Control of Peened Layer Development

INTRODUCTION

The prime objective with shot peening is to induce a well-developed protective surface layer of plastically-deformed material. This layer has two important properties: compressive residual stress and work-hardening. Both of these properties act to improve service performance of components. Development of the layer proceeds with increase in amount of peening until it has stabilized in the required thickness range. Fig.1 represents, schematically, the development of a peened surface layer.

Control is needed in order to ensure that the layer is fully-developed, has the required thickness and is not over-peened.

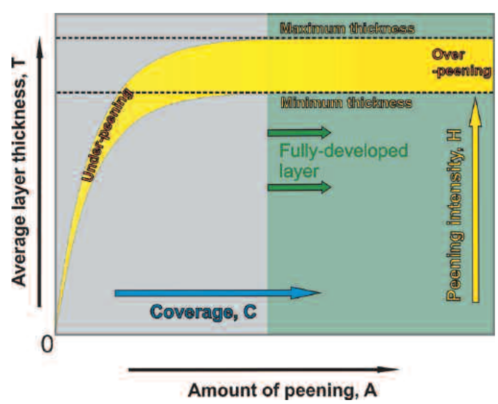

Fig.1. Development of shot-peened surface layer.

There are two primary control parameters:

1 **Peening intensity**, **H.** Peening intensity (also called "Saturation Intensity") controls the thickness of a fully-developed peened layer. The average layer thickness, **T**, is proportional to the average diameter, **d**, of the indentations produced by impacting shot particles. **d**, in turn, depends on the peening intensity that has been specified. Hence:

$$\mathbf{T} \ \alpha \ \mathbf{H}$$

Peening intensity has to lie between specified minimum and maximum values – with corresponding minimum and maximum layer thicknesses.

2 **Coverage**, **C**. The development of the layer is gauged by the coverage of the surface by indentations. Coverage depends on the **amount of peening**, **A**, which has been applied. The amount of peening, **A**, is the number of indentations per unit area of peened surface, **n**, multiplied by the average area of the individual indentations, **a**. Hence:

$$\mathbf{A = n*a}$$

Coverage, **C**, is proportional to the amount of peening, **A** so that:

$$\mathbf{C} \ \alpha \ \mathbf{A}$$

Peening intensity is readily quantifiable and measurable – using sets of Almen strips. Coverage is easily quantifiable (being simply the percentage of surface area that has been covered by indentations) but measurement is relatively difficult – particularly on the shop floor.

This article is an over-view of the control of layer development – using peening intensity and coverage. Peening intensity control has been very adequately covered by other authors and by published specification documents. Coverage control, on the other hand, still presents problems. Coverage control requires knowledge of the required component coverage. There are several 'ad hoc' definitions used in the shot peening industry. These are generally based on the imprecise concept of '100% coverage' as being a level at which unpeened areas are not detected using low-power visual inspection. Following that concept we have terms such as '200% coverage' - requiring that peening is continued for twice as long (or for twice as many passes) as that required to achieve so-called '100% coverage'.

LAYER THICKNESS CONTROL

Peening Intensity and Peened Layer Thickness

Peening intensity is the arc height, **H**, of an Almen strip peened to the 'saturation point'. **There is a direct, almost linear, relationship between peening intensity and fully-developed peened layer thickness of a component.** This relationship and the allowance for component material hardness are illustrated schematically in fig.2 (page 26). At any specified peening intensity, **h**, the layer thickness will be greater for a component that is softer than Almen strip material. For component material that is harder than Almen strips the layer thickness will be

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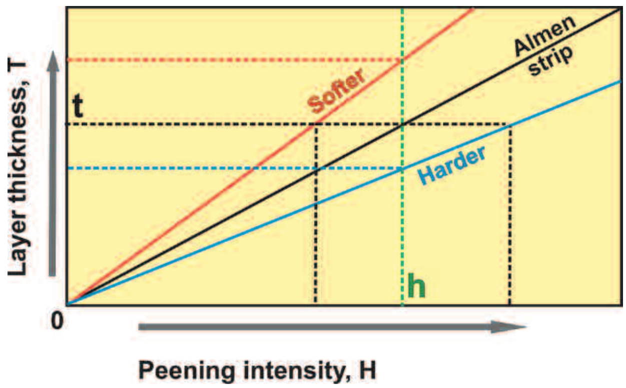


Fig.2. Effects of peening intensity and relative component hardness on fully-developed layer thickness.

