Review of Shot Peened Surface Properties

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INTRODUCTION

Shot peening is applied to components in order to induce improvements in their service performance. These improvements depend, to a large extent, on the properties of the shot-peened surface. Peening induces four major effects at the surface of components:

• Hardening
• Structural changes
• Compressive residual stress
• Surface dimpling

Fig.1 is a schematic representation of the effects.

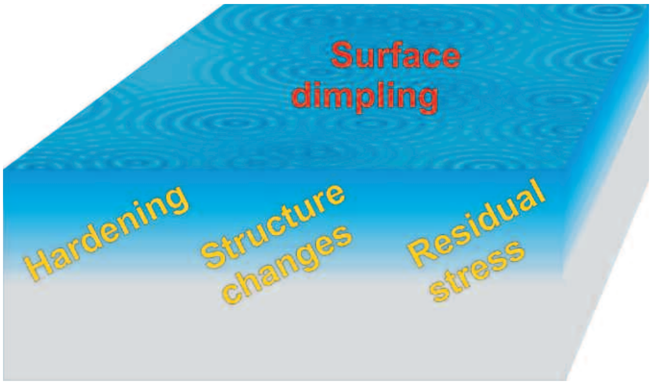

Fig.1. Major surface effects of shot peening.

Peening is, essentially, a surface hardening process that operates by plastic deformation of the component's surface. It follows that the component material must be capable of being plastically-deformed. The deformed surface layer has been called a "magic skin" because it generally imparts remarkable performance enhancement.

The most important service performance property is fatigue resistance – which is influenced by all four surface layer effects.

Fig.2 illustrates the effect of shot peening severity on a service performance property – such as fatigue resistance. Improvement reaches a maximum and then falls as excessive peening is applied. Property improvement does, however, depend upon post-peening factors such as loading, temperature and plastic strain.

Shot peening is a very 'forgiving' process, in the sense that even crude applications generally induce substantial property improvement. Optimal property improvement, however, requires a careful consideration of the peening severity that should be applied to particular components.

This article is a review of the major factors affecting the properties of shot-peened surfaces.

IMPACTING SHOT EFFECTS

Each shot particle impacting a component's surface has a kinetic energy, $\frac{1}{2}mv^2$. Approximately half of this energy is transferred to the surface. **Ninety percent of that transferred energy is converted into heat and 10% into the stored energy of cold work.** It follows that we can think of the effect as that of a miniature thermal bomb. The plastic deformation creating a dimple occurs in a few millionths' of a second. Heat is generated around the dimple simultaneously – being caused by the plastic deformation. This adiabatic heating is absorbed relatively slowly by the surrounding material, which acts as a heat sink. Fig.3 is an 'artist's impression' of the heat generation distribution.

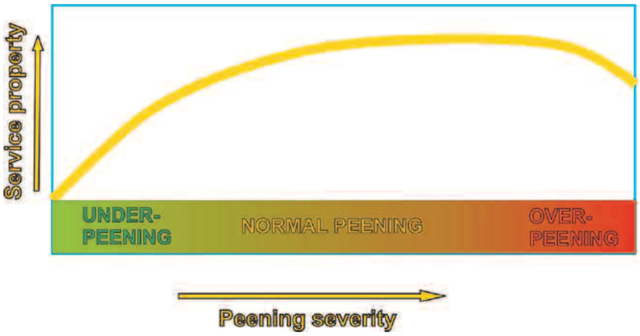

Fig.2. Schematic representation of service property change with peening severity.

