ACADEMIC STUDY
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COMPONENT SHAPE CHANGES CAUSED BY SHOT PEENING

INTRODUCTION

Shot peening is a cold-working process that has the potential to effect useful shape changes. Every cold-working process injects a residual stress system on shaping a metallic component. As a consequence the shape change has two contributions – a plastic contribution and an elastic contribution. This is different from hot-working processes where residual stresses are eliminated by self-annealing so that there is only a plastic contribution. The elastic shape change contribution due to cold-working is a consequence of the residual stress system that is imposed on the component.

Fig.1 illustrates the two contributions that would be involved in any cold-working process that converted a flat strip into a curved strip. The plastic contribution, **hp**, adds to the elastic (residual stress) contribution, **he**, to generate the total deflection, **h**. Hence, **hp** + **he** = **h**.

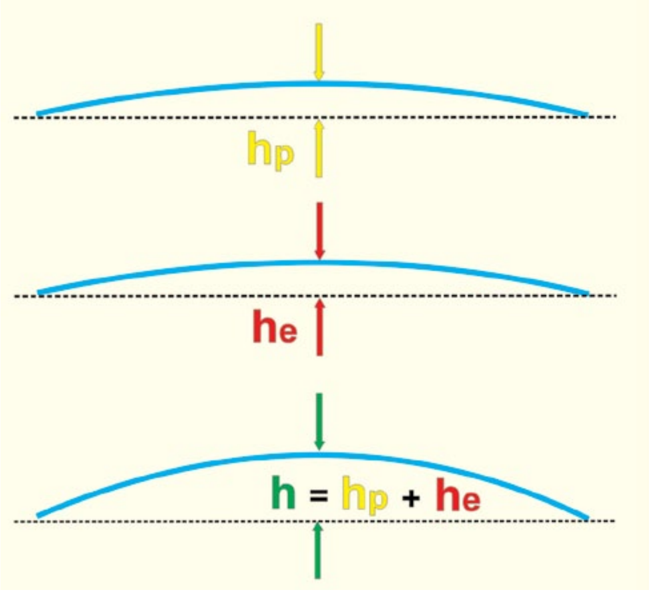

*Fig.1. Addition of plastic and elastic contributions, **hp** and **he**, to bending of strip.*

The elastic contribution is not permanent because it can be eliminated, almost, by stress-relieving treatments. A familiar example is that of peened Almen strips, which reduce their deflections when stress-relieved, leaving only the plastic contribution.

Analysis of shape changes induced by peening is complicated as it involves simultaneous use of both plasticity and elasticity theories. A simplified approach is used in this article by invoking the two theories separately.

Component shape changes are always a consequence of shot peening. These changes may be desirable, undesirable or so small that they can be ignored. Desirable shape changes can be generalized as either "peen-forming" or "distortion rectification" whereas undesirable shape changes can be generalized as "distortion".

The component shape change most familiar to shot peeners is that of an Almen strip. One major face of the strip is peened, which changes its shape from a flat (almost) rectangular shape to a doubly-curved shape. This is a desirable shape change since the induced deviation from flatness, arc height, is a required parameter. The shape change is well-known to have the form of two curves at right angles to one another. Plasticity theory predicts this shape change. Elasticity theory involving bending of beams gives useful predictions of the magnitudes of induced bending. This treats the shape changes as if they were caused by an 'Equivalent Bending Moment'. In effect:

Shot peening induces bending that is the same as would result from applying an external bending moment. This external bending moment is therefore <u>equivalent</u> to the bending moment induced by peening.

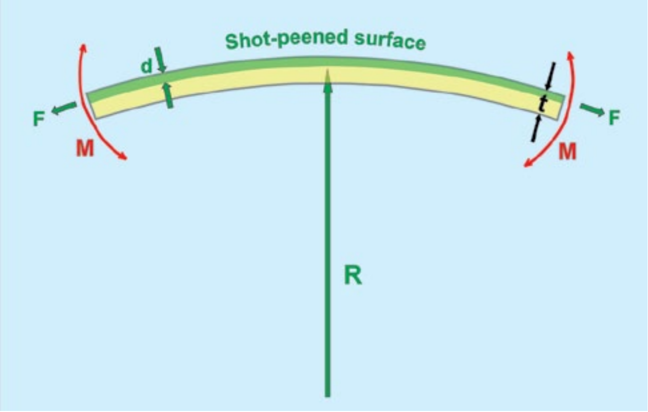

Fig.2. Shot peening shape change parameters.