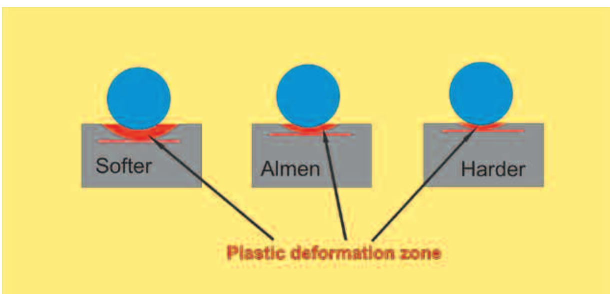


Fig.3. Effect of component hardness on depth of plastically-deformed surface layer.

less than that developed in the Almen strip. It follows that in order to achieve a specified layer thickness, say **t**, that a greater peening intensity is needed for harder materials than it is for softer materials.

Peening intensity is a direct measure of the indentation capability of the flying shot particles. The size of the indentations that will be made on the surface of the component increases with increasing peening intensity. The harder the component the shallower will be the deformation zone created by a given impacting shot particle. This is illustrated in fig.3.

A fully-developed peened surface layer consists of merged individual deformation zones. Hence, softer materials will develop a thicker deformed layer than will harder materials - for a specified Almen intensity. That explains the difference in slope of the lines shown in fig.2.

Control of Peening Intensity, H

We need to control peening intensity – if only to satisfy inspectors! Peening intensity depends upon a number of factors but only two are under the direct control of the shot peener – the others being pre-specified. These are shot velocity, **v**, and shot diameter, **D**. Users may have specified a particular type and size of shot e.g. S230 but that does not mean that the shot diameter is constant. Shot wears down progressively to smaller diameters and it is standard practice to add a proportion of new shot at intervals. This new shot has a larger average diameter than the worn shot of the same grade. Control therefore depends upon appropriate admixture regimes.

To a first approximation peening intensity, **H**, <u>for a given set-up</u>, is given by:

$$\mathbf{H = K{*}D{*}v^{0.5}} \qquad (1)$$

where **K** is a constant.

D, as mentioned earlier, depends on our shot maintenance regime (based on shot additions and re-cycling). **v** depends mainly upon air velocity/wheel speed but is also affected by such factors as nozzle wear and shot flow rate. Nozzle wear must therefore be monitored and shot flow rate carefully controlled.

It follows from equation (1) that changes in shot diameter are more significant then changes in shot velocity. For example a 10% increase in shot diameter will give a predicted 10% increase in peening intensity. A 10% increase in shot velocity, on the other hand, will give only a 3% predicted increase in peening intensity (√10 = 3·14).

A wide range of shot sizes is available. For each shot size there is an appropriate range of peening intensity - which determines the corresponding layer thickness range. This is illustrated schematically in fig.4. **A very important feature is that peening intensity, layer thickness and shot diameter all vary by an order of magnitude (10 to 1)**. It is no coincidence that there are three thicknesses of Almen strip (N, A and C) that also cover a sensitivity range of 10 to 1 (approximately). Specifications indicate that a given Almen arc height obtained on an N strip is 3 times that which would be given by an A strip and that a given Almen arc height obtained on an A strip is 3·4 times that which would be given by a C strip. Hence **N:A:C = 10·2:3·4:1**. Fig.4 indicates that N strips are suitable for the smallest intensities/layer thicknesses/shot sizes whereas C strips are suitable for the largest. For each available shot size there will be a range between allowed 'minimum' and 'maximum' values of the specified peening intensity. This range recognizes the impossibility of guaranteeing a precise peening intensity value using commercial facilities (shot size and velocity <u>must</u> vary to some extent - even with the best control equipment).

