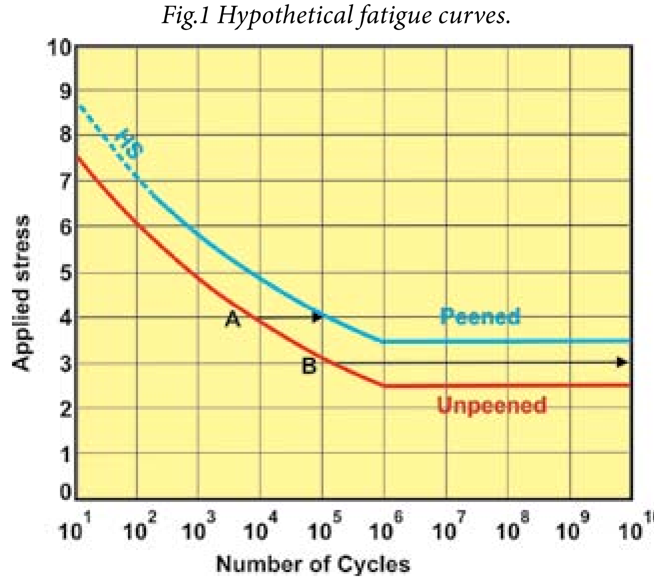

Fig.2 Stylized effect of peening on fatigue curves for carbon/low-alloy steels

stress that is applied. If, for example, the applied stress was **2** (on the arbitrary scale of fig.1) then the peenability is zero! In that situation carbon/low-alloy steels components already have an infinite life - without being shot peened. With higher levels of applied stress then one or other of two benefits can be achieved by shot peening. For a stress level of **4** peening could increase the fatigue life from approximately 10^4 cycles to 10^5 cycles – see **A** in fig.2. Alternatively, for a stress level of **3**, peening could increase the fatigue life from 10^5 cycles to infinity. It should be noted that these values are purely illustrative of the possible effects for a particular component.

Generally speaking, peening increases the fatigue strength and fatigue limit for carbon/low-alloy steel components. This is due to a combination of surface work-hardening and compressive surface residual stress. The region marked as **HS** in fig.2 indicates, however, the potentially-dangerous high-stress region. It has been shown that with very high applied cyclic stresses plastic deformation can occur which changes the surface compressive residual stress into tensile residual stress. That would correspond to negative peenability.

Austenitic steels do not normally show a fatigue limit. The beneficial effect of peening on fatigue, for these materials, is illustrated by fig.3.

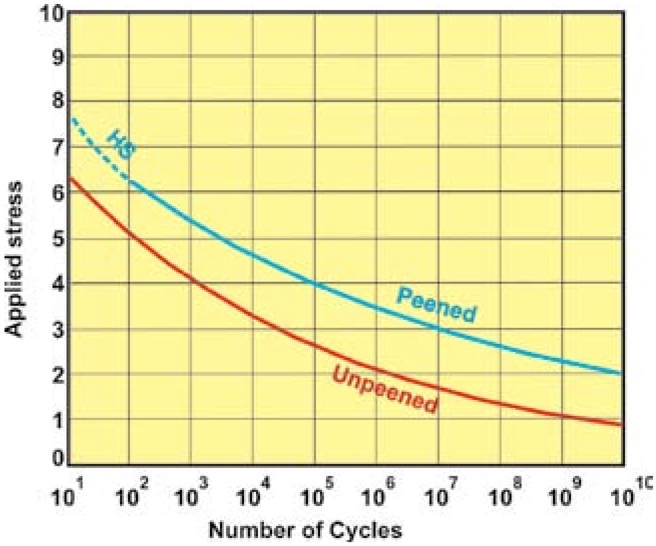

Fig.3 Stylized effect of peening on fatigue curves for austenitic steels.

The usefulness of shot peening for weight saving is a debatable subject. There is very little published information dedicated to the topic. That does not mean that shot peening is not an effective weight-saver. If any given component is 'over-engineered', then it will have an infinite fatigue life. If, however, the service fatigue life is shorter than is required, then shot peening can extend the life to required levels. The alternative would be to increase the dimensions of the component in order to reduce the stress levels – meaning that the weight would have to be increased. Hence we have a situation of indirect weight reduction. With 'cutting-edge' situations, such as Formula 1 racing cars, every tiny amount of weight saving is important. Designers therefore require certain components to be shot-peened, knowing that they would fail in service without the application of shot peening. That corresponds to direct weight saving by shot peening.

