Shot Peening Coverage: Prediction and Control

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INTRODUCTION

For both peeners and customers, coverage is of vital importance. Our central problem is to be able to predict and control coverage so as to reach a specified level. It is not sufficient, however, to reach the specified coverage at just one location. Different locations, subject to greater amounts of peening, would then suffer excessive peening. An efficient, quantitative procedure for coverage prediction and control should be applied at several locations leading, if required, to 'coverage maps' for components. Two basic problems can be associated with coverage prediction and control:

1 Specifying and achieving a required level of coverage and

2 Specifying and achieving a required distribution of coverage.

This article concentrates on the first problem but includes the second as 'coverage mapping'. The next article in this series concentrates on the second problem but utilizes the procedures proposed to solve the first problem.

Specifying a required level of coverage is a necessary starting point. Unfortunately, the only logical feature of coverage specification appears to be its definition: "Coverage is the percentage of a surface that has been indented at least once". With that as a definition, it appears absurd to talk of factors such as "200% coverage". 100% coverage is impossible to either measure or guarantee for a finite component. All theoretical and practical evidence points to an exponential approach to 100% coverage as the amount of peening is increased. True 100% coverage is possible for a small component, as a statistical freak, but is the exception rather than the rule. It is, on the other hand, reasonable to specify a predicted level of coverage – so long as that level is less than 100%. An alternative target level is the so-called "Full coverage" which is defined as 98% actual coverage.

Achieving a specified, quantified level of coverage at a particular point is possible. It is proposed that such achievement should be based on multiples of the amount of peening required to achieve a modest, easily-measured level of coverage. The principles underlying this approach are described together with simple computer programs that carry out all necessary calculations and graph plotting.

CAUSE AND EFFECT

Coverage is a classic case of 'cause and effect'. It is caused by impacting shot particles producing a near-random array of indentations. This generates the effect that components are covered, to a greater or lesser extent, with indentations. The extent of the coverage is the subject of specifications such as SAE J2277.

Coverage, our basic 'effect' parameter, is defined as:

C% = the percentage of a surface that has been indented at least once

The ratio of total indent area to target area, **Ar**, our 'cause' parameter, is given by:

Ar = Total indent area/target area.

The difference between the cause and effect parameters is illustrated in fig.1. This shows a model of randomly-distributed circular indentations - equivalent to a photograph of a selected peened area. The corresponding coverage, **C**, happens to be 63% (confirmed using image analysis). The total area of the indentations within the square excluding overlapping is the same as the area of the square. Hence the indent area ratio, **Ar**, is **1·0**.

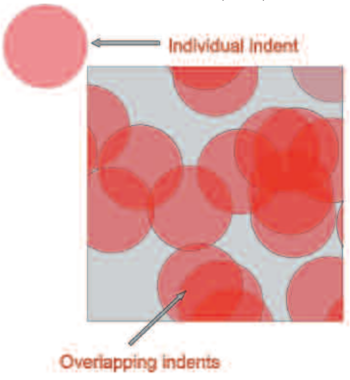

Fig.1. Model of 63% coverage created by randomly-distributed circular indentations.

The causative parameter, **Ar**, may be appreciated more readily from the following analogy. Twenty identical bombs are dropped randomly onto a target area of 2000m^2. Each bomb produces a circular crater of 100m^2. We therefore have 2000m^2 of craters produced within the target area of 2000m^2. The ratio of crater area to target area is therefore equal to **1** (2000m^2/2000m^2). Aerial photography indicates that about 63% of the target area has been covered by craters (as per Fig.1). A second, identical bombing of the target area is carried out - resulting in about 86% coverage - with the ratio of crater area to target area now equal to **2** (4000m^2/2000m^2). This analogy illustrates the factor (**Ar**) that governs coverage control: total area of craters divided by target area.

The ratio of total indent area to target area, **Ar**, may be regarded as the amount of peening that has to be done per unit area in order to cause a corresponding amount of coverage. It is a simple linear function of our basic peening variables: average area of individual indents, number of indents per unit area and time of peening. That means, for example, that doubling the time of peening (by either doubling the number of passes or halving the traverse speed) doubles **Ar**.