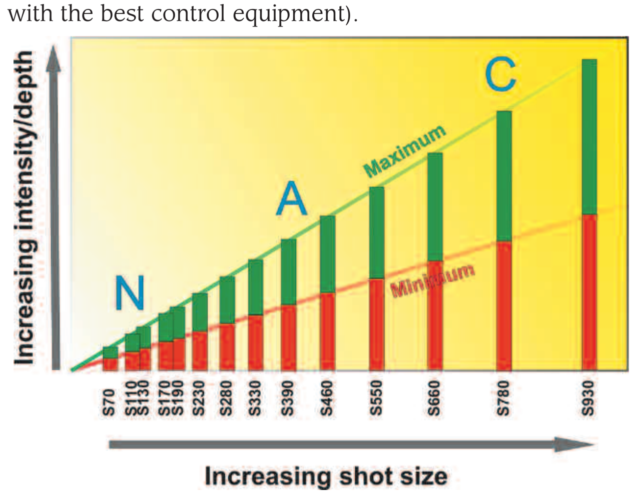


Fig.4. Influence of shot size on normal minimum and maximum specified peening intensities.

Shot velocity is the major factor used by shot peeners to control peening intensity/layer depth. The depth of a fully-developed peened layer is indicated by equation (1) as being proportional to the square root of the shot velocity. This variation is illustrated in fig.5 (page 28).

It is worth noting that, within the normal commercial range of shot velocities, A to B, the variation is almost linear. Departure from linearity is only acute at very low shot velocities.

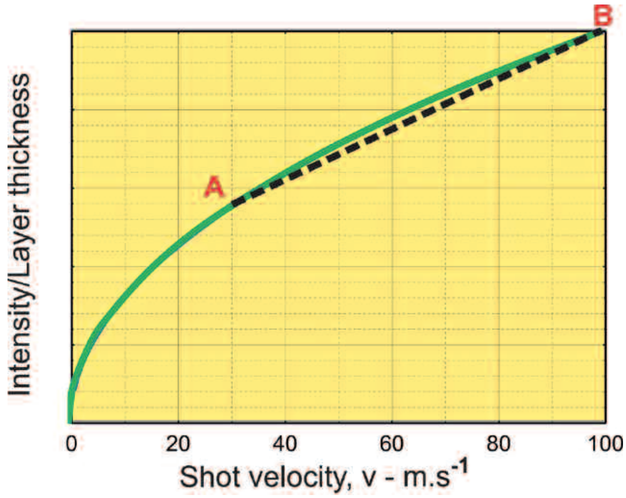


Fig.5. Variation of peening intensity and layer thickness with velocity of shot.

CONTROL OF THE AMOUNT OF PEENING

Coverage, C, versus Amount of Peening, A.

Coverage is a measure of the amount of peening that has been applied to a component. 'Amount of Peening', **A**, is the total area of the indentations imposed per unit area of the component. Hence:

$$A = n*a \qquad (2)$$

where **n = number of indentations per unit area** and **a = average area of the n indentations.**

For example, if we impose **240** indentations having an average area of **1**mm^2 on an area of 100mm^2 then the amount of peening, **A**, is **2·4** (240*1mm^2/100mm^2). Control of **A** is normally effected by varying **n**, the number of indentations per unit area. The average area, **a**, is normally pre-determined by the peening intensity and the hardness of the component.

