ACADEMIC STUDY
Dr. David Kirk | Coventry University

Back to Basics: Coverage

INTRODUCTION

Coverage and peening intensity are the two major properties for peened components that have to be both measured and controlled. As with all definitions "The Devil is in the Detail." SAE's J2277 does not help clarity of understanding and is somewhat misleading as the following extract indicates: "Coverage is defined as the percentage of a surface that has been impacted by the peening media. The minimum peening time required to obtain 100% coverage is determined by gradually increasing total peening time until the entire surface being peened exhibits overlapping dimpling. Coverages above 100% are multiples of the exposure time required to achieve 100% coverage." Only the first sentence is accurate!

Coverage measurement has to be an average as it is based on being made over a selected area. Coverage varies over the surface of a peened component. Both manual and computer-aided measurement procedures are available. As peening progresses, coverage increases. However, accuracy of coverage measurement decreases as coverage increases. This is so important that an alternative expression to 100% coverage has been coined. "Full coverage" occurs when 98% of the peened surface is covered with dents. The rate of coverage increase is very similar to that of a simple exponential curve. This allows prediction of the coverage achieved using different peening times.

An important feature of coverage development is the increasing probability of multiple impacting as illustrated by fig.1 (Fig.6 of *The Shot Peener* article, Spring, 2016).

On a sub-microscopic scale, coverage is either 0% or 100% as can be seen in fig.1. On a macroscopic scale coverage is an average of dented and undented areas.

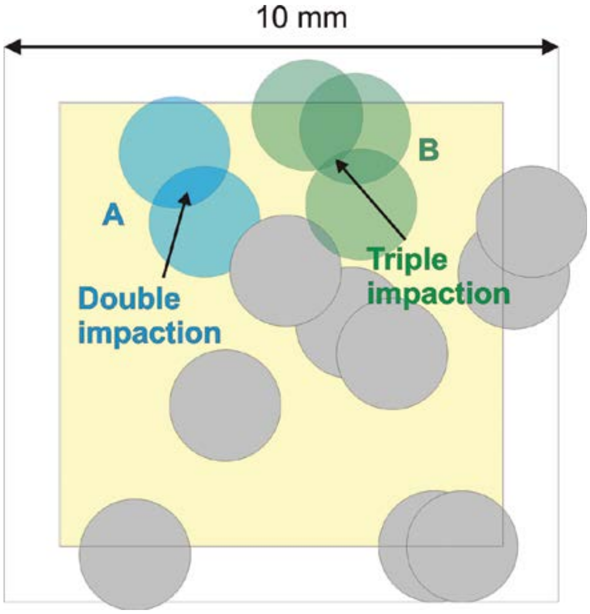

Fig.1. Multiple impactions with 42% coverage.

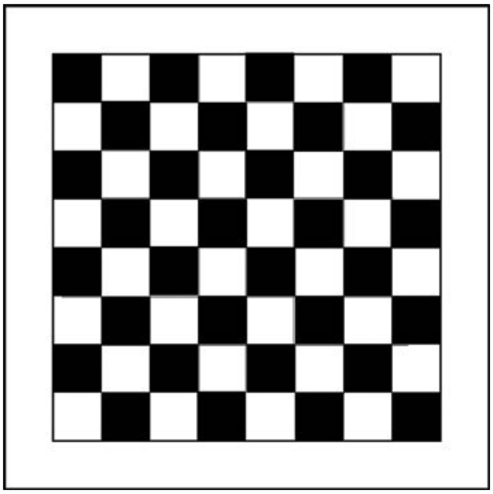

Fig.2. Chess board coverage.

AVERAGED COVERAGE

For sub-microscopic coverage, consider the analogous situation represented as a standard chess board in fig.2. We see that the board contains precisely 50% each of black and white squares—analogous to 100% and 0% coverage of individual squares.

