RESIDUAL STRESSES IN SHOT PEENED COMPONENTS

by

David Kirk

INTRODUCTION

Shot peening of components produces a 'magic skin' containing compressive residual macro-stress. This skin has a thickness that is largely determined by the size of the shot particles that have been used. The level of compressive residual stress in the skin is a large fraction of the yield strength of the as-peened surface material. Residual and applied stresses superimpose themselves, so that compressive surface residual stresses offset tensile applied surface stresses. It is that lowering of net surface stress that improves the service performance of shot peened components.

Residual stresses are produced whenever inhomogeneous plastic deformation is applied to a component. Shot peening is a prime example of inhomogeneous plastic deformation. Peening involves tensile plastic deformation of a surface layer - produced as the sum of numerous indentation expansions. Compressive residual stresses are generated at the surface because of this tensile deformation. Peening can impose huge amounts of deformation without cracking because of the hydrostatic compression that is involved. Gold has a tensile ductility of 40% but can be hammered until it is almost transparent. The imposed stored energy is so great, however, that gold leaf (normal M.Pt. 1064^{0}C) will melt in one's hand.

ORIGIN OF SURFACE COMPRESSIVE RESIDUAL STRESS IN PEENED COMPONENTS

The 'Law of Residual Stresses' states that:

The sign (+ or -) of the residual stress is opposite to the sign (+ or -) of the non-uniform plastic deformation that caused the stress.

N.B. **"+"** corresponds to tensile stress and deformation whereas **"-"** corresponds to compressive stress or deformation. Peening introduces surface **tensile** plastic strain so that the surface must be left in **compressive** residual elastic stress.

Fig.1 shows a simplified, macroscopic, representation of the logic behind the development of residual stress profiles by shot peening. The upper and lower surfaces of a rectangular block have been equally peened. If the peened layers were free to move relative to the underlying material then we would have generated slightly larger surface 'slices' – as shown in (a). The layers cannot, however, move independently. Restraint by the underlying material pushes the surfaces inwards, generating compressive residual stress in the two surface 'slices'. Each surface layer has a corresponding compressive force, F, which requires a balancing tensile force, 2F, within the core – as shown in (b).

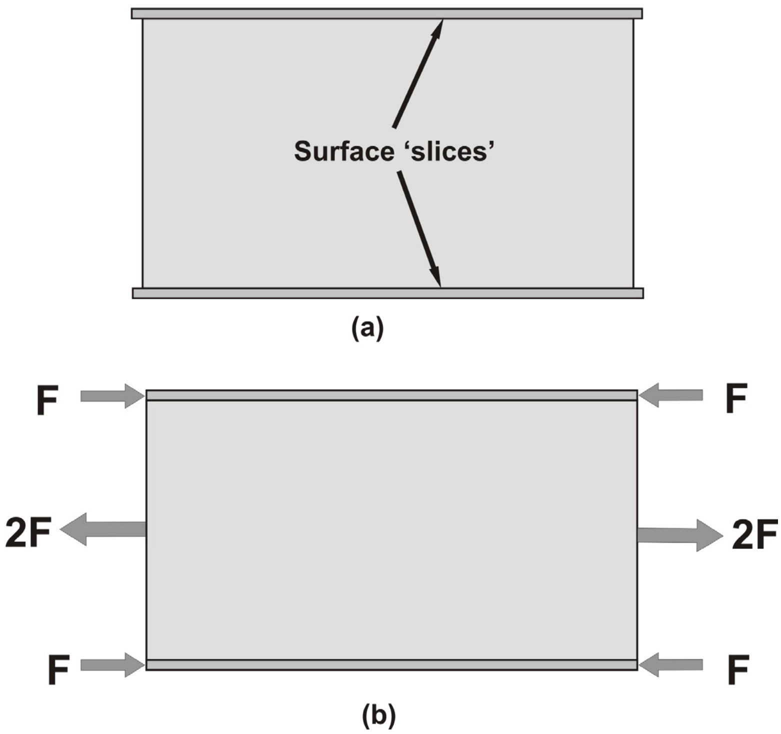

Fig.1 Model of forces constraining the surface tensile plastic extension imposed by peening.

The attempted expansion of the peened surfaces is the sum of the numerous indentations made by the impacting shot particles. Each indentation requires that some surface material be pushed away from its original position, see fig.2. The indent material undergoes a net tensile movement parallel to the component's surface and away from the indent's center.