Fig. 2 illustrates the essential peening parameters that are involved in shape changes. The example shown is that of a peened Almen strip where **d** is the depth of plastic deformation, **t** is the strip thickness, **F** is the bending force generated by the peening, and **M** is the 'equivalent bending moment' that causes the strip to become curved to a radius, **R**. The greater the bending the smaller is the radius of bending.

Curvature is the reciprocal of the radius of bending. Hence curvature increases with the amount of bending because the radius is decreasing. Equation (1) is the fundamental relationship that tells us how bending is induced by the application of a bending moment.

$$\mathbf{R = E.I/M} \qquad (1)$$

where **E** is the elastic modulus and **I** is the rigidity factor for the component (properly called the "second moment of area").

This article aims to show how the fundamental equation (1) can be used to estimate the shape changes that can be induced by shot peening of components. It does not aim to be either detailed or comprehensive but merely to serve as an introduction to the subject for non-specialists.

INDUCED EQUIVALENT BENDING MOMENTS AND RIGIDITY FACTORS

A qualitative feel for bending moments and rigidity factors can be obtained by trying to bend a measuring ruler. Gripped at its ends the ruler is easy to bend – in its 'thin' direction. Gripped with both thumbs touching in the middle of the ruler and it is very difficult to bend. Turn the ruler through 90° and it is very difficult to bend (in its now 'thick' direction) even when gripped at its ends. These simple tests illustrate that (a) bending moment is force times distance and (b) that thickness has a much greater effect on rigidity than has width. The rigidity factor, **I**, for a rectangular section is given by equation (2):

$$\mathbf{I = w.t^3/12} \qquad (2)$$

where **w** is width and **t** is thickness.

Shot peening induces a bending moment that is resisted by the rigidity of the component.

SHAPE CHANGE OF ALMEN STRIPS CAUSED BY PEENING

Origin of shape change

The plastic deformation stress requirements for ordinary peening have been described in a previous article (TSP Spring 2006). Fig.3 shows the state of stressing for a very tiny unit cube of material being impacted by a shot particle. The particle imposes a compressive principal stress, -s, in the z-direction and outward material flow is resisted by two identical principal stresses, -r, acting in the x- and y-directions. The Tresca yield criterion states that yielding will occur if the difference between the largest and smallest principal stresses equals the tensile yield strength, Y. Applying this criterion shows that yielding is equally likely in both x- and y-directions, when Y = -r - (-s) or:

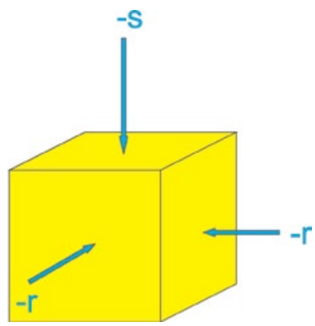

Fig.3. Principal stresses acting on a unit cube of material during shot particle impact.

$$\mathbf{Y = s - r} \qquad (3)$$

-r is the largest principal stress because it is less negative than is –s (being a smaller 'bank overdraft' by analogy). The fact that plastic flow is equally-likely in both x- and y-directions means that duplex curvature of an Almen strip must occur.

Magnitude of Shape Change

The shape change of peened Almen strips is usually quantified by the measured 'arc height'. This deflection of Almen strips is the shape change most familiar to shot peeners. Almen strips have a rectangular section of width, w, equaling 19mm but having approximate thicknesses, t, of 0.8, 1.3 and 2.4mm for N, A and C strips respectively. These values readily give us rigidity factors when fed into equation (2). The calculated rigidity factors together with an assumed elastic modulus of 210GPa can then be fed into equation (1). That gives us the relationship between any given radius of bending and the required equivalent bending moment. Radius of bending, however, is not deflection. The next step, therefore, is to convert deflection (arc height) into radius of bending.

Assuming that the radius of bending is constant along a simply-loaded strip we have the relationship given as equation (4):

$$\mathbf{h = l^2/8R} \qquad (4)$$

where **h** is arc height, **l** is length of Almen strip (76mm) and **R** is the radius of bending.