COMPRESSIVE SURFACE RESIDUAL STRESS AND WORK-HARDENING

Compressive surface residual stress and work-hardening are of primary importance in gaging peenability. It follows that these two factors relate to peenability. Residual stress and applied stress are additive. Hence compressive surface stress offsets applied surface tensile stress. Work-hardening of the component's surface also improves its fatigue resistance.

In order to be able to generate useful compressive surface residual stress and work-hardening, the component material being peened must have significant ductility. Each indentation stretches the surface material by about 40% - and each point may suffer dozens of indentations. Tensile tests show that different steels elongate within a range of about 10 to 40%. The stressing system in a tensile test is, however, very different from that of a shot impact. That is why localized peen stretching by several hundred percent can occur without fracture. All steels work-harden as a consequence of the localized plastic stretching that occurs on peening. The level of residual compressive stress that can be retained (without self-relief) is a large fraction of the yield strength of the work-hardened surface layer. Peenability of steels is therefore proportional to that of yield strength. This effect is schematically illustrated by fig.4. Steel B has double the yield strength of steel A, allowing doubled residual stress levels. This is not always completely advantageous. The compressed surface layer has a compressive force associated with it. This must be balanced by a sub-surface tensile force – extending deep into the component (as indicated by the red arrow). For steel B the maximum tensile stress in this balancing region is

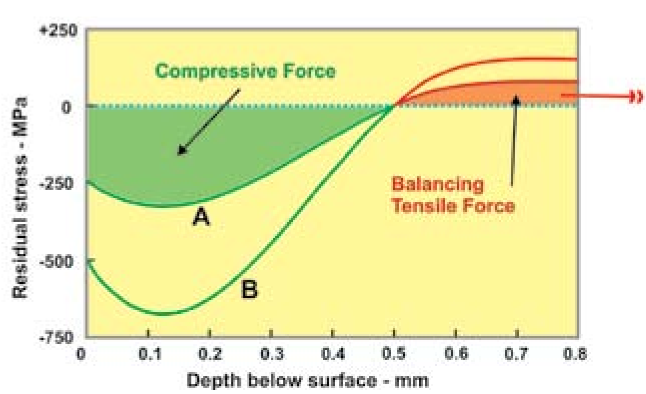

Fig.4. Effect of yield strength on residual stress profiles induced by shot peening.

double that for steel A. This may give rise to sub-surface crack initiation.

Austenitic steels generally work-harden at a faster rate than do ferritic/martensitic steels. Both types of steels reach a maximum level of work-hardening with increase of coverage. This maximum coverage is smaller for austenitic steels because of the greater rate of work-hardening.

In order to retain residual stresses and work-hardening, the component material must be temperature resistant. Steels have substantial temperature resistance when compared with lower melting-point materials such as aluminum. Hence they have greater peenability. Strength combined with ductility equates to toughness of the component's material.

Work-hardening increases the amount of energy stored in the peened metal. The greater the amount of stored energy the greater is the instability of the work-hardened layer. It is a fundamental law of thermodynamics that every system tries to reduce its stored energy level. This tendency is accelerated by increases of temperature. Specifications indicate the maximum temperature at which shot-peened components should be used. Fig.5 illustrates different curve shapes for property decrease with increasing temperature. Type A is characteristic of ferritic steels which show an initial small drop in property value. This is followed by accelerating property reduction, and eventually complete removal of peening enhancement – when the steel either recrystallizes or transforms to austenite. Type B is characteristic of austenitic steels where phase transformation does not occur – but recrystallization of the work-hardened surface will occur at a high enough temperature.

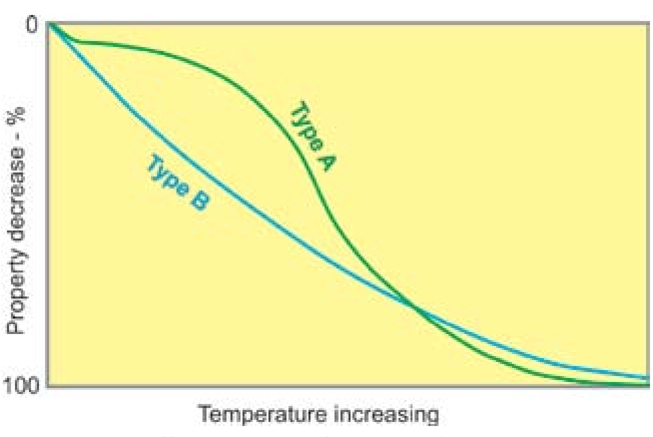

Fig.5. Different shapes of property decrease curve.