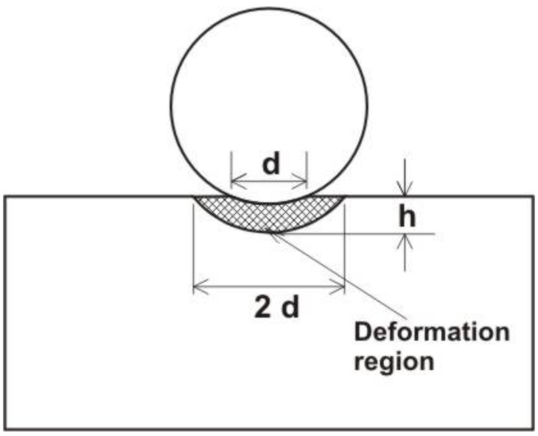

Fig.2 Model of indentation produced by shot particle.

During each indentation we have the equivalent of a classic loading and unloading cycle - creating a plastically-deformed region containing residual compressive elastic strain. As the impacting particle strikes the component's surface the contact stress is initially zero, see fig.3. The stress thereafter increases elastically until the yield strength is reached – point A in fig.3. The surface material subsequently deforms plastically until the shot particle starts to rebound – point B. During rebound the surface material relaxes elastically until it reaches zero – point C. The difference between the original and final strains is the residual strain – which when multiplied by elastic modulus gives the level of localized compressive residual stress. That localized residual stress varies with distance from the center of each indentation. The variation must be smooth because abrupt changes of stress level are physically impossible.

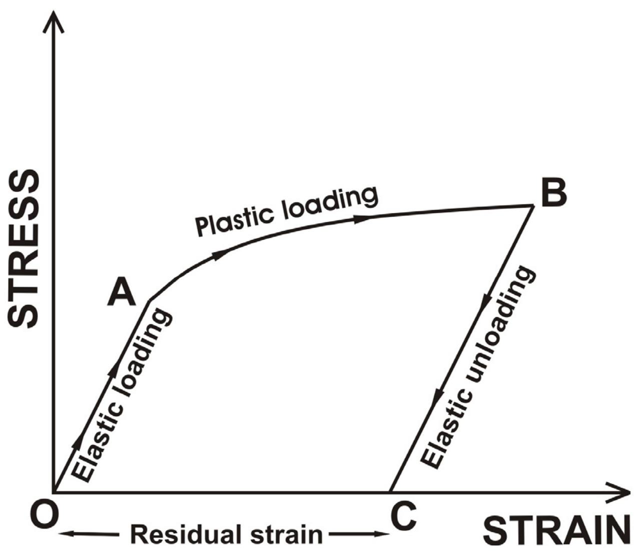

Fig.3 Simplified stress-strain diagram for a single peening indentation.

Fig.4 shows a simplified representation of the logic behind the residual stresses associated with an individual peening indentation. The deformation region of fig.2 is simplified to become a disk. We imagine that the disk has been lifted out from the surface, plastically stretched, and then inserted back into the surface. Compressive force parallel to the surface is required in order to compress the extended disk so that it can be fitted. Once fitted into the surface the disk of material presses against the sides at A and B. That pressure causes the disk to expand slightly - to the position showed by the dotted lines – but is still elastically compressed. This expansion means that compressive strains are also generated to the left of A and to the right of B. The material immediately under the disk, between C and D, has to stretch slightly - setting up a balancing tensile force in that region.

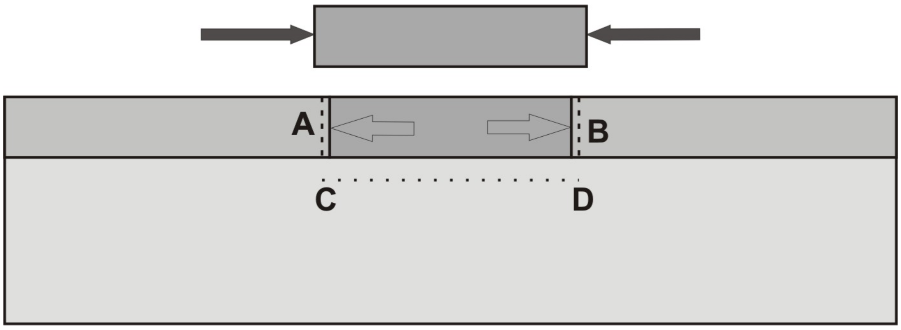

Fig.4 Model of forces developed by an individual peening indentation.

Important questions are “How does the compressive stress vary in the surface region around an individual indentation?” and “How does the stress field from one indentation interact with that from a neighboring indentation?” It is generally accepted that a zone of surface compressive residual stress surrounds each indentation and we do know that stress must vary continuously (rather than abruptly). Fig.5 shows one way of representing the surface stress fields, surrounding an isolated indentation at A and around groups of indentations, at B.