RELATIONSHIP BETWEEN Ar AND C%

Prediction and control of shot peening hinges on the relationship between **Ar** and **C%**. Equation (1) gives us the established relationship between coverage and indent ratio, **Ar**.

$$C\% = 100[1 - \exp(- Ar)] \tag{1}$$

where: **C** = coverage and **Ar** = ratio of total indent area to target area.

Coverage increases as **Ar** increases. The rate of increase falls with increasing **Ar**. Fig.2 shows the exponential shape of equation (1). Two particular Ar ratios, **Ar** = 1 and 4, have been highlighted. If, for example, one pass imposed an indent ratio of 1, we would predict 63% coverage. An indent ratio of 4 would give a predicted 98% coverage. 98% coverage is specified as "full coverage" in J2277.

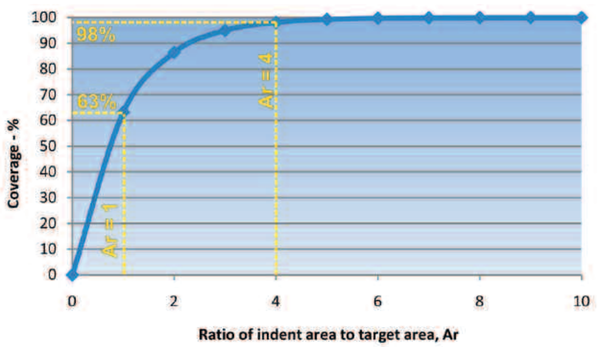

Fig.2 Exponential variation of coverage with ratio of indent area to target area.

Table 1 gives the coverage values shown in fig.2 for corresponding integral values of **Ar**. Coverage values are quoted to three decimal places even though such precision has no practical significance. We cannot measure coverage to three significant figures – they are included purely to indicate that 100% is never reached.

Table 1. Coverage, **C**, for Integral values of Indent Ratio, **Ar**.

Ar	C%	Unpeened - %
1	63.212	36.788
2	86.466	13.534
3	95.021	4.979
4	98.168	1.832
5	99.326	0.674
6	99.752	0.248
7	99.909	0.091
8	99.966	0.034
9	99.988	0.012
10	99.995	0.005

The unpeened percentages (100-C%) have been included in Table 1 as they can be used to explain why 100% is never reached. After applying one pass imposing an **Ar** equal to 1 then 36.788% has not been peened. A second identical pass will peen only 63% of that unpeened 37% (in round figures) – leaving 37% of the 37% unpeened which equals 13.5%. A third pass leaves 37% of that 13.5% unpeened or 5%, and so on. We will always have some material unpeened, however small a percentage.

FULL COVERAGE AND Ar

Full coverage is defined in J2277 as being equivalent to 98% actual coverage. This sets a realistic target for coverage as it is almost impossible to measure coverages higher than 98%. Full coverage is achieved when an indent ratio of 4 is reached – as indicated in fig.1 and Table 1. We can impose an indent ratio of 4 either in a single pass or by repeating a number of identical passes. Both approaches require that at least one coverage measurement is made. This measurement can then be used to adjust peening parameters so as to give 'full coverage'.

Solving for **Ar** using one coverage measurement is simplified by using equation (2) which is just a re-arrangement of equation (1):

$$Ar = - \ln[(100 - C\%)/100] \tag{2}$$

where **ln** stands for natural logarithm.

If, for example, we measure coverage after a single pass as being 39% then substitution into equation (2) shows that **Ar** equals 0·5. In order to impose an indent ratio of 4 we therefore need to either use 8 identical passes over the same area or to increase the effective flow rate eightfold.

Manual calculation of the number of passes needed to achieve 'full coverage' can be avoided - either by using a graphical approach or by using simple computer programs (detailed in a later section). One such graphical approach uses a function that is derived from a modified version of equation (1). The modified version is that:

$$Cn\% = 100[1 - (1 - C1)^n] \tag{3}$$

where **Cn** is the coverage after **n** passes and **C1** is the measured coverage after **1** pass.

