ACADEMIC STUDY
by Dr. David Kirk | Coventry University

Principles of Peening Intensity Selection

INTRODUCTION
The most difficult shot peening question to answer is, probably, "What peening intensity should I apply to my component?" For any specific component, an answer should be based on a combination of prior knowledge and an understanding of the basic principles that are involved. Five basic principles are discussed as illustrated in fig.1. Prior knowledge is being aware of peening intensities that have previously been applied to similar components.

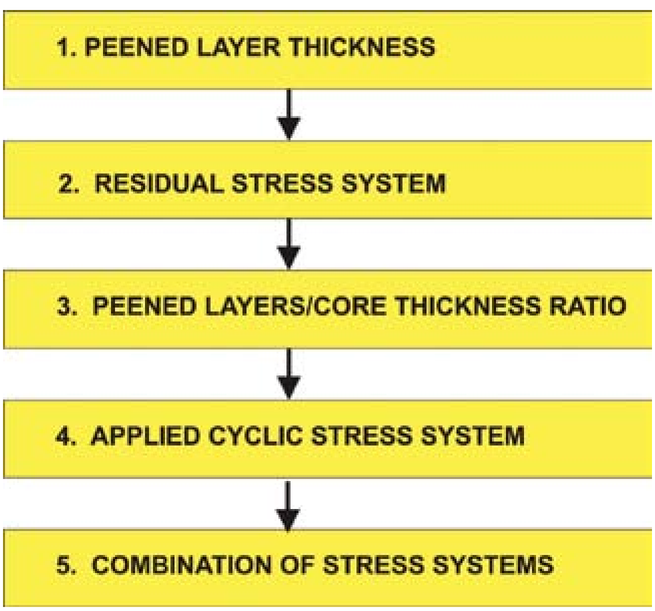

Fig.1 Basic principles affecting Peening Intensity Selection.

"Peening intensity" is, of itself, a confusing term. We all know how it is quantified—as the arc height at a particular point on a "saturation curve" produced using one of three thicknesses of Almen strips. But what does that really imply? A reasonable interpretation is that it is a measure of the "indentation capability" of the individual particles that make up a shot stream. One analogy is that of a stream of machine gun bullets. Each bullet is capable of making an indentation where indentation size depends on the velocity, size, shape and density of the individual bullets.

All of the factors affecting peening intensity selection are quantifiable. It is therefore necessary to consider them quantitatively. Only basic calculations are used in this article. These are mainly applied to components having the simple geometry of leaf springs. Several readings of the article may be needed in order to appreciate all of the diagrams that have been included—unless one is a mechanical engineer!

BASIC PRINCIPLES
1 Peened layer thickness
When a shot stream covers a component's surface with indentations it produces a work-hardened surface layer that contains compressive residual stress. This surface layer has a thickness that is directly proportional to the peening intensity (indentation capability) of the shot particles. The induced work-hardening and compressive residual stresses combine to improve the service performance of the component, especially its fatigue life in bending situations. That does not, however, mean that "thicker is better" when referring to the peened surface layer.

Fig.2 illustrates the effect of applying low and high peening intensities to a given component's surface. Low peening intensities are normally produced when using relatively-small shot particles and high peening intensities by using relatively-large shot particles. Shot velocity and density have an effect regardless of shot size—higher velocity and

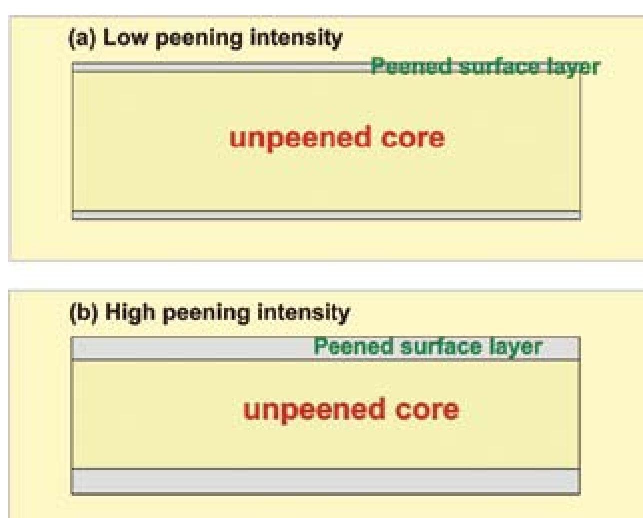

Fig.2. Low and high peening intensities producing thin and thick surface layers respectively.

density both giving greater peening intensities.