Consider next the coverage if we only sampled part of the board. Fig.3 highlights just nine squares. Black squares occupy five of the nine squares and white the remaining four. The coverage is no longer 50/50. If the sample was of only the top left-hand square the coverage would be 100%. This analogy may seem trivial but it serves to highlight an important feature of coverage estimation. The sample area should (a) be large enough to obviate statistical fluctuation of the average whilst (b) be small enough so as to not mask any true variability of average coverage. Fig.4 illustrates this important principle, using the popular line-intersection measurement technique (described later) and indicating a suggested optimum line length.

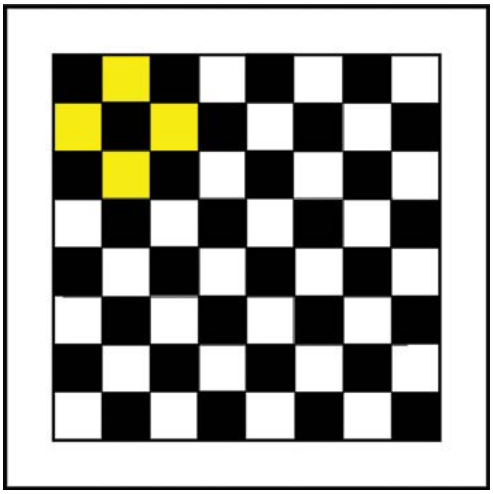

Fig.3. Highlighted area of chess board.

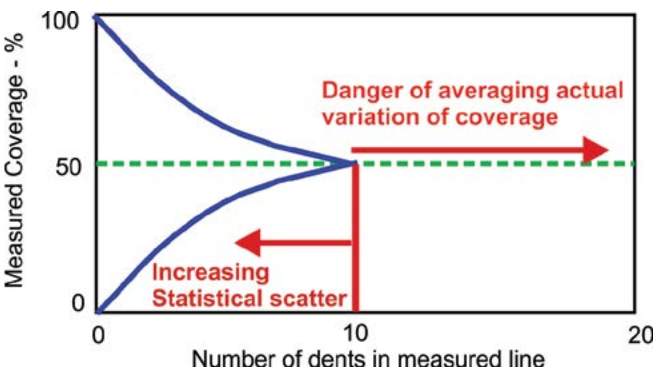

Fig.4. Suggested optimization of selected line length for coverage measurement.

INCREASE OF COVERAGE WITH INCREASE OF PEENING

As peening progresses, the average percentage of the surface containing dents increases. This increase, for a given shot stream, is exponential towards 100%, rather than being linear. Fig.5 illustrates the theoretical shape of a coverage/peening time curve. The peening time scale is arbitrary as it depends on the indentation rate.

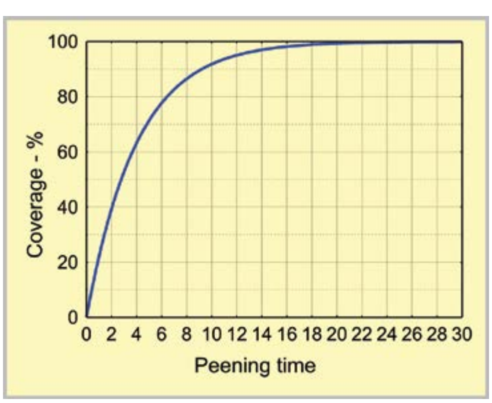

Fig.5. Theoretical coverage versus peening time curve.

The equation for coverage versus peening time is:

$$\mathbf{C = 100(1 - exp(-\pi D^2/4.R.t))} \qquad (1)$$

Where **C** is the percentage coverage, **D** is the average diameter of each dent, **R** is the rate of impacting (number of dents imparted per unit area of surface per unit of peening time) and **t** is the peening time.

COVERAGE RATE

Coverage rate is important for shot peeners because it determines how long a component needs to be peened in order to impart the customer's specified amount of coverage. The coverage rate, **K**, extracted from equation (1) is t given by:

$$\mathbf{K = \pi D^2/4. R} \qquad (2)$$

For which the $\boldsymbol{\pi D^2/4}$ term is the projected area of each dent.