If we substitute **Cn = 98** into equation (3) and do some re-arrangement we arrive at:

$$\mathbf{C1 = 100[1 - 0{\cdot}02^{1/n}]} \qquad (4)$$

Equation (4) has been plotted as fig.3 (using log-log scales to produce a straighter curve). The 'arrowed path', **ABC**, illustrates how, for example, a 39% coverage measured for one pass leads to a predicted 8 passes for 98% coverage.

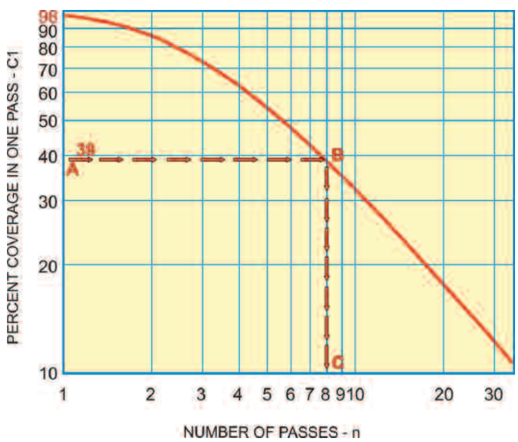

Fig.3 Prediction of number of passes, n, required to induce 98% (full) coverage.

FACTORS AFFECTING INDENT AREA/TARGET AREA RATIO, Ar

Coverage for a specified target area depends only on the indent area/target area ratio, **Ar** that has been imposed on the component. It follows that any of the three factors that affect **Ar** can be used to control coverage. These three factors are:

1) Peening time, t,

2) Average area of the indentations, a, and

3) Indenting rate, n.

There is a very simple relationship between **Ar** and the three controlling factors:

$$\mathbf{Ar = t*a*n} \qquad (5)$$

It is worth noting that **Ar** is what is called a "dimensionless quantity" (i.e., it is a number that has no dimensions). If we multiply together the units for each of the three controlling factors they cancel each other out: $(s)\cdot(m^2)\ (s^{-1}m^{-2}) = 0$. If we can keep any two of the three factors constant then **Ar** is directly proportional to the third factor. It follows that coverage versus **t**, coverage versus **a** and coverage versus **n** curves must all have the same exponential shape as the coverage versus **Ar** curve.

1) Peening time, t

Peening time is the simplest of the three control factors to employ. This is because peening time does not affect the other two factors. It is axiomatic that as we increase the peening time then coverage increases. Peening time is the commonest method of controlling coverage. Peening 'time' itself is normally a combination of two parameters: (1) the number of times that the shot stream passes over a given point on the component and (2) the speed at which the shot stream is moving. If speed is kept constant then we can plot coverage against number of passes, **p**. If the number of passes is kept constant then we should plot coverage against the reciprocal of speed to maintain the exponential curve shape.

2) Average area of the indentations, a

There is an equation that relates indentation area, **a**, to shot particle parameters and component hardness, **B**:

$$a = 2{\cdot}6*S^{2}*\rho^{0{\cdot}5}*v/B^{0{\cdot}5} \qquad (6)$$

where **S** is shot diameter, **ρ** is shot density and **v** is shot velocity.

If the only peening variable was shot diameter then this would exert a substantial effect on **a** and therefore on **Ar**. In practice, however, shot diameter interacts with the third factor, **n**. Component hardness is, however, independent of shot stream properties. The harder the component the smaller are the indentations induced by a particular shot stream – reducing **Ar** and therefore reducing coverage rate.

3) Indenting rate, n.

The number of indentations produced per second per unit area of target can be termed "indenting rate", **n**. It is a function of shot flow rate, shot stream geometry and shot size. If the shot flow rate and shot stream geometry are kept constant then **n** is inversely proportional to the cube of the shot diameter, **S**:

$$\mathbf{n = K/S^3} \qquad (7)$$

where **K** is a constant.