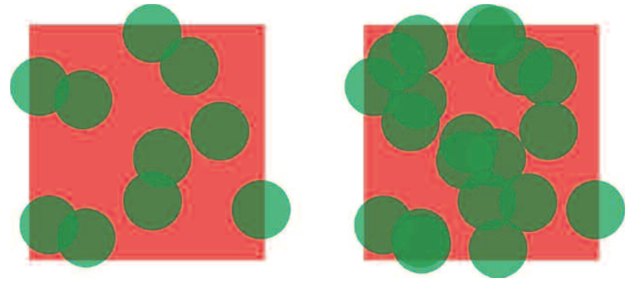
Coverage, **C**, is the proportion of area that has been indented. Its value is determined by the amount of peening that has been applied. However, **C** does not have the same value as a corresponding value of **A**. If, for example, **A% = 100** then **C% = 63** (reason given later). The basic problem is that indentations have an annoying habit of overlapping one another – the more so as coverage increases. Hence we do <u>not</u> have a linear relationship between amount of peening, **A**, and coverage, **C**. The cause of the difference between amount of peening and coverage is illustrated by fig.6. The <u>amount of peening</u> is exactly doubled in (b) as compared with (a) but the <u>coverage</u> is less than doubled.

Numerous experiments have shown that the actual variation of coverage with amount of peening closely approximates to what is known as an "Avrami curve". This is illustrated in fig.7.

The curve shows that **coverage increases at a decreasing rate** – eventually approaching 100% very slowly. An Avrami curve has a corresponding equation that describes it. A useful form of the equation for shot peeners is:

$$C\% = 100[1 - \exp(- p*A)] \qquad (3)$$

where: **C** = coverage, **p** = number of 'passes' and **A** = total area of indents per pass per unit area of component (amount of peening per pass).



(a) 10 indentations **(b) 20 indentations**

Fig.6 Representation of (a) ten and (b) twenty indentations randomly distributed in a unit area.

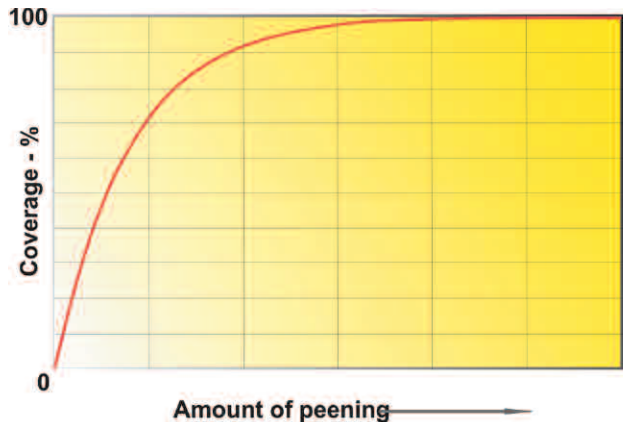


Fig.7 Avrami curve representation of coverage variation with amount of peening.

Equation (3) can be re-written as:

$$p*A = - \ln[(100 - C\%)/100] \qquad (4)$$

where: **ln** stands for 'natural logarithm'.

Equations (3) and (4) represent vital relationships between coverage and amount of peening.

Direct Coverage Control

Direct coverage control is based on measuring the actual coverage and modifying the amount of peening in order to achieve a target coverage value.

The simplest technique is that of 'trial and error'. The amount of peening is increased in stages until the component is adjudged to have reached a nominal '100%' coverage. Coverage measurement is then based on a subjective visual judgment that '100%' has been attained.

A much more efficient approach can be applied if objective quantitative coverage measurement is available. Equations (3) and (4) can then be used to <u>predict</u> the changes in coverage that result from more and more passes being made of a shot stream over a component. **All we need is one, reasonably-accurate, measurement of the actual coverage achieved**. Let us assume that our standard practice is to make several passes of a defined shot stream over a particular component. We measure the coverage after the first pass (**n = 1**) and find that it is, say, **58%**. Substituting **p = 1** and **C = 58** into equation (4) gives that **A=0·87**. We can now substitute **0·87 for A** in equation (1) to give: **C% = 100[1-exp(-0·87*p)]**. Substituting <u>different values for **p**</u> then gives us the predicted coverage percentage for each of a number of passes. Fig.8 is pasted from an