Equations (1) and (2) allow us to exercise quantitative coverage control!

If we can assign a value to **K**, we can predict the coverage that will be achieved in any given peening time, **t**. Equation (1) simplifies to:

$$\mathbf{C = 100(1 - exp(-K.t))} \qquad (3)$$

The coverage rate, **K**, is simply the product of the dents' average area multiplied by the rate at which these dents are being produced. Dent diameter can be determined either directly on a peened component or theoretically using a dent diameter prediction equation as published in the Spring, 2004 edition of *The Shot Peener*. The rate of denting can be predicted using the cone area of the shot stream and the shot flow rate. If, for example, 100 shot particles per second are indenting a cone area of 400 square millimetres the rate of impacting is 0.25 dents per square millimetre per second. If the area of each dent is 1 square millimetre then the coverage rate, K, will be 0.25 per second (1 mm^2 times 0.25 $mm^{-2}s^{-1}$).

MULTIPLE DENTING DURING COVERAGE DEVELOPMENT

As indicated in fig.1, multiple denting occurs even at low coverages. Fig.6 illustrates, quantitatively, how multiple

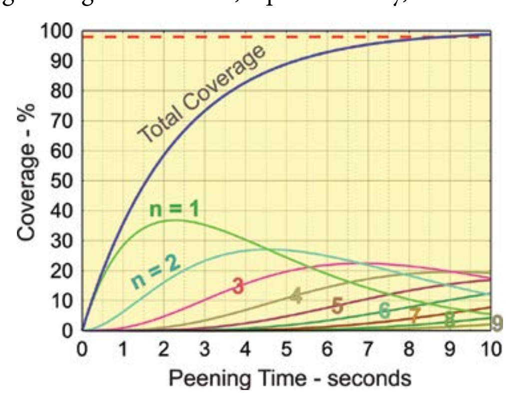

Fig.6. Increase of multiple denting with peening time.

denting increases as peening progresses. After some five seconds (for this example) total coverage is about 90% but more of the surface has received two dents than has received a single dent. Twenty percent of the surface has received triple denting.

Again we must appreciate that the predicted multiple denting is only the average value for a peened component. Some parts of the peened surface will experience more than the average multiple denting and some parts less.

In one sense, we are "Caught between the Devil and the Deep Blue Sea." If we try to get close to 100% average coverage, we run the risk of exceeding the component's tolerance for massive plastic deformation. On the other hand, if we reduce the amount of peening to avoid that danger, we run the risk of leaving large islands of undented component surface. This leads to a consideration of what should be the optimum average coverage.

OPTIMUM AVERAGE COVERAGE

The optimum coverage of a component, for a given peening intensity, varies according to material and service conditions. Experience has shown that the optimum coverage can be as low as 50% but rarely exceeds 90%. Fig.7 is a graphical representation of one particular set of conditions. It is worth noting that when maximum improvement is being indicated there is only a tiny reduction on either side of the optimum coverage.

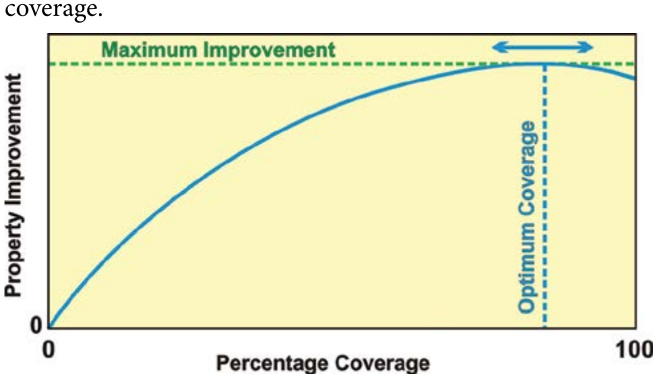

Fig.7. Example of a coverage optimization curve.