A complication is that the arc height, h, for Almen strips is made up from longitudinal and transverse contributions, h1 and h2 respectively, see fig.4.

Since the length of an Almen strip is precisely four times its width, equation (4) predicts that h1 should be sixteen times h2.

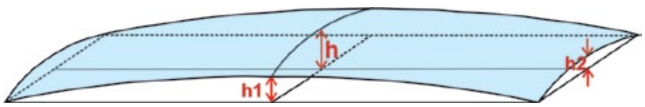

Fig.4. Doubly-curved peen formed Almen strip.

This is an important relationship, as actual measurements will indicate any anisotropy of induced curvature. If the induced curvature is isotropic (same in all directions) then:

$$\mathbf{h1 = l^2/7{\cdot}53R} \quad (5)$$

Actual measurements by the author indicate that induced curvature of standard-peened Almen strips is substantially anisotropic (h1 being normally only ten times h2). Two explanations are (1) the steel itself is anisotropic and (2) that the standard test involves pre-straining of the Almen strip while it is still held in place by the four screws/bolts.

Required Bending Moments for Almen Strips

Equations (1), (2) and (4) can be combined as rows on an Excel spreadsheet to allow easy estimation of any one unknown factor. Assume, for example, that the one unknown factor is the equivalent bending moment, **M**, induced by peening an Almen strip (**h**, **w**, **t** and **E** being known). An appropriate Excel spreadsheet is shown as Table 1. The arc height of 0·5mm was chosen because it is close to the maximum peening intensity that would normally be applied to components.

Table 1 Bending moments required to give specified arc heights to Almen strips.

Strip Type	E = GPa	w - mm	t - mm	l - mm	h - mm	M - N mm
N	210	19	0.8	76	0•5	119
A	210	19	1.3	76	0•5	506
C	210	19	2.4	76	0•5	3183

It follows that:

Almen arc height is a direct measure of the induced equivalent bending moment.

Re-arranging equations (1), (2) and (4) gives that:

$$\mathbf{M = 2{*}E{*}w{*}t^3.h/(3{*}l^2)} \quad (6)$$

Equation (6) is a simple linear equation between **M** and **h** and is plotted in fig.5 for the three standard Almen strip thicknesses.

Origin of Bending Moments

Bending moments are the result of force acting through a distance. It is well-known that peening induces a compressive stress and plastic stretching in the deformed surface layer.

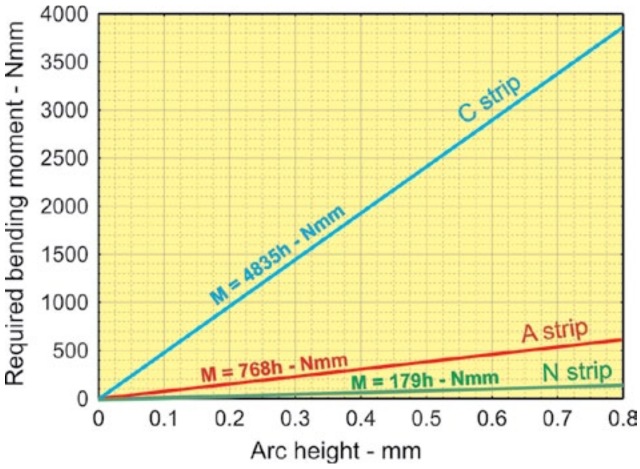

Fig.5. Bending moments required to induce deflections in Almen strips.

The resulting force is equivalent to an average stress, σ, in the peen-deformed surface layer multiplied by the cross-sectional area of the deformed layer. The distance is that from the force to the so-called "neutral axis" of the strip. These requirements are illustrated in the example shown in fig.6.

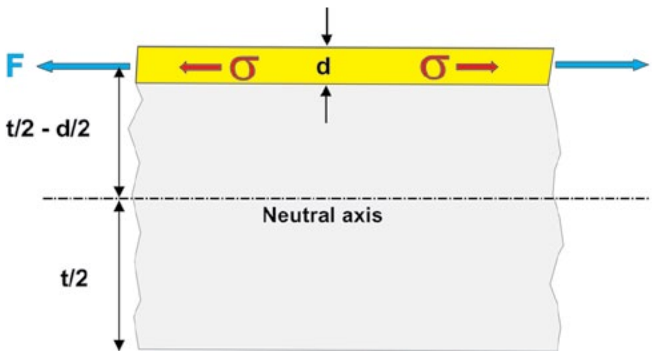

Fig.6. Example of bending moment origin in an Almen N strip.