The peened layer thickness has an important effect on the residual stress system that is a vital feature of all shot-peened components.

2 Residual stress systems

The Heyn Spring Model is a very useful way of describing a residual stress system. Consider the following analogy of how a spring model of a residual stress system could be generated.

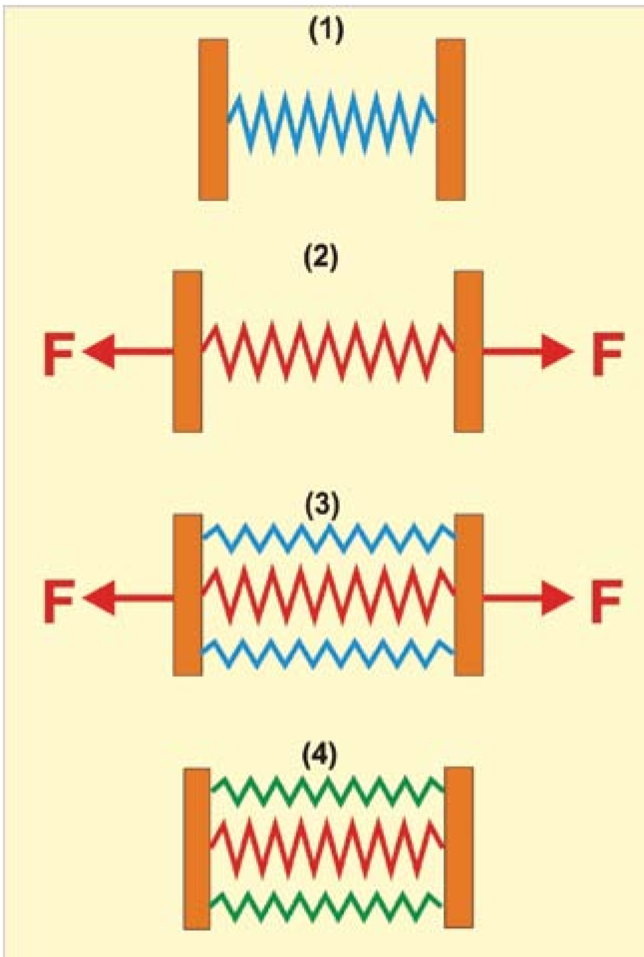

Fig.3. Sequence leading to the spring model of a residual stress system.

Imagine that (1) in fig.3 represents a spring attached to two handles. The spring is colored blue to indicate that it is not being stressed. This corresponds to a "zero stress system". Now imagine that a "Strong Man of the Circus" exerts a very large tensile force, F, by pulling on the handles—(2) in fig.2. The central spring stretches and the spring is colored red to indicate that it is now in tension. We now have an "applied stress system" because an applied force is responsible for the stress. Imagine next that the Strong Man's assistants slot two springs on either side of the stretched central spring. These two springs are of the same length as for the stretched-apart handles and are therefore not stressed—hence colored blue as in (3) of fig.2. We still have an "applied stress system". Finally, imagine that the Strong Man stops exerting the force, F, so that the handles move towards one another. As they do so the two outer springs become compressed—colored green. A stable position is reached when the sum of the compressive forces on the outer springs is equal to the remaining tensile force on the central spring—colored red. For any stable system the universal law that "For every force there must be an equal and opposite force" applies. We now have a "residual stress system" because no external force is involved.

Fig.4 shows the shot-peening equivalent of the foregoing spring model. Peening introduces compressive forces, F/2, in the surface layers, shaded green, which must be balanced by a tensile force in the unpeened core of the component, shaded red. The example shown is equivalent to the cross-section of a leaf spring that has been peened on both major faces.