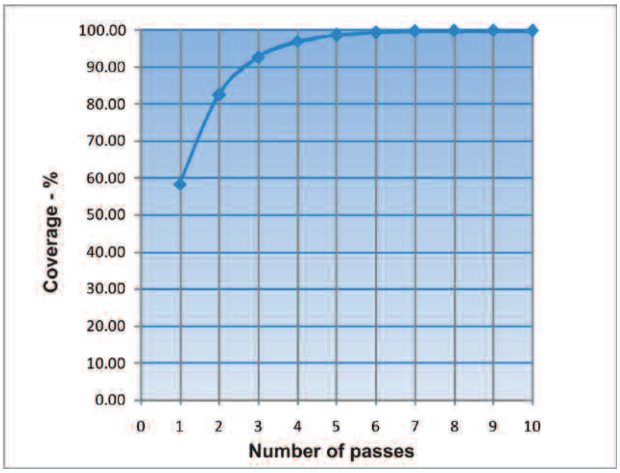


Fig.8. Automatic prediction of Coverage versus Number of passes.

Excel spreadsheet that does all of the arithmetic and graph plotting. Only the measured value (58%) has to be entered into the spreadsheet. The spreadsheet values are also given in Table 1.

Consider, for example, that a user has specified 99·8% actual coverage. This can be achieved, to the nearest decimal point, by applying seven passes to the component used for the data derived in Table 1. Eight passes would definitely satisfy the specification and would allow for a certain amount of process variability. This depends, however, on a reasonable maintenance of the defined shot stream parameters: velocity, size, material, feed rate, etc. that regulate average indentation area, **a**.

If the predicted/actual number of passes required is considered to be excessive then we must vary the amount of peening per pass.

Table 1. Predicted coverage values at different pass numbers.

No. of Passes	Coverage - %
1	58
2	83
3	93
4	97
5	98.7
6	99.5
7	99.8
8	99.91
9	99.96
10	99.98
A-value 0.87	

Varying the Amount of Peening

The amount of peening per pass, **A**, can be varied by changing either **n** (number of indentations per unit area) or **a** (average area per indentation) or both. **n** can be changed by varying either the nozzle movement rate or the shot flow rate. **a** is, however, prescribed by the peening intensity and hardness of component.

Example: Referring to the values given in Table 1 we can expect that doubling n would have the same effect as using two passes. Hence we expect that we would then get a coverage of **83%** in one pass - with a corresponding **A** value of **1·74**. That is only true, however, if we have adjusted air-pressure/wheel-speed to maintain the same shot velocity and hence indentation area, **a**. Assuming that we have done that, then we should get near to 83% coverage in one pass. **83** then substituted for **58** in equation (4). Four passes will then be predicted as applying 99·91% coverage. **A** is now **1·743** for 83% coverage in one pass. We should, however, actually measure the coverage achieved in one pass with the doubled flow rate – just to be sure.

a can be changed by varying the average indentation diameter, **d**. Since $a = \pi * d^2/4$ then, using the value of **d** predicted by equation (1), we have that:

$$a = P*D^2*v \qquad (5)$$

where: **P** is a constant, **D** is shot diameter and **v** is shot velocity.

Equation (5) predicts, for example, that doubling the shot velocity (other parameters remaining constant) will double the average area of the indentations. That, in turn, means that the amount of peening per pass, **A**, will be doubled.

LAYER EVOLUTION CONTROL USING SATURATION 'TIME'

The primary function of a saturation curve is to indicate the 'saturation intensity'. This gives us our direct measure of layer depth potential. Saturation intensity occurs at a 'saturation time', **T**.

T corresponds to the amount of peening that was needed to reach the saturation point for flat Almen strips. Experience may lead users to be confident that the amount of peening that corresponds to some multiple of **T** will give a satisfactory layer evolution if applied to a particular component. This approach is crude but pragmatic. Its great attraction is that we have a readily-available, objective, quantitative, measure of an amount of peening. Three factors must, however, be borne in mind:

1 Components normally have a different hardness from that of Almen strips,
2 Components are not flat Almen strips - they will certainly have a different geometry and
3 At the saturation point the deformed surface layer of an Almen strip is not 'fully-developed'.