Take as an example t = 0·80mm, d = 0·05mm σ = 300Nmm^{-2}. The force, F, is then given by F = 300Nmm^{-2} x 0·05mm x 19mm (width of strip) so that F = 285N. This generates a bending moment given by M = 285N x 0·375mm, so that M = 107Nmm.

Uniformity of Bending Moment acting on peened Almen strips

It has been assumed so far that the bending moment generated by peening is uniform, i.e., does not vary either along or across the strip. If that is correct, beam bending theory predicts that a peened strip should take on a parabolic shape rather than a circular one. Actual measurements show that this is indeed the case. One example is shown as fig.7 for which measurements were made along the major axis of a heavily-peened Almen N strip. Data points obtained using a computer-controlled X-Y-Z coordinate measuring system are shown together with a fitted parabola. The observed uniformity of bending moment is the same as that for the classic example of uniform loading described in beam-bending textbooks.

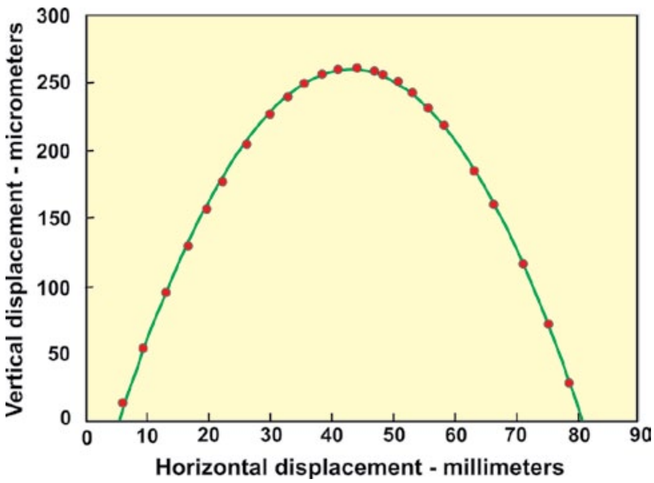

Fig.7. Parabolic shape of a peened Almen N strip.

Variability of Elastic Modulus

The bulk elastic modulus, E, varies with the thermo-mechanical history of the rolled steel strip. Equation (6) when re-arranged shows that an observed arc height, h, is an inverse function of the elastic modulus:

$$h = 3*l^2*M/(2*E*w*t^3) \quad (7)$$

This effect is illustrated by fig.8 which shows how measured arc heights vary with elastic modulus. It follows that strip manufacturers must be careful to ensure that the elastic modulus is maintained within fairly narrow limits.

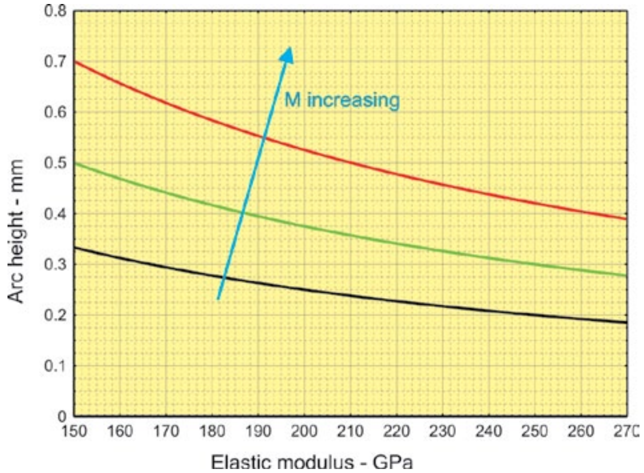

Fig.8. Variability of measured arc height with elastic modulus of Almen strip.

PEEN FORMING OF SHEET METALS

Peen forming of sheet metals is well-established as a metal-working procedure. The curvature that can be induced depends primarily on the thickness and elastic modulus of the metal together with the magnitude of the induced equivalent bending moment. Most peen forming operations are carried out using 'shot' but a few are carried out using 'balls'. A rough distinction is that 'shot' diameters are an order of magnitude less than the sheet thickness whereas 'ball' diameters are of the same order of magnitude.