MACRO VARIATION OF AVERAGE COVERAGE

Another basic feature of a shot stream's coverage is that it varies considerably. This variability is curiously under-publicized. In order to appreciate variability, consider the following analogous situation.

Squaddies in training

A drill sergeant, having a warped sense of humor, decided to organize his squad into an unusual formation. Instead of their normal rectangle, they had to adopt a near-circular array. Then they were marched across a wet, soggy, rectangular field leaving clear bootprints as they marched in unison. The result is represented as a cartoon in fig.8.

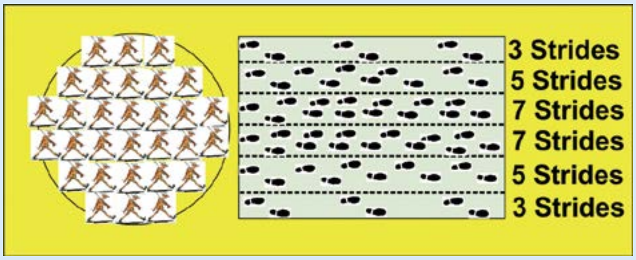

Fig.8. Analogous variation of bootprint coverage.

The coverage of bootprints varies from three to seven for this small squad analogy. For a squad more equivalent to a shot stream, the squad would have to number in the thousands. For that size, the effect could be represented as an aerial photograph of the field as in fig.9.

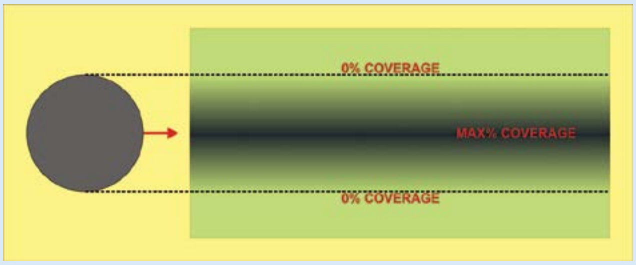

Fig.9. Imagined aerial photograph of bootprints left by huge squad marched across a field.

As alternatives to the squaddie analogy, consider the following analogies:

(1) Painting a barn door. Would you use a round or a flat brush? The relative effects are illustrated in fig.10.

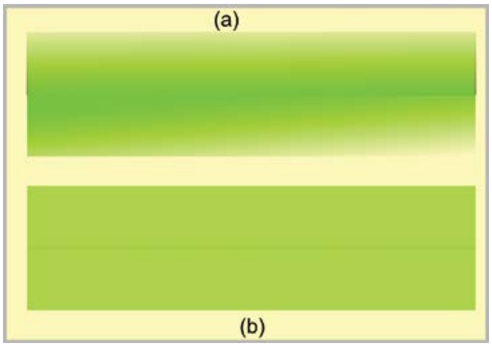

Fig.10. Paint stripes using (a) round brush and (b) flat brush.

(2) Try using an aerosol spray, moving quickly over a sheet of cardboard. The effect is very similar to that of a shot stream, as well as to (a) in fig.10.

COVERAGE CONTROL

It must be stressed that:

Coverage achieved is the product of coverage rate multiplied by the actual time of peening.

As already pointed out, the coverage rate varies because of its macro-variation. Coverage rate control depends upon the offset of repeat passes. Fig.11 illustrates the stripe effect of offsetting by an amount equal to the shot stream's diameter. Fig.12 illustrates the reduction in stripe severity due to reducing the offset.

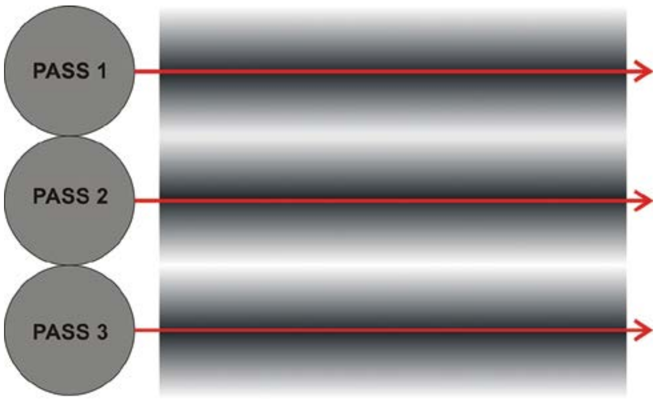

Fig.11. Stripe effect produced by an offset equal to the shot stream's diameter.