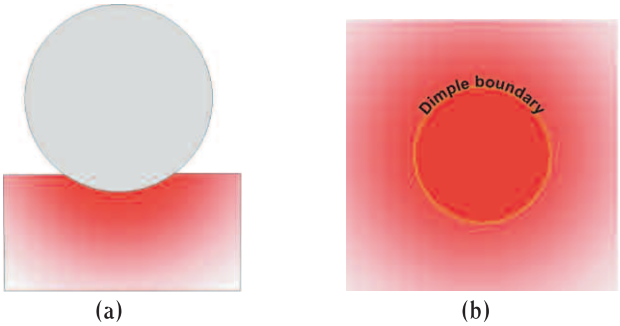

Fig.3. Heat generated just as impact is completed, (a) sectional and (b) plan view.

The maximum temperature in the heated zone will be at the surface and will be affected by multiple impacts which impart additive heat inputs. It is suggested that the temperature rise very near to the peened surface will be sufficient to cause a significant degree of stress-relief.

WORK-HARDENING and WORK-SOFTENING

Our normal concept of work-hardening is in the context of simple low-strain situations. With standard tensile testing (where deformation is slow and uniform) the resistance to further deformation increases, albeit at a decreasing rate, with increase of strain. This is the standard text-book concept which is explained in terms of increased dislocation content and dislocation movement restrictions. Yield-strength and ultimate tensile strength can then be equated to hardness.

Peening imposes enormous amounts of plastic strain (rapidly and heterogeneously) on the surface layers of component material. With nominal '100% coverage' a large fraction of the surface will have been impacted at least ten times. Each impact corresponds to plastic deformation varying around 100% – equivalent to a plastic strain of 1.0. We therefore have a high-strain situation which requires a different concept of work-

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hardening (from that associated with tensile testing). Fig.4 illustrates the general features of hardness change with large plastic strain.

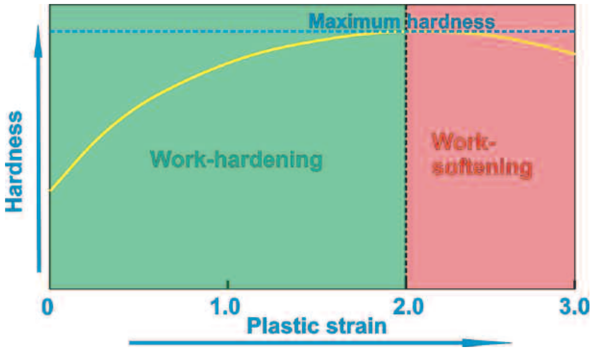

Fig.4 Effect of large plastic strain on hardness.

A maximum hardness is achieved at strains in the region of 2.0. As strain increases, more and more dislocations are being generated but, at the same time, more and more are being annihilated (for example by forcing positive and negative dislocations together). At a certain strain the rate of dislocation generation equals the rate of annihilation, so that we have reached maximum hardness. Larger strains will induce a degree of work-softening.

During peening it is suggested that the extreme surface hardness will reach its maximum value, even before full coverage is achieved, see fig.5.

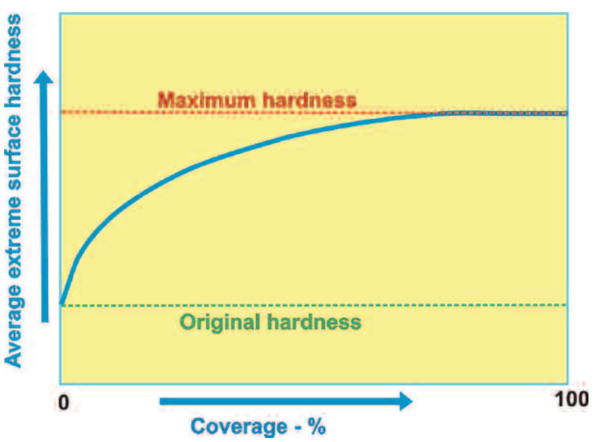

Fig.5. Effect of coverage on extreme surface hardness.

Throughout peening, work-hardening develops to greater depths. An increase of peening severity would not be predicted to increase the maximum surface hardness. It would, however, be predicted to increase the depth of the hardening effect - for full coverage situations. Fig.6 illustrates these predictions.