The 'cube effect' arises because particle mass is its volume multiplied by its density and the volume of a spherical particle is proportional to the cube of its diameter.

The separate effects of the three factors **t**, **a** and **n** are depicted in fig.4.

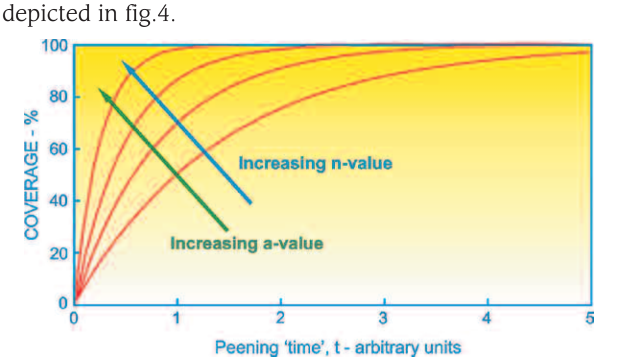

Fig.4 Effects on coverage of peening time, t, average indent area, a, and indenting rate, n.

If we multiply equation (6) by equation (7) then **a*n = M/S** where **M** is a constant. Hence, substituting into equation (5):

$$\mathbf{Ar/t = M/S} \qquad (8)$$

Ar/t is the rate of producing indentation area. Equation (8) is, therefore, a quantification of the well-known expression that "Other things being equal, smaller shot gives faster coverage".

COMPUTER-BASED PREDICTION PROGRAMS

Simple computer-based programs can be used to produce objective predictions of coverage evolution. Two programs are described here for (1) single-measurements of coverage – preferably at an early stage of peening and (2) multi-measurements of coverage at progressive stages of peening. The programs assume that constant peening conditions are being maintained.

Single-Measurement Coverage Prediction

The indent-to-target area ratio, **Ar**, can be regarded as the product of **A** and **n** so that:

$$\mathbf{Ar = A*n} \quad (9)$$

where **A** is the value of **Ar** after one pass and **n** is the number of identical passes.

Equation (2) can then be re-written as:

$$\mathbf{A = \{-\ln[(100 - C\%)/100]\}/n} \quad (10)$$

Equation (1) can also be re-written as:

$$\mathbf{C\% = 100[1 - \exp(- A*n)]} \quad (11)$$

We can use equation (11) to predict coverage after any number of passes - provided that we have one measurement of coverage available. That measurement allows us to calculate **A**. The value of **A** can be determined by substituting one measured value of **C** for a known value of **n** into equation (10). For example, if **C = 0.58** when **n = 1** then **A = 0·87**. Substituting 0·87 for A into equation (11) gives:

$$\mathbf{C\% = 100[1 - \exp(- n*0{\cdot}87)]} \quad (12)$$

The derived equation (11) can now be used to predict coverage for different values of **n** and thence to construct a coverage curve specific to the single measurement. The Excel-based program for carrying out the procedure is illustrated in fig.5. Different parts of a component will normally show different levels of coverage for a given amount of peening – as discussed later. The 'single-measurement' program can be applied to measurements made at different locations on a given component - predicting the passes required to satisfy a specified minimum coverage level. If coverage has been measured after, say, two passes then that is also catered for by the program.

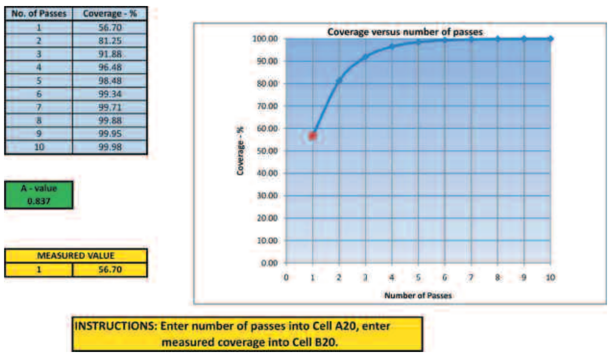

Fig.5 Worksheet of Coverage Predictor program using a Single coverage measurement.