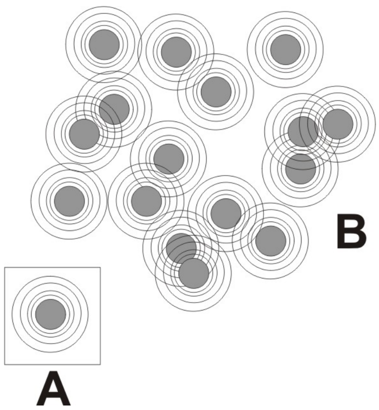

Fig.5 Compressively-stressed regions surrounding peening indents.

It can be assumed that the compressive stress at and parallel to the surface has a ‘normal’ distribution about the indentation center – as shown in fig.6 using arbitrary units for stress and distance. For fig.6 it is further assumed that the ‘spread’ (standard deviation) for the residual stress is equal to the radius of the indentation.

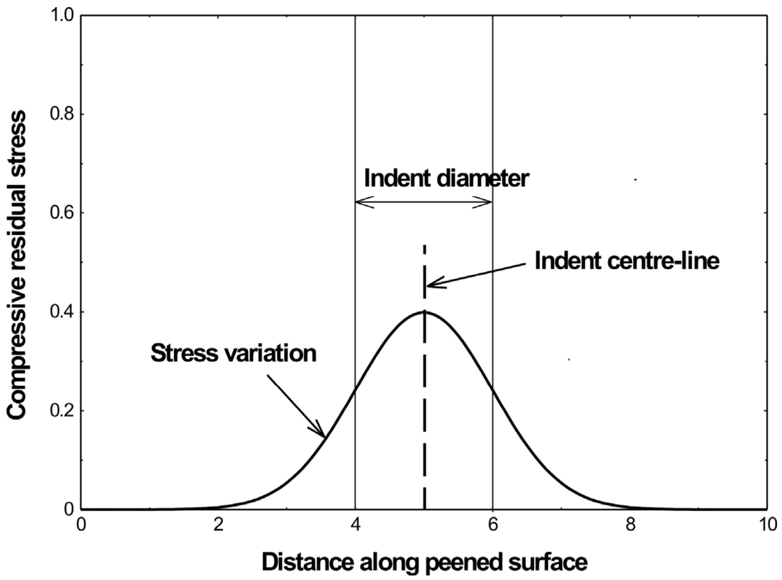

Fig.6 Assumed surface residual distribution around a single indentation.

The equation for a normal distribution is:

$$y = \exp(-(x - \mu)^2/2\sigma^2)/\sqrt{(2\pi\sigma)} \quad (1)$$

where: y can correspond to residual stress, x to distance along the peened surface, μ to position of the indent center and σ to the standard deviation (spread).

Substituting $\mu = 5$ and $\sigma = 1$ into equation (1) for an isolated indentation gives the shape shown in fig.6.

The compressive residual stress from one indentation will add significantly to that of a neighboring indentation, provided that they are close enough. Fig.7 shows how stress addition varies for different indentation separations, where each indentation is assumed to have the same diameter, D. The curves are generated by substituting two different values for μ into equation (1) and adding the result. Note that the separation of 1.5D means that a distance equal to the radius separates two indentations. A separation of 3D is required before there is no significant overlap of compressive stress fields.

With the very high coverages associated with most practical peening there will be multiple overlapping and reinforcement of compressive stress fields. That will mean that we have a continuous layer of compressively-stressed material. Work-hardening will mean that the level of compressive stress will rise progressively – but will eventually level out.

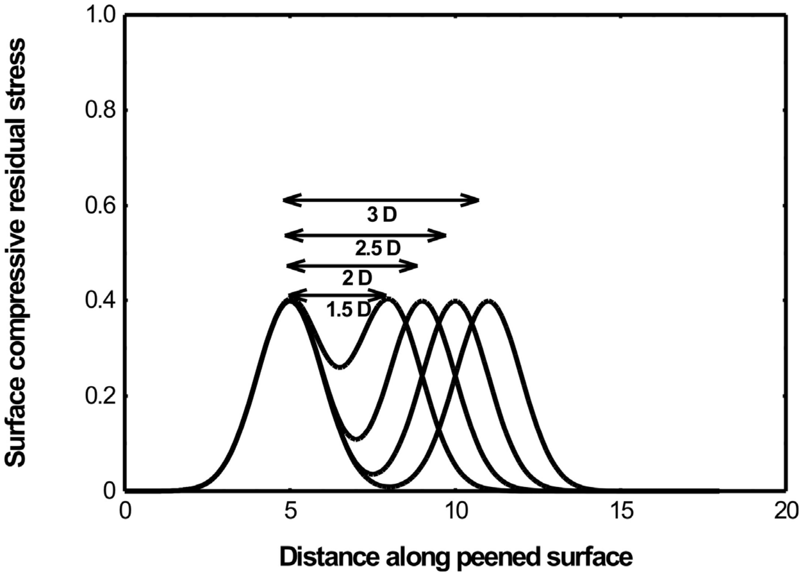

Fig.7 Addition of stress from neighboring peening indentations.