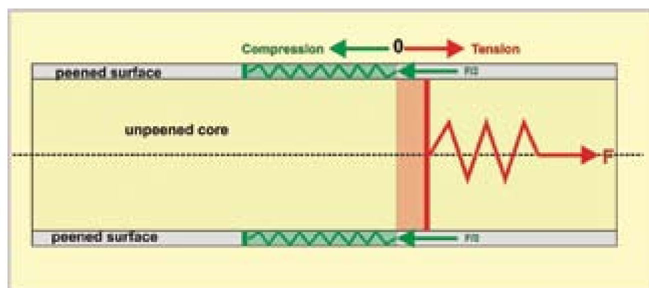

Fig.4. Peened leaf spring section showing balanced forces.

We must note that force is stress multiplied by the area over which it acts. Fig.5 includes the stress distribution that corresponds to the situation in fig.4. Two compressive surface forces, F/2, are present. These are equal to the average compressive stress multiplied by the area over which they act. That area is the depth of the compressed layer, d, multiplied by the fixed width of the leaf spring, W. The balancing tensile force, F, in the core is equal to the average tensile stress in the core multiplied by the area over which it acts. That area is the thickness of the core, c, also multiplied by the fixed width of the leaf spring, W.

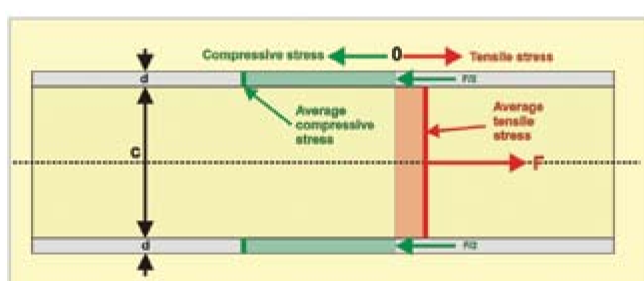

Fig.5. Force generation in leaf spring due to stress multiplied by area over which it acts.

Example:

*Assume that a 12 mm thick by 100 mm wide steel leaf spring has been peened on both major faces to a depth, d, of 1 mm. The unpeened core thickness, c, is therefore 10mm. A typical average compressive stress in the peened surface layers could be 500 Newtons per square millimeter (MPa). The force, F/2, generated in each surface layer is therefore given by: F/2 = 500Nmm^{-2} * 1mm * 100mm or F/2 = 50,000N. The balancing tensile force, F, must therefore equal 100,000 Newtons! 100,000 Newtons is approximately the force exerted by a mass of 10 metric tons. For the "Strong Man of the Circus" analogy, applying a force of just 1,000 Newtons would probably be more than he could manage to maintain. Even if the peened depth was only 0.1 mm the required tensile force would be 10,000 Newtons.*

*Working backwards, we can estimate the average tensile stress in the unpeened core. This is the required force, F, divided by the area over which it acts. For the 10 mm thick unpeened core this area is 10 mm * 100mm. Hence, when the force is 100,000 Newtons the average tensile stress in the core is 100,000 N/1000 mm^2 or 100 Nmm^{-2}. Fig. 5 is 'true to scale' for this situation, showing the average balancing tensile stress as being a fifth of the average surface compressive stress level.*

3 Peened layers/ core thickness ratio

The ratio of the thickness of the peened layers to that of the unpeened core is crucial for deciding peening intensity. That very important ratio, **R**, is given by equation (1) for two-sided peening:

$$\mathbf{R = 2d/c} \qquad (1)$$

Where **d** is the thickness of both peened surface layers and **c** is the thickness of the unpeened core. The magnitude of **R** is so important because it also tells us the ratio of the average residual stress in the core to that of the average residual stress in the two peened layers. For the previous example, with **d** equal to 1 mm and **c** equal to 10 mm, the ratio **R** is given as **0.2** (one-fifth).

Imagine next that a leaf spring had been peened with such a high intensity that the depth of the compressed surface layer, **d**, was half of **c**. The ratio of stresses predicted by equation (1) is now **1** (2*½/1). In other words the average compressive residual stress in the surface layer is equal to the average tensile residual stress in the core. Fig.6 shows the corresponding effect on distribution of average residual stresses.

Peening intensity must, however, be selected to give an **R** ratio that is appropriate for specific components. It is shown later that **R** is commonly about 0.025 for double-sided peening and 0.0125 for single-sided peening of real components.