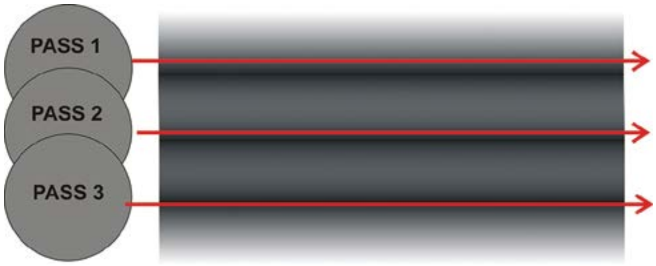

Fig.12. Reduced stripe effect by reduced offset.

Fig.13 indicates that optimum coverage uniformity would result from using an offset half of the shot stream's indenting area diameter, D.

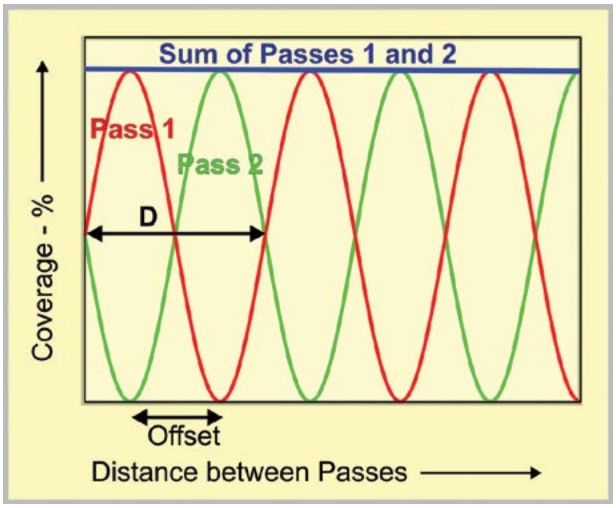

Fig.13. Prediction of uniform coverage using an offset of half of the shot-stream's diameter, ***D****.*

The effects just shown have been applied to the simple case of peening flat surfaces. Controlled offset should be applied to more complex components and is particularly important when peening holes.

COVERAGE MEASUREMENT

Coverage measurements can be made either manually, using the naked eye, or by employing computer-based image-analysis software.

(a) Manual Coverage Measurement

The most commonly-used manual method is to compare a magnified image of the shot-peened surface with "standard" images, such as those in fig.14. There is, however, a subjective element in this procedure. On the other hand, the human brain can act as a marvellous computer. Indeed, in many areas of image analysis, manual measurement is still considered superior to computer-based measurement.

Often overlooked is the lineal analysis method for quantifying coverage. It is similar to computer-based methods insofar as lines on an image are divided into dent and non-dent lengths. The principle involved is illustrated schematically by fig.15.

As an exercise, printing fig.15 allows the "dent lengths" to be measured using an office ruler. The sum of the "dent lengths" on each line is then divided by the "100%" length. By way of illustration, on a print of fig.15 and using 170 mm lines the author found the total "dent lengths" to be 137, 140,120 and 140 mm for lines 1, 2, 3 and 4 respectively. Dividing these by 1.7 (in order to arrive at coverage percentage) gave values of 80.6, 82.4, 70.6 and 82.4 respectively. The average is 79.0%. The variation of the values reflects the variability of coverage that occurs, on a micro scale, for actual peened components. In practice, a high-resolution photograph of a peened area can be enlarged and printed for lineal examination. On real peened components the author aims for making about 20 measurements of dent lengths per line on up to 10 lines (it comes quicker with practice!).