The massive localised strains, together with the heat generated by impacting shot particles, can induce changes/modifications to the major phases that are present. These changes generally have the effect of lowering the hardness. Peening then involves two mechanisms that affect hardness – peen-hardening and peen-softening. The combination of these two factors is modelled in fig.7. With this model it is assumed that peen-softening is capable of reducing the original material hardness to some minimum value. Superimposed peen-hardening gives a

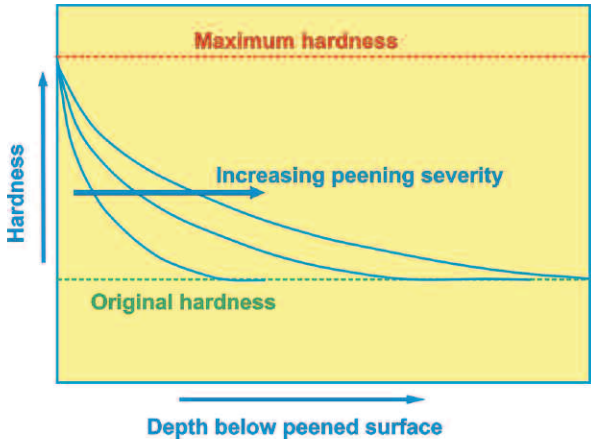

Fig.6. Effect of peening severity on hardness profile.

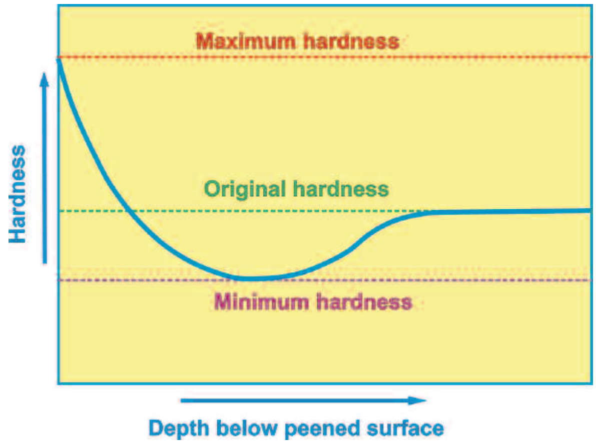

Fig.7. Combination of peen-hardening and peen-softening.

hardness profile having a minimum well below the surface. Lower strains below that depth mean that peen-softening becomes less effective.

Some method of hardness measurement is needed in order to quantify hardness changes for specific situations. The commonest methods employed are micro-hardness and x-ray diffraction line breadth.

One exception to softening by peen-induced phase changes is when retained austenite undergoes transformation. Carburised components normally have substantial retained austenite content in the carburised and quenched surface. Peening transforms most of this relatively-soft phase into much harder martensite.

STRUCTURAL CHANGES

Most metallic engineering components have a relatively-ductile matrix embedded with a variety of hard, relatively-brittle, strengthening, phases. Plastic strain on peening is then concentrated in the matrix. Some 90% of the energy absorbed from impacting shot particles is converted into heat energy. The remaining 10% is largely used to produce a vast increase in the dislocation population. This increase is from about 10^6 to about 10^{10} (ten billion) dislocation lines per square millimetre. Such an increase and such numbers are difficult to visualise. On a scale of a square micrometer the increase is by a factor of 1 to 10,000. This scale is used for fig.8 where in (a) there is just one dislocation (represented as a single dot) whereas in (b) there are 10,000.