The significance of having a very high tensile stress in the core becomes apparent when we consider its superposition on applied bending stresses.

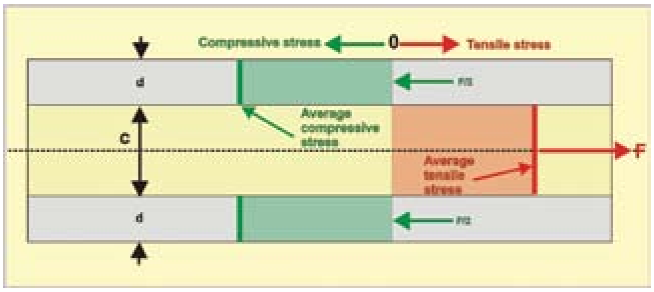

Fig.6. High core tensile residual stress in a deep-peened leaf spring.

4 Applied cyclic stress systems

Shot peening is most effective when cyclic bending stresses (rather than push-pull) are being applied to the peened component.

Imagine gripping an office ruler and applying different cyclic bending stress regimes – simulating the loading of a leaf spring. As the ruler is bent the convex side is put into tension and the concave side is put into compression. The maximum stress level, ±A, is at the surfaces and is zero along the centerline. This is illustrated in fig.7.

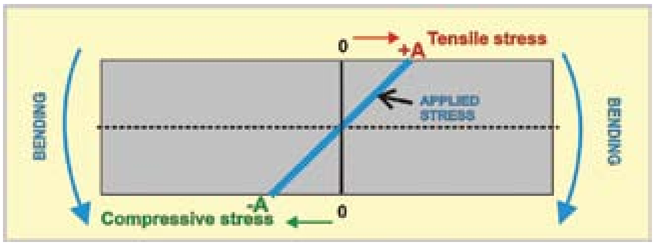

Fig.7. Simple bending applied to a rectangular section.

The simplest cyclic bending stress regime can be simulated by bending the ruler in one direction, relaxing the applied bending and then re-applying it. This produces the type of cyclic stressing regime shown in fig.8.

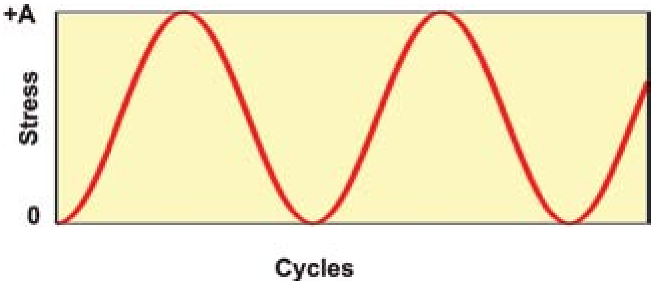

Fig.8. Stress cycling induced by one-way bending.

Repeated bending of the ruler by equal amounts in opposite directions will generate a cyclic stressing regime of +A to –A for both sides of the ruler. The corresponding cyclic stressing regime is shown in fig.9. (There are, altogether, seven different types of cyclic stressing regimes that can be applied. These are: +A/+B, +A/0, +A/-B, +A/-A, +B/-A, -A/0 and –A/-B where B denotes a lower stress level than A.)

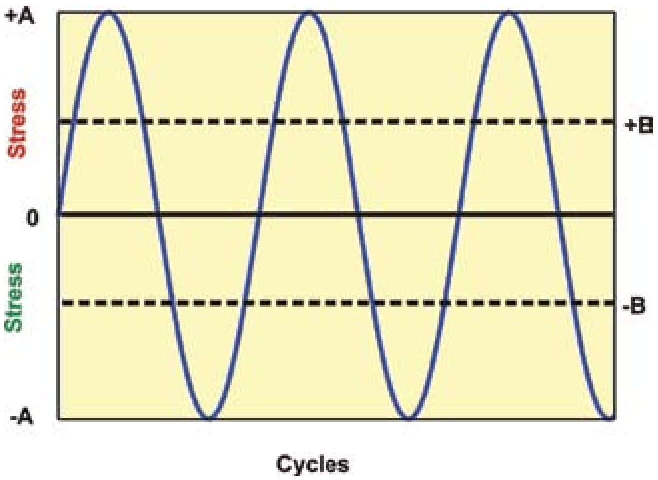

Fig.9. Stress cycling induced by reversed bending.