Two important factors are the level of compressive residual stress in the peened surface layer and the depth of the compressed layer. Numerous measurements have shown that the level of compressive residual stress in the peened surface layer is in the region of Y/2, where Y is the yield strength of the as-peened surface material. Y is not a constant; it depends upon the degree of shot peening and generally exceeds the published ultimate tensile strength (as measured by tensile testing of annealed specimens). The depth of the compressed surface layer depends mainly on the size of shot used but also on the degree of shot peening. For any given size of shot the compressed surface layer gets deeper as peening progresses and contains increasing levels of residual stress. The rate of increase, for both depth and level of compressive residual stress, falls rapidly with increased peening coverage. There is a temptation, which should be avoided, to specify excessive amounts of peening in order to maximize both level and depth of compressive residual stress. That is because (a) excessive peening exhausts the ductility of the component material - leading to the danger of cracking and (b) very heavily cold-worked metal becomes increasingly thermodynamically unstable – leading to an increased possibility of self-activated stress-relief.

The magnitude of the surface force, F, shown in fig.1 is simply the average compressive residual stress, σ, multiplied by the cross-sectional area of the peened surface layer. Residual stress varies within and below that layer – as illustrated in Fig.8. The maximum level of compressive stress does not occur at the extreme surface of a peened component. That is because the extreme surface is 'free', in a mechanical deformation sense.

Maximum compressive residual stress occurs well within the plastically deformed surface layer. Compressive stress falls to zero at approximately the maximum depth of plastic deformation. The stress must then give way to balancing sub-surface tensile stress. The level of tensile stress depends on the ratio of cross-sectional areas of peened surface layer and sub-surface.

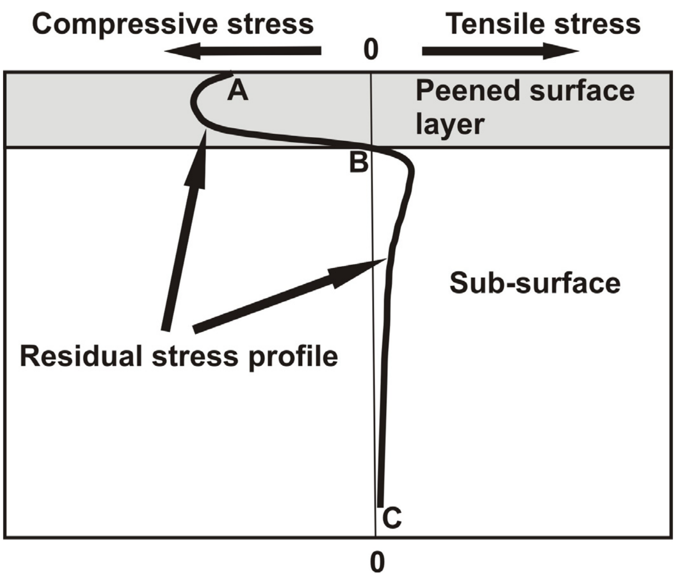

Fig.8 Residual stress profile with compressed surface layer AB and balancing sub-surface tension BC.

CONCLUSIONS

Peening induces a surface layer that contains a high level of compressive residual stress. That compressive stress is the result of overlapping stress fields from numerous indentations. Compressive residual stress extends below the surface to a depth similar to the diameter of the peening indentations. Substantial levels of compressive surface residual stress occur even between isolated indentations. The degree of overlap, and therefore stress level, will depend upon the spread of the stress field associated with each indentation. That spread can be estimated either directly, by experimental studies or indirectly, by the effect of low coverage levels on component properties. Because peening imposes a hydrostatic compressive component, very high levels of work hardening can be generated as a result of multiple deformation of the same region in the surface. The level of surface compressive residual stress is approximately half of the yield strength for the heavily work-hardened surface. Excessive peening must, however, be avoided as it will exhaust even the high plasticity of the surface material and could render the surface prone to self-annealing.