During peen forming plastic deformation must, of necessity, take place.

Relationship between thickness, elastic modulus and induced equivalent bending moment

Equation (1) can be re-written as:

$$1/R = M/E.I \quad (8)$$

The bending moment, **M**, in the numerator is approximately proportional to the sheet's thickness, **t**, whereas the rigidity factor, **I**, in the denominator is proportional to t^3. Hence the curvature that can be produced is inversely proportional to the square of the sheet's thickness (one power of **t** cancelling). For example, the curvature that can be produced in 10mm thick sheet is only about one-hundredth of that which can be produced in 1mm thick sheet of the same material on applying the same bending moment. Equation (8) shows that the curvature increases linearly with increase of applied bending moment and decrease of elastic modulus.

Magnitude of induced equivalent bending moment

A required curvature can only be achieved by the application of the corresponding bending moment, as predicted by equation (8). Values of M for Almen strip steel are readily available. For other materials possible curvatures have to be determined experimentally. A convenient technique is to use samples cut to the 19mm by 76mm Almen strip dimensions. These can then be peened using peening intensity fixtures.

Effect of pre-stressing

In the absence of pre-stressing peen formed sheet will deform equally in two directions. This is not usually desirable. Unidirectional pre-stressing, however, has a profound effect on the principal stress system that is causing plastic deformation during impact of shot particles. This pre-stressing, which can be either tensile or compressive, adds an extra component to the state of stress.

Fig.9 corresponds to where a surface tensile pre-stress, +p, has been applied due to an external bending effect. The largest principal stress is now (+ p – r) and the smallest is still – s. Applying the Tresca yield criterion gives that Y = (+

p - r) – (-s) so that yielding in the x-direction is given by:

$$Y = s + p - r \tag{9}$$

Comparing equations (3) and (9) shows that the absolute magnitude of the required compressive stress, s, has been reduced by p. For example, a pre-stress of 200MPa would reduce the required value of s by 200MPa (assuming that r remains constant). Reducing the level of stress that must be imparted by the shot particle means that deformation will extend deeper below the component's surface. Pre-stressing therefore strongly encourages yielding in the x- and z-directions and also promotes a greater bending moment. Yielding in the y-direction, on the other hand, is discouraged. That is helped by 'Poisson contraction'.

Fig.10 corresponds to where a compressive pre-stress of magnitude -p has been applied as an external effect. The largest principal stress is now – r and the smallest is still – s. Applying the Tresca yield criterion gives that Y = - r – (-s) so

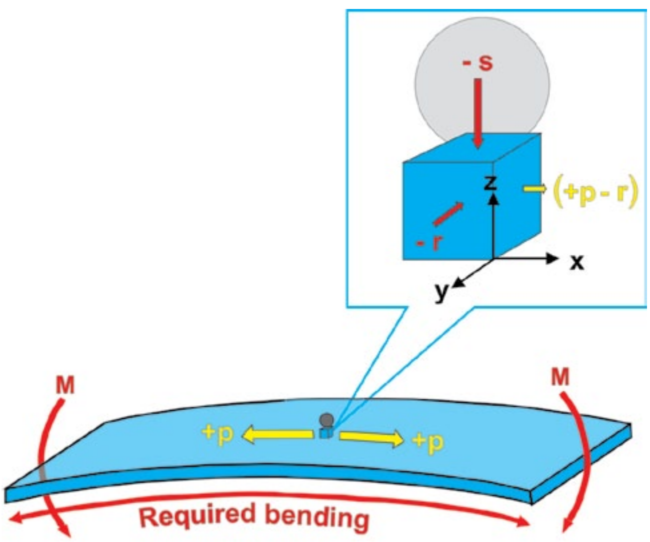

Fig.9. Principal stresses during tensile peen forming.