The dislocation distribution represented in fig.8(b) is extremely non-uniform. High-strain deformation has generated

Continued on page 28

Continued from page 26

a sub-grain structure. This is a characteristic feature of heavily-worked metals. Peening changes the structure for each crystal from one of relative perfection to one where we have a 'mashed-up' structure - regions of intense dislocation content (sub-grain boundaries) surrounding regions of merely high dislocation content (sub-grains). When plastic strain has induced maximum hardening the sub-grain size has reached its minimum. The dislocation density in the sub-grain boundaries is then so high that they are semi-amorphous. Further plastic strain does not thereafter increase the dislocation content. We have a situation, because peening is an intermittent process, where impact-generated heat is softening some regions and hardening is occurring in other regions. These mechanisms balance to give a maximum average hardness.

A classic exception (mentioned previously) to the general soft matrix/hard phase mixture is that of carburised components. These generally contain a small proportion of a soft phase, retained austenite, embedded in a hard, martensitic, matrix. Martensite is too brittle to be able to withstand substantial plastic deformation. The major structural change that then occurs is that plastic deformation of the retained austenite phase transforms most of it into martensite.

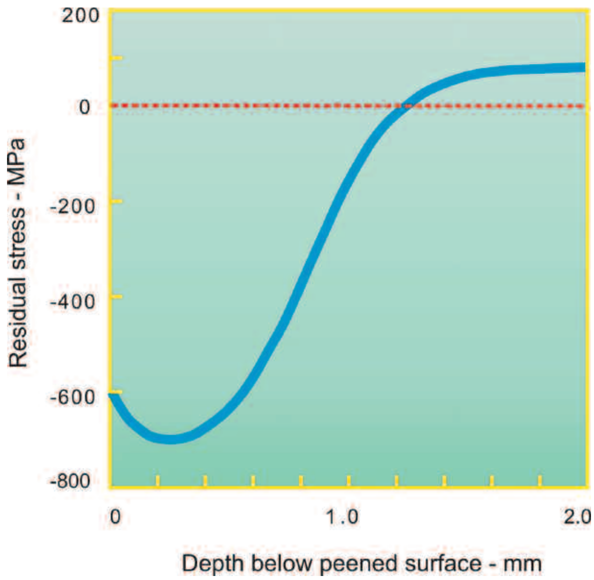

Fig.9. Typical residual stress profile induced by peening.

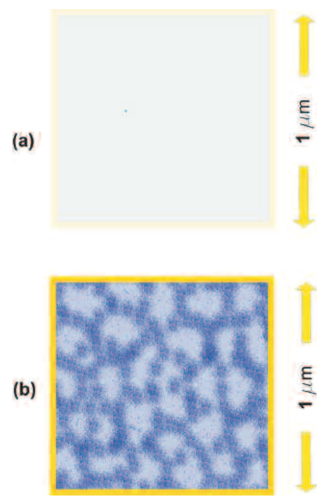

Fig.8. Model of dislocation distributions in (a) un-peened and (b) peened material.

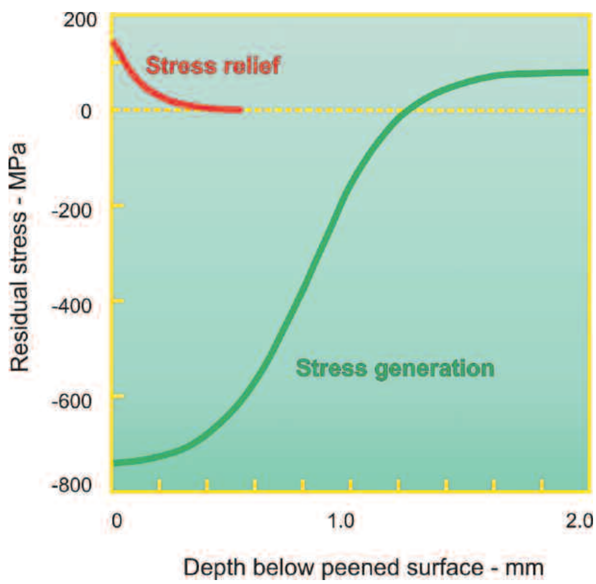

Fig.10. Constituent factors which combine to give the profile shape shown in fig.9.