Taking the three factors in isolation:

1 Hardness. The average area of an indentation, $\pi d^2/4$, is inversely proportional to the square root of the hardness of the component (other things being equal). In order to achieve the same amount of peening of a component, A_c, as has been applied to the Almen strips, A_s, we can use the equation:

$$A_c = A_s*\sqrt{(H_s/H_c)} \qquad (6)$$

where H_s is strip hardness and H_c is the component's hardness.

As examples: if the ratio of hardnesses is 4:1 then A_c would be doubled and if it is 1:4 then AC would be halved.

2 Geometry. Life would be much easier for shot peeners if all components were simple rectangular blocks. In reality, a great deal of expertise has to be applied in order to ensure that complex-shaped components receive full peening coverage. Specifications require, however, that the Almen strips used for saturation curve determination are in relevant positions. It is, of course, impossible to generalize about the effect of component geometry on degree of coverage. Doubling the amount of peening to **2T**, would be sufficient to allow for most geometrical shapes. One exception would be the well-known situation of deep-hole peening.

3 **Layer development at T for Almen strips.** A full discussion of this factor would require (at least) a complete article. As a guide it is simply suggested that at **2T** we have fully-developed layers on Almen strips.

Example of considering all three factors together (rather than in isolation):

A typical component having a hardness only a quarter of that of Almen strips would approach full development of the peened surface layer at **2T**. That estimate is based on allowing the amount of peening to be halved because of hardness, then doubled to allow for geometry and then doubled again to allow for the fact that Almen strips do not have a fully-developed layer at **T**.

It must be emphasized that predictions of required amounts of peening must be confirmed by actual inspection.

Confirmation of Coverage Attainment using Saturation 'Time'.

Let us assume that we have a particular set-up for which we have established the minimum amount of peening, **B**, that will give the required level of coverage. That minimum amount of peening has been found, for example, to correspond to a peening 'time' of **1·8T** (which might be the equivalent of, for example, **4·6 passes**). We now know that we can reach the required coverage level by applying **5 passes** – provided that the conditions that gave the measured T value are maintained.

DISCUSSION

This article has attempted to show that we can exercise effective control of peened layer development provided that we separate layer thickness control from layer evolution control. The 'Golden Rules' are:

1 **Layer thickness is controlled by applying a specified range of saturation intensity and**

2 **Layer evolution is controlled by applying a specified amount of peening.**

Layer thickness control is exercised effectively by deriving a saturation curve for each production set-up. Saturation curve testing is well-established, reliable and objective. Layer evolution is generally monitored by determining the amount of coverage that has been applied. The only specified procedure (to the best of the author's knowledge) is that of so-called "100% coverage". This is highly subjective and is based on an individual's opinion that there are no detectable unpeened areas. It follows that there must be a significant difference between "100% coverage" and true 100% coverage.

The procedures proposed in this article for objective layer evolution control are based on making coverage measurements well below '100%' – ideally in the region of 50% which gives optimum accuracy. Coverage changes close to a true 100% value are virtually impossible to detect. It is no coincidence that several patented methods of coverage inspection have been developed. Perhaps the best known of these is "Peenscan" which involves a fluorescent lacquer being peened off and any residue being detected using UV light.

The great problem with conventional visual coverage inspection is that human eyes (and camera lenses) accept reflected light from a variety of angles. This makes it extremely difficult to differentiate between an indentation and surrounding 'rumple zones'. Visual inspection is, however, very useful for detecting substantial under-peening and macro variation of coverage.

Effective control of layer evolution leads to higher productivity. If we can apply the optimum amount of peening we can avoid both under-peening and over-peening. Over-peening is all too prevalent with its consequential effects on increased shot breakdown, wasted peening time and surface property deterioration.

Characterization of peened surfaces will be the subject of the author's next article. This will include a novel, low-cost, objective, layer evolution detection procedure.

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