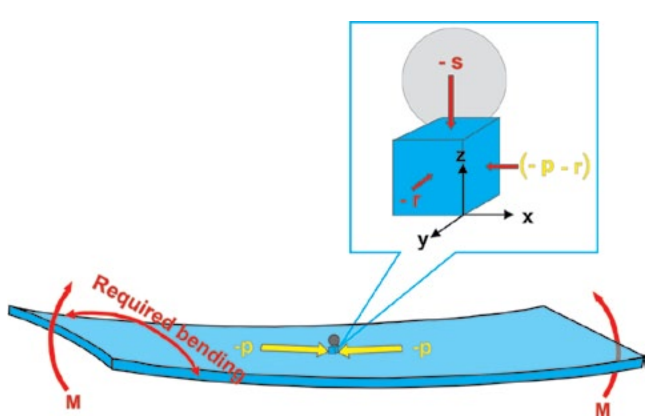

Fig.10. Principal stresses during compressive peen forming.

that yielding in the y-direction is now given by:

$$Y = s - r \tag{10}$$

Equation (10) is identical to equation (3). This then predicts that compressive pre-stressing will not reduce the impact stress required to cause yielding and therefore deeper deformation will not occur. The resistance to flow in the long direction has, however, been greatly increased - by **p**. Conversely, flow in the cross direction will be encouraged – by the Poisson effect. Note that the bending in the x-direction will be removed when the external applied bending moment, M, is removed.

Distortion Rectification

Distortion rectification is a specialized technique that is generally carried out on an empirical basis. Some distorted components can have the distortion rectified to a degree that may only require minor machine finishing. This is achieved by peening appropriate areas of the component with sufficient intensity. Basic considerations are the bending moment that is imparted, the rectification needed and the rigidity of the component.

The following is a simple example which illustrates some of the basic considerations. A 1m long plate is found to be distorted as shown in fig.11. It is known that peening a 10cm section, AB, would induce a bending of that section to a radius, R, equal to 1m. If we equally peen the underside of the plate between C and D then the plate will bend upwards by the same amount. Estimation of the straightening that would be achieved involves some geometry. The angle COD is given by CD/R or 10cm/100cm so that COD = 0·1 radians. Multiplying radians by 180/À converts them to degrees. Hence the angle COD = 6˚. The angle BEF also happens to be 6˚ (for this example), so that the required rectification would be achieved.

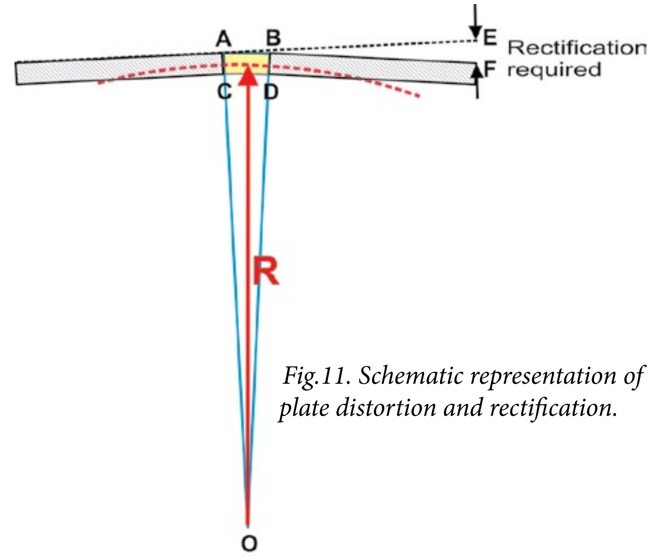

Fig.11. Schematic representation of plate distortion and rectification.

DISCUSSION

Shape changes are an inevitable consequence of shot peening. The magnitude of these changes can be estimated from knowledge of the imposed bending moment. Analysis of shape change should, however, involve plasticity principles as well as elasticity principles. This was recognized as early as 1865 when Tresca introduced his yield criterion. A deliberately simplified application of plasticity and elasticity principles has been used in this article – in order to reach a larger proportion of shotpeeners.

Almen strips are held down only along their longer edges. As peening progresses a transverse tensile pre-stressing is therefore generated. This transverse tensile pre-stressing will encourage transverse plastic flow. That is a reasonable explanation of the fact that the transverse contribution to arc height is observed to be greater than would be expected from isotropic flow.

Shape changes induced by shot peening can be partially recovered by stress-relieving. If this is undesirable then one solution is to induce excessive shape change and then temper it back to the required shape change.