5 Combinations of applied service stresses and residual stresses

A key feature of applied service stresses and residual stresses is that they are additive. This feature is illustrated in fig.10. These are simplified diagrams - showing average core and surface residual stresses (rather than the smooth curves of varying residual stress) - together with an applied bending stress distribution. The simplification allows the combination of residual and applied stress to be estimated visually.

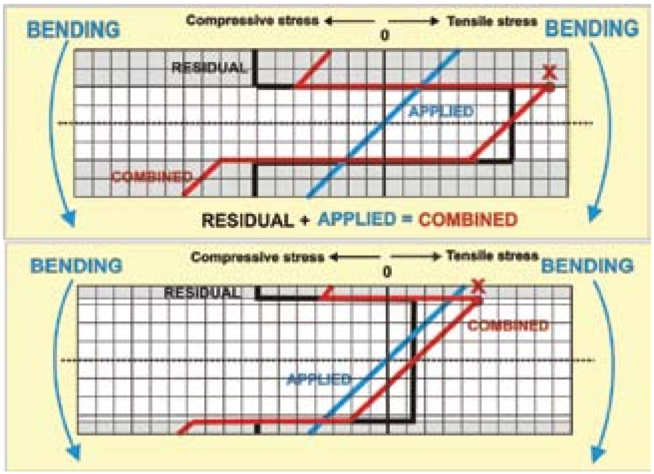

Fig.10. Combination of Applied and Residual Stresses in peened leaf springs.

For the upper diagram in fig.10 we can see that the combined stress at the upper surface is (using the graphical units shown) -7 plus +4 which equals -3. Below the upper surface the combined stress falls (because the applied stress is falling) reaching -5 at the interface with the core -7 plus +2). Just into the core the core stress of +7 now adds to an applied stress of +2 to give a total of +9 – shown as the spot marked “X”. That is more than double the maximum stress applied at the surface and is a source of potential component failure. Below the point “X” the combined stress falls until it reaches a maximum of -11 graphical units at the lower surface. This would cause severe problems if it exceeds the compressive yield strength of the peened surface’s material.

For the lower diagram in fig.10 there is a much thinner compressed surface layer. The shape of the combined stress pattern is similar to that for the thicker compressed layer. One important quantitative difference is that the combined stress at the critical point “X” is now only +5 graphical units. This is only one unit higher than the maximum applied stress (+4 at the surface) and does not pose the problem of the +9 units of the thicker compressed surface layer. This example shows, in a quantitative way, why we must control the relative depth of the compressed surface layer by correct selection of peening intensity.

PRIOR KNOWLEDGE

Prior knowledge is a ‘two-edged sword’. Correct application of prior knowledge allows satisfactory estimates to be made. Incorrect application, on the other hand, will lead to unsatisfactory estimates. Decisions based on prior knowledge rely on the quantity, relevance and quality of that prior knowledge. Multi-national and large aerospace companies have the luxury of enormous amounts of prior knowledge and experience to call upon. Beginners to shot peening and small companies have relatively limited access to prior knowledge. They may have to rely upon advice given by either consultants or by outsourced shot peening companies. That advice should be consistent with the five basic principles described previously.

Any search for prior knowledge on optimum peening intensity is facilitated by employing the internet. A vast amount of information is, however, available and the main problems are to separate ‘wheat from chaff’ and not to get overwhelmed.

The information given in fig.11 is copied from an article by H. O. Fuchs published in the Mechanical Engineers’ Handbook 1986. The effect of thickness appears as being linear because of the log-log scales that have been used. These log-log scales allow inclusion of most component thicknesses that might be encountered. At the same time the corresponding peening intensity ranges for steels are also accommodated. For any given thickness of component a range of applied peening intensities is indicated. That is because steels themselves exhibit a wide range of hardness. For 12.5 mm thick components (0.5") the specified peening intensity ranges from about 200A (metric) for soft steels up to about 600A (metric) for hard steels.