Multi-measurement Coverage Prediction

Several coverage measurements could have been made, at the same location, on a given component that has been peened progressively using an increasing number of, say, passes. We can then 'best-fit' these measurements to the exponential coverage curve - equation (11). The program is illustrated by the worksheet shown as fig.6. This includes two graphs – one of the data points and the corresponding best-fit curve and the other a complete curve based on the deduced 'best' value for **A**.

Coverage Mapping

Coverage mapping is becoming increasingly important. Users realize that some parts of a component reach, for example, 'full coverage' much earlier during peening than do other parts of the component. This means that some parts may become seriously over-peened. It is virtually impossible to monitor this over-peening since 'full coverage' represents an absolute limit for accurate coverage measurement. Single-measurement coverage prediction provides a solution to the problem.

Single measurements of coverage at an early stage of peening – corresponding to a modest, easily-measured, level of coverage – can be carried out at a range of points on a component that are representative of the several geometrical features of the component. These measurements, together with their locations, comprise a 'coverage map'. The "Single Measurement Coverage Predictor Program" can then be applied to each measurement to indicate the adjustments to the amount of peening that are needed at each point in order to achieve the target coverage. If individual adjustments are not to be made then application of the program would provide an 'over-peening coverage map'.

As a hypothetical example, consider just two points on a component. At Point 1 the coverage after one pass is measured as 56·7%, leading to a predicted requirement of 5 passes to achieve 98% - as per fig.5. At point 2 the coverage after one pass is measured as 36%, leading to a predicted requirement of 10 passes to achieve 98%. If 10 identical passes are applied to both points then Point 1 will have received twice the necessary amount of peening. Alternatively, the effective peening rate at Point 2 could have been doubled so that both points need only have 5 passes to achieve 'full coverage'.

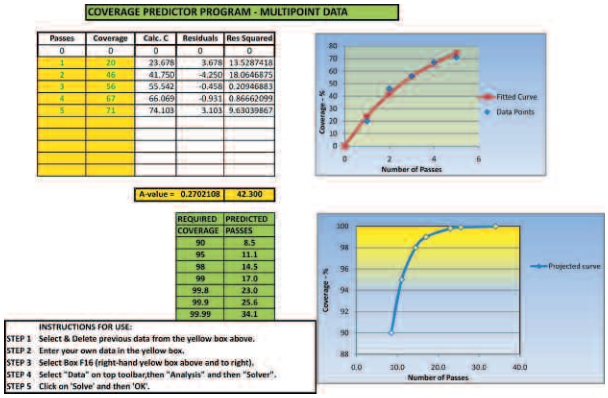

Fig.6 Worksheet of Coverage Predictor program using Multi-measurements.

DISCUSSION

Quantitative coverage prediction and control is becoming increasingly important. There is a growing realization that optimum component properties are attained at coverage levels well below 98%. That is due to the avoidance of gross over-peening.

Application of the principle that "All areas of the component shall be 100% covered with indentations when examined in a specified manner" does not ensure a controlled, optimum, amount of coverage. With that approach some regions may have been peened many times more than other regions – the difference cannot be detected. Over-peening can be avoided by making reasonably-accurate coverage measurements, possible in the region of 30 to 60% coverage, followed by planned increases in indent ratio.

An extra advantage of using computer programs is that they can easily be used to accumulate a data base of information. Machine parameters that previously led to established coverage curves can then be accessed.

Shop-floor coverage measurements present a different scenario from those that are possible using laboratory conditions. The availability of low-cost USB microscopes allows, however, shop-floor images to be compared with stored images of reference coverage samples that have previously been image analyzed.

Both the Predictor programs and the Saturation Curve Solver programs are available free at www.shotpeener.com. Free 'Customer support' is available from the author – shotpeener@btinternet.com.

It is important to note that this article is based on the prediction and control of coverage at specific target locations on a component. Coverage will vary with position on a component. This is due to the inhomogeneous way in which shot streams induce coverage at different locations. Analysis of this inhomogeneity will be described in the next article in this series.