PHASE TRANSFORMATIONS DURING SHOT PEENING

Phase transformations can occur during shot peening of steels. Two important examples are those of carburized steels and high-manganese steels.

Phase transformation for carburized steels

Carburization involves diffusing carbon into the surface layer of a component followed by quenching and tempering. This produces a surface layer that is much harder, but less tough, than the core. The quenching process itself introduces a surface layer of compressive residual stress. Shot peening can be applied to further enhance the surface properties. The quenched-and-tempered surface layer consists mainly of martensite/bainite – both of which are based on the body-centered cubic structure of ferrite. An important additional constituent is known as "retained austenite".

When a carburized component is quenched, the surface layer transforms to martensite – to a greater or lesser extent – as illustrated in fig.6. Complete transformation, indicated by A-B, is almost impossible to achieve. Normally there is a significant percentage of retained austenite in the carburized case material, following the path A-C. The retained austenite can be as high as about 30%.

Any form of cold-working introduces energy into steel. It is this energy that retained austenite uses to help it to transform to the more energy-stable phase – martensite.

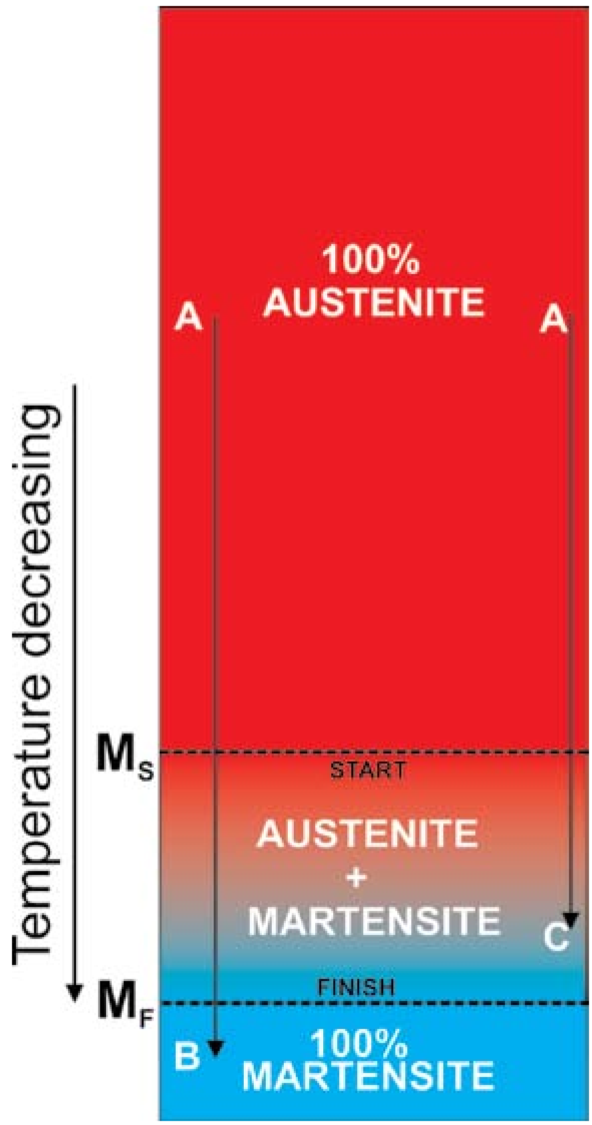

Fig.6. Transformation of austenite on quenching.