INDUCED COMPRESSIVE RESIDUAL STRESS

Shot peening induces a characteristic residual stress profile with extreme surface compressive stress at about 50% of the as-deformed yield strength, increasing with depth to about 60% of that yield strength before giving way to balancing tensile stress. Increased peening severity increases the depth at which the maximum compressive stress occurs. Fig.9 shows a typical residual stress profile. This general shape is well-established and varies only in terms of specific values.

It is proposed that the 'general shape' can be explained by the combined action of two factors. These are stress generation and stress relief. Fig.10 illustrates their separate effects.

The actual equations used in fig.10 were 200*exp(-1.5*x) for stress relief and -750 + 1250/ (1.5*exp(5-x)) for stress generation. Fig.9 used exactly the same equations – added together to give: Residual stress = 200*exp(-1.5*x) -750 + 1250/ (1.5*exp(5-x)). The form of the stress relief curve is **exponential** – which is reasonable since 'recovery' mechanisms are involved. The form of the stress generation curve is **sigmoidal** – which accommodates the duality of increases in both lateral strain and yield strength as the surface is approached. The relative magnitude of the stress-relief factor would be expected to increase with coverage and peening severity – both giving increases in surface instability, work-softening and induced heating.

SURFACE DIMPLING

Shot peening induces a surface texture due to the superposition of indentations. Individual indentations have a 'favourable' profile. That is because the profile is made up of smooth curves – as illustrated in fig.11 (page 30). The stress required to make metal flow through a 90° angle is infinitely high. It is therefore impossible for dimples to have sharp-edged ridges.

A peened surface consists of over-lapping dimples, all of which have smooth-profile ridges. Fig.12 illustrates the effect of multiple indentations on surface smoothness. This is a profilometer trace along an Almen strip that has been peened to its

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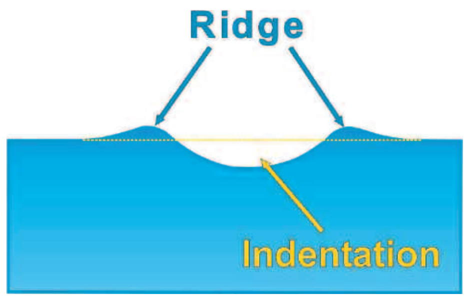

Fig.11. Profile of an individual indentation.

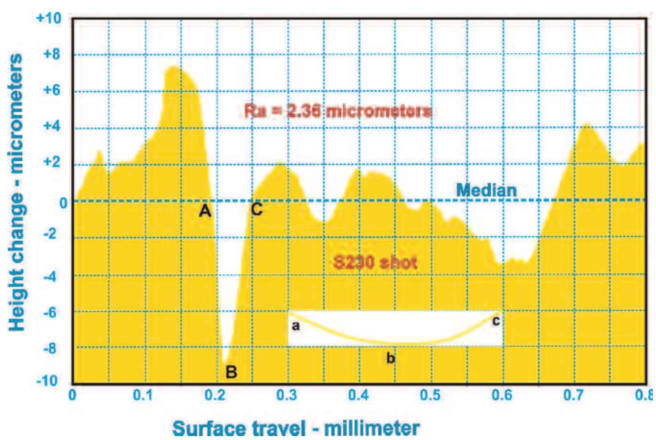

Fig.12. Surface profile of Almen strip peened to saturation point using S230 shot.

saturation point using S230 shot. Apparent roughness is an illusion because the vertical scale of distance is 25 times that of the horizontal scale. The illusion is removed in the inset **abc** which is an equal-scale version of the indentation **ABC**.

Roughness can be quantified by deriving the **Ra** value which, for peened surfaces, is approximately half of the average peak height above the median. Ra values are directly related to the size of shot used.

One considerable advantage of peened surfaces is that they can induce an element of hydrodynamic lubrication between moving parts. Essentially, oil dragged into the dimples generates a load-carrying pressure. This, in turn, reduces surface wear. Fig.13 models the load-carrying pressure effect.