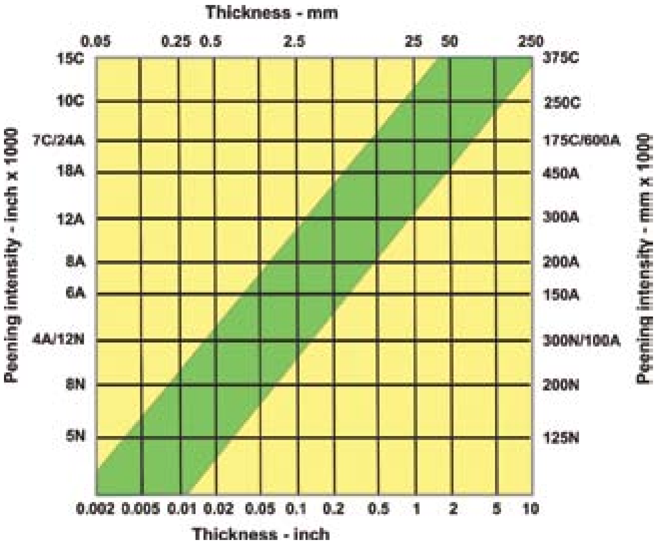

Fig.11. Peening intensities commonly used on steel parts of different thickness.

It is clear from fig.11 that as the thickness of a component increases so does the peening intensity that is usually applied. That is consistent with the basic principles previously described.

Fig.12 is copied from the Charts section of the EI library. There is an almost linear increase of depth of compression with increase of peening intensity. The depth of compression increases with increasing softness of the impacted material.

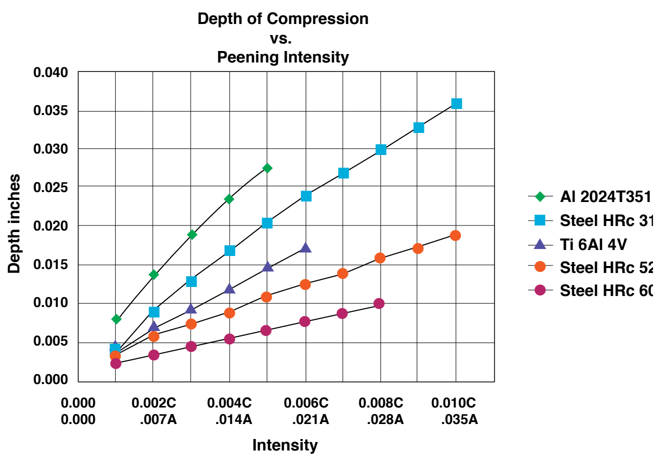

Fig.12. Variation of Depth of Compression with Peening Intensity.

As an example of using figs.12 and 11 consider a steel of hardness HRc 52 peened to an (imperial) intensity of 0.021A. The corresponding depth of compression is 0.0125" (using fig.12). Fig.11 indicates that an intensity of 0.021A is commonly applied to 1" thick steel components of average hardness. Hence we find that the compressed layer depth, d, is some 1.25% of the component thickness.

Fuchs pointed out (ASTM Special Technical Publication 196, 1962) that depth of compression is governed by the diameter of individual indents. For Almen strip hardness steel he showed that the depth of compression is approximately half of the indent diameter and approximately equal for aluminum (alloy?). Measurement of indent diameter on peened components is therefore a quick method of indicating the depth of the compressed layer. This depth can then be correlated with a peening intensity requirement.

DISCUSSION

Thickness of the peening-induced compressed surface layer is obviously the prime factor when deciding on peening intensity. This thickness depends upon the applied peening intensity and the softness of the component material. A layer/core thickness ratio of about 0.0125 appears to be a 'norm'. Any substantial deviation from that ratio should be questioned. Secondary factors, such as shot properties, also influence optimum peening intensity.

It has been shown that huge forces are normally developed by shot peening, especially when high intensities are involved. These forces can induce undesirable bending moments and hence distortion of components.

In an ideal situation a large range of peening intensities could be applied to a number of identical components. Required property enhancement, such as fatigue strength, could then be measured as a function of applied peening intensity. Plotting of these measurements would indicate an optimum peening intensity value. Such an ideal situation involves huge expenditure—which can, however, be minimized by an application of prior knowledge and a consideration of the basic principles involved.