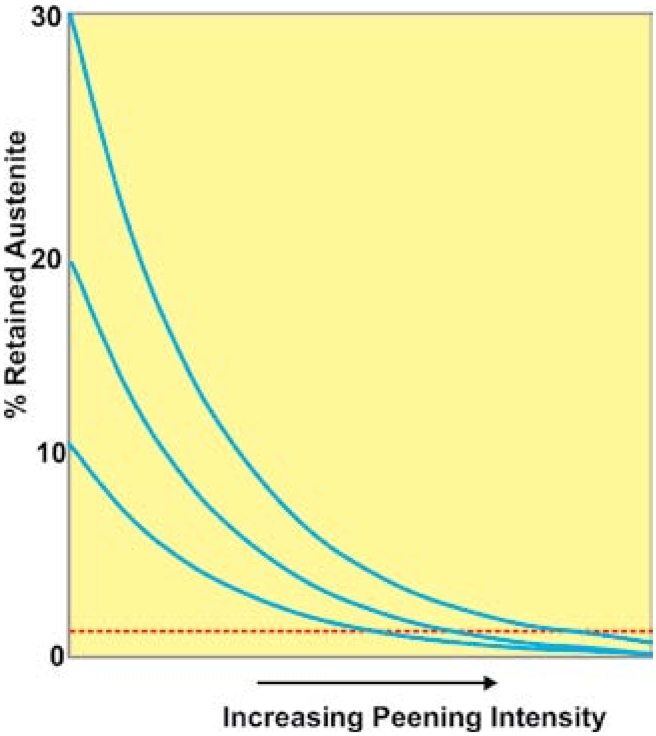

Fig.7. Effect of shot peening intensity on retained austenite content.

The greater the amount of cold-working the greater is the reduction in retained austenite content. This effect is illustrated schematically by fig.7. Steels with as-quenched retained austenite contents of 10, 20 and 30% are shown to have their content reduced to about 1% with increasing shot peening intensity. Retained austenite reduction becomes increasingly difficult – hence the curve shape is roughly exponential. Reduction below the 1% (shown as a dashed red line) would be almost impossible using plastic deformation.

As with all shot peening "more is better" is an illusion. There is an optimum amount of peening, for each steel and component, that maximizes service performance. Maximum performance generally occurs with retained austenite content in the range 1 to 4%.

Phase transformation for austenitic steels

A minority of shot-peened components are made from austenitic steel, which is non-magnetic. Austenitic steels have a face-centered-cubic crystal structure, f.c.c. – as opposed to the normal ferritic/bainitic/tempered-martensite structures. Austenite is promoted by alloying elements such as nickel and manganese and opposed by elements such as chromium, silicon and molybdenum. The most familiar austenitic steels, stainless steels, are based on iron, nickel and chromium. Nickel promotes the non-magnetic f.c.c. structure and chromium imparts corrosion resistance.

A key feature of austenitic steels is that they have a tendency to transform to martensite when subjected to severe plastic deformation. This is the same phenomenon as occurs with the retained austenite of carburized steels. Two common stainless steels, AISI 304 and 316 have been studied in detail (Kirk and Payne, ICSP7). This showed that peening 304 with a variety of intensities always gave approximately 50% of martensite, remainder austenite. No martensite formation was found for the 316 grade – which has 14% of austenite-stabilizing nickel as opposed to only 10.5% in 304. Peened 304 components therefore have a surface layer mixture of magnetic martensite and non-magnetic austenite. Such a mixture destroys a great deal of the corrosion resistance. 'Lean' stainless steels (lean in terms of relatively-low nickel content) can be said to have low peenability.

Less familiar austenitic steels are those termed "high-manganese". The first high-manganese steel was discovered in 1882 by the English metallurgist Sir Robert Hadfield, FRS, First Baronet of Sheffield. Manganese occurs in iron ores used for steelmaking. Some such ores have very high manganese content so that it becomes a very cheap alloying element. Most steels contain about 1% of manganese. As the manganese content is increased, steels become brittle so that at 5% manganese the steel can be pulverized by a hammer blow. This is the reason for manganese contents being normally kept lower than 1.5%. There is an apocryphal story (told to the author as a child by a studious steelmaker) that a trial batch of steel being made for Hadfield was accidently given three 4% additions of manganese separately by three different people. The resulting cast was tested by Hadfield and found to have remarkable properties - though he did not then know why. Production batches were termed "Hadfield High Manganese Steel". The Brodie helmet, introduced in 1915 in World War 1, was a classic application of this steel's properties – it could withstand a bullet fired at a distance of three meters. This helmet is still being manufactured today. Manganese steels are commonly used with manganese content in the range of 11 to 17%. Common applications are for railway crossing points and ore-crusher teeth.

The mechanism of deformation hardening of manganese steels varies with the particular steel and with its heat treatment. Mechanisms are still being investigated and include martensite formation, conventional work-hardening (by dislocation multiplication), twin formation and C-Mn atom pairings in the core of dislocations – very complicated!