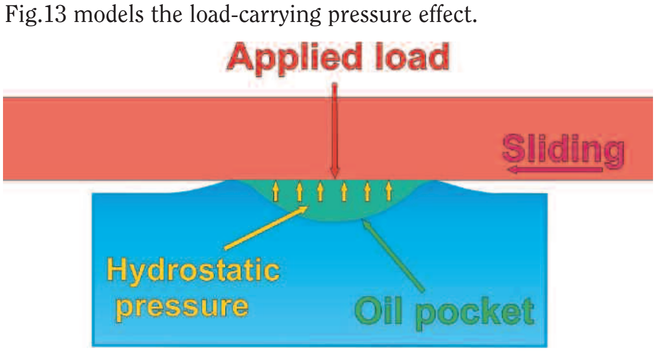

Fig.13. Model of hydrodynamic lubrication in peening dimple.

STABILITY OF COLD-WORKED SURFACES

It is an inescapable law of physics that all systems try to revert to their lowest energy state. Reversion is accelerated by an increase of temperature. Various specifications, e.g. AMS 2430, indicate maximum post-peening temperatures appropriate to individual materials.

The several properties that have been increased by shot peening are all reduced after peening, to a greater or lesser extent, depending on the temperature. The reduction that normally occurs (in peened components) is achieved by crystallographic processes collectively called “recovery”. Recovery rates reduce exponentially with time and increase with temperature. This exponential effect is illustrated in fig.14. The “unacceptable operating temperature” shown would be equivalent to a stress-relieving temperature.

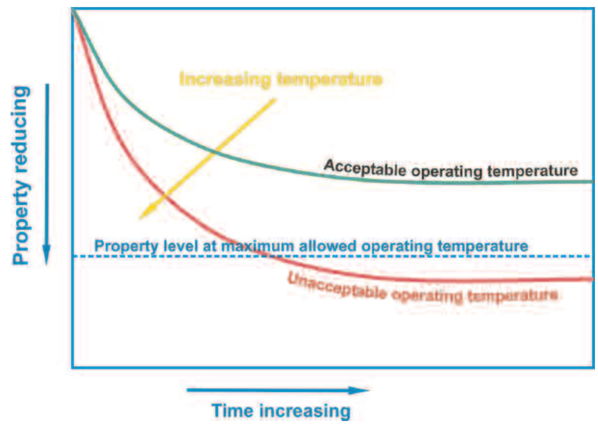

Fig.14. Property reduction caused by recovery.

DISCUSSION AND CONCLUSIONS

This account has, of necessity, involved broad generalisations about the properties of shot peened surfaces. That is because component materials vary enormously in terms of their physical properties. Nevertheless it is felt that the general features described here are reasonable. The most important of these are that:

1) Multiple impacting invokes very high plastic strains with a maximum surface hardness being a characteristic feature.
2) The very high strain rates associated with dimple formation induce adiabatic heating that contributes to a degree of recovery of extreme-surface properties.
3) Heavily-deformed peened surfaces are thermodynamically unstable – requiring careful control of post-peening service temperatures.
4) A combination of strain-softening and surface temperature rise produces a reduction of the extreme surface compressive residual stress level.
5) Dimpling of peened surfaces can have a useful influence on high-load lubrication regimes.

There is a temptation to apply the principle of “more is better” in commercial shot peening. This is contrary to evolving knowledge that indicates that optimum service properties are developed by applying coverage that is nearer to the nominal 100% than, say, 300%. ●

Dr. David Kirk, our “Shot Peening Academic”, is a regular contributor to The Shot Peener. Since his retirement, Dr. Kirk has been an Honorary Research Fellow at Coventry University, U.K. and is now a member of their Faculty of Engineering and Computing. We greatly appreciate his contribution to our publication.