Fig.15 is schematic, being designed solely to illustrate the principle of the lineal analysis method when applied to coverage measurement. Real peened surfaces are, of course, much less clearly defined. That is where the human eye can score over one aspect of computer-based image analysis. An experienced observer can distinguish dent edge borders individually with reasonable accuracy. The human visual cortex is an excellent image analysis apparatus.

(b) Computer-based Image Analysis of Coverage

This method is based on exactly the same principle as the manual lineal analysis technique. The main differences are that: each computer scan line normally embraces far more dents and far more scan lines are involved. One major problem, however, is the difficulty of identifying dent edges.

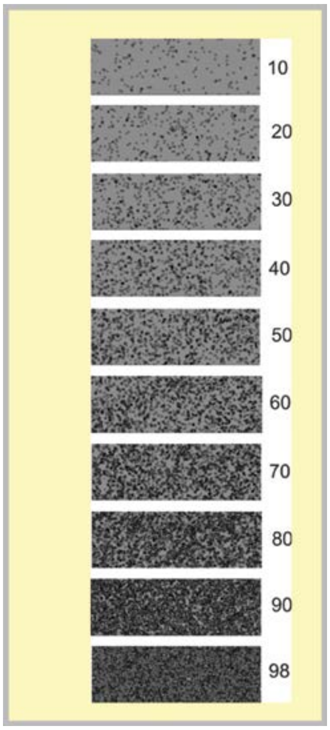

Fig.14. Standard Comparison images for Coverage Assessment.

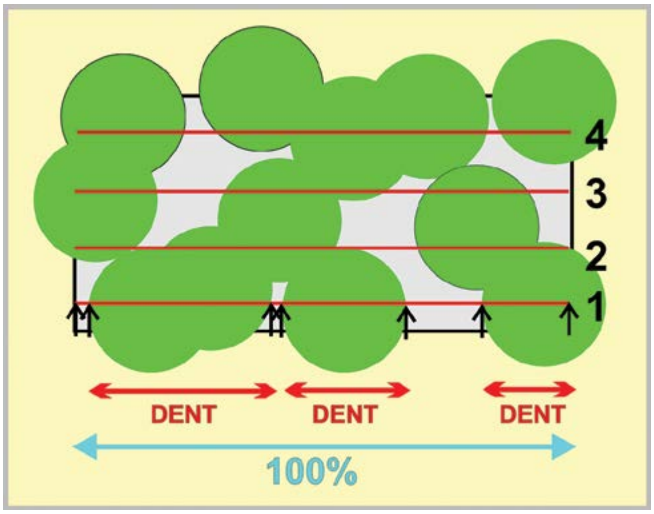

Fig.15. Identifying "Dent" lengths for a fixed length of measurement.

This does not arise when computer-based image analysis is being employed to study shot size and shape variation. "Image Analysis and Computer Microscopy of Shot Particles" was the very first article that I submitted to *The Shot Peener* (Vol.15, Issue 3, Fall 2001).

DISCUSSION

Coverage is very important and warrants very serious consideration. At least nine of the author's Shot Peener articles have been devoted to the topic.

Coverage measurement is, of course, a primary consideration. It is needed in order to confirm the satisfying of customer requirements. Other relevant factors need to be understood. Only the basic principles governing these factors have been presented in this article. Attached is a chronological list of *The Shot Peener* articles that give expanded treatments of those factors.

***The Shot Peener* Articles**

1. Coverage – Development, Measurement, Control and Significance. Fall, 2002.
2. Theoretical Principles of Shot Peening Coverage. Spring, 2005.
3. Shot Peening Coverage: Prediction and Control. Spring, 2009.
4. Non-uniformity of Shot Peening Coverage. Summer, 2009.
5. Shot Peening Coverage Requirements. Summer, 2012.
6. Quantification of Shot Peening Coverage. Fall, 2014.
7. Optimization of Shot Peening Coverage. Spring, 2010.
8. Coverage Variability. Winter, 2017.
9. Coverage Science. Fall, 2019.