The unique property of high-manganese steel components is that a deformation-hardened surface layer will regenerate itself if subjected to wear. This indicates potential applications for shot peening components – particularly surface-hardened steel shot.

Surface Hardening of Steel Shot

Carburized steel shot has been introduced because it combines a hard, wear-resistant, surface layer with a tough core. On quenching, the high carbon surface layer transforms

Fig.8. Carburized shot particle, before and after wear removal of hard case.

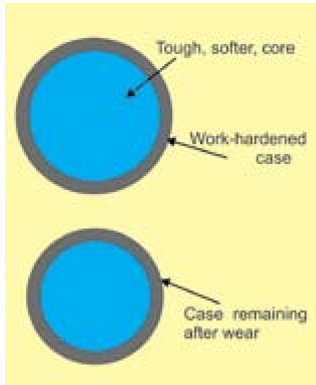

Fig.9. High-manganese shot particle before and after substantial wear.

to martensite – with some retained austenite. Subsequent tempering reduces the brittleness of the surface layer whilst maintaining wear resistance. An alternate approach could be even more effective – using high-manganese steel for shot manufacture.

Figs. 8 and 9 (Page 30) give a schematic comparison of the two approaches (carburized versus high-manganese). Both cast and cut-wire shot can be carburized. Cast high-manganese shot can be surface hardened by plastic deformation – in a similar way to that used for rounding cut-wire shot. With carburized steel shot the hardened case is progressively worn away in use – eventually removing the case altogether, see fig.8.. With high-manganese steel shot the wearing mechanism (high speed impact with components) constantly regenerates surface work-hardening, see fig.9.

DISCUSSION AND CONCLUSIONS

In order to benefit from shot peening, steel components must have certain properties. These include:

Ability to be work-hardened,

Retention of induced compressive residual stresses,

Some degree of under-engineering and

Favorable phase transformations.

The first two properties are well-established. Under-engineering means that the component would, in the absence of shot peening, fail prematurely – particularly in fatigue situations. This leads to the general concept of shot peening being a weight-saving technique. Favorable phase transformations are particularly significant for steel components that contain retained austenite.

Some emphasis has been placed on the possible uses of high-manganese steels. These, in the author's opinion, have not yet received sufficient attention as useful shot-peened products. A great deal of research is currently being carried out to try and solve the mystery of why they develop such substantial, durable, surface hardening.

Joe McGreal Promoted to Vice President of Sales and Marketing

Joe McGreal of Ervin Industries, Inc. has been promoted to Vice President of Sales and Marketing. Mr. McGreal was the General Sales Manager for Ervin and has been with the company for the past 14 years.

Ervin Industries, established in 1920, is a privately held company based in Ann Arbor, Michigan.

Leaders Recognized at Nadcap Meeting

At the October 2013 Nadcap meeting in Pittsburgh, Pennsylvania, the following individuals were acknowledged for their outstanding contribution to quality through participation in Nadcap.

In recognition of service as Chairperson of the Measurement & Inspection (M&I) Task Group: **Phil Bamforth - Rolls-Royce**

In recognition of service as Vice Chairperson of the Aerospace Quality Systems (AQS) Task Group: **Harold Finch - Spirit AeroSystems**

For work on development of Non Metallic Materials Manufacturing fiber and core checklist: **Laura Benedetti - SAFRAN**

In recognition of long-term Non-Destructive Testing (NDT) Task Group support: **David Vaughn - Spirit AeroSystems**

For work on translation of the Conventional Machining checklist into Spanish: **Mario Enriquez, Ken Abram, and the Honeywell Chihuahua Conventional Machining team**

For outstanding support of Sealants Task Group, NMC, and Supplier Support Committee (SSC): **Suzanna DeMoss - 3M**

For contribution and work on Nadcap Management Council: **Amie Emerson - Spirit AeroSystems and Peter Krutoholow - Sikorsky Aircraft**

Joe Pinto, PRI's Executive Vice President & Chief Operating Officer explained "It is only with the support and dedication of aerospace industry leaders that Nadcap can continue to meet their needs in a collaborative, open way. The number of awards given out for so many different reasons to different companies underlines the commitment of the aerospace industry to supply chain quality through Nadcap. I would like to add my personal thanks and congratulations to all award recipients for their well-deserved recognition by their peers."