**ACADEMIC STUDY**
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# Coverage Science

## INTRODUCTION

Science is almost always able to provide answers to questions about observed phenomena. Consider as examples: "Why are snowflakes sometimes large and sometimes small?", "Why are honeycombs made up of regular hexagons?" and "Why will a glass of warm milk solidify more quickly than an identical glass of cold milk when placed together in a freezer?" The ability of science to provide answers also applies to subject areas such as metals science, aka metallurgy. We do not need, however, to be subject specialists in order to appreciate and utilize the answers that can be obtained.

This article concerns shot peening coverage science. Most of the actual science involved is already available in several previous articles in *The Shot Peener*. Their content has been condensed so as to produce a simplified presentation.

Coverage is defined as the percentage of a component's surface that contains peen-induced dents. As peening progresses, the percentage of the surface containing dents increases. This increase, for a given shot stream, is exponential towards 100%, rather than being linear. Fig. 1 illustrates the theoretical shape of a coverage/peening time curve. The peening time scale is arbitrary as it depends on the indentation rate.

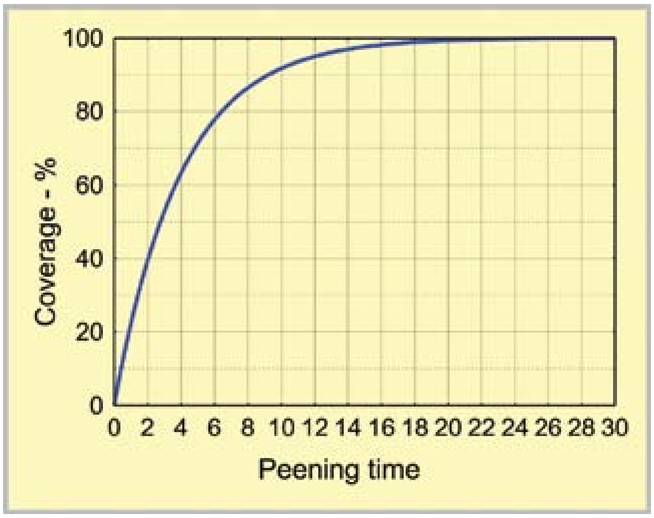


*Fig. 1. Theoretical coverage versus peening time curve.*

## COVERAGE RATE

Coverage rate is important to shot peeners because it determines how long a component must be peened in order to impart a customer's specified amount of coverage. The equation for coverage versus peening time is:

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

Where **C** is the percentage coverage, **r** is the average radius 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. The coverage rate, **K**, extracted from equation (1) is therefore given by:

$$\mathbf{K = \pi r^2.R} \qquad (2)$$

For which the $\pi r^2$ term is the 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) then 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. The equation was published in the Spring, 2004 edition of *The Shot Peener* as:

$$\mathbf{d = 1.278\ D.(1 - e^2)^{0.25}\ .\rho^{0.25}.v^{0.5}/B^{0.25}} \qquad (4)$$

Where **d = dent diameter, D = shot diameter, e = coefficient of restitution, ρ = sphere density, v = sphere velocity and B = Brinell hardness of component.**

It is much simpler, and quicker, to actually measure average dent diameters on a component that has been subjected to a low coverage percentage. Having established the average size of dents we next need a value for the rate, **R**, at which the indents are being produced.

A value for the rate of impacting, **R**, can be predicted by considering the geometry of the shot stream and the flow rate of shot particles. Consider, as an example, an air blast nozzle producing a conical shot stream (see fig. 2 on page 30). We know the feed rate, **F**, and the shot diameter, **D**, of shot flowing through the nozzle and we can measure the diameter of the peened circle, **CD**, when the shot stream is impacting a flat component's surface. From the feed rate and the average mass of the shot particles, we can estimate the flow rate of particles. If, for example, 100 shot particles per second are indenting an 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 $mm^{-2}s^{-1}$). This $0.25s^{-1}$ coverage rate happens to be that used in plotting fig. 1.

An ability to vary the coverage rate, **K**, allows us to tailor peening in order to give a desired coverage in an economical time. The three control parameters are: size of dents, rate of denting and peening time. Size of dents depends on the factors included in equation (4). In practice, peeners have little control over the size of dents being imparted. Varying the shot velocity, for example, would affect the peening intensity. This leaves us with having to rely on the rate of impacting, **R**, and the peening time, **t**, in order to control coverage. As a reminder, **R** is the rate of impacting (number of dents imparted per unit area of surface per unit of peening time). For a specific nozzle, **R** can be varied by simply varying the feed rate. Two factors must be borne in mind: (1) the feed rate has a maximum at which the nozzle becomes choked and shot flow stops and (2) increasing feed rate for a given nozzle increases the efficiency of power usage. The first factor is very familiar to air-blast shot peeners, the second factor much less so.

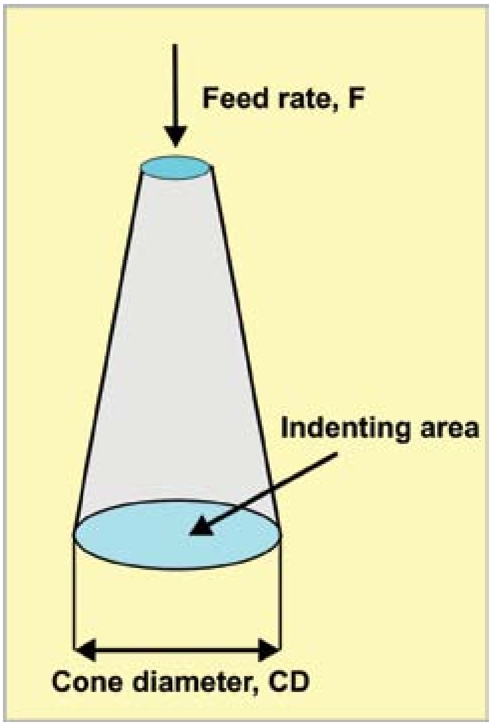


*Fig. 2. Conical shot stream.*

The reason for the conical shape of a shot stream emerging from a straight bore nozzle is that emerging air pushes the particles sideways. This is a non-uniform effect so that the indenting area becomes inhomogeneous. The center of the indenting area receives higher velocity shot particles than does outer areas. As a consequence, the coverage rate is highest at the center.

## EFFICIENCY OF AIR-BLAST POWER USAGE

Power is required to accelerate the air in the nozzle. It is also required to accelerate the shot particles. Power usage efficiency, $\eta$ can be defined as:

$$\eta = P_{shot}/P_{air} \tag{5}$$

Where $P_{shot}$ is the power needed to accelerate the shot and $P_{air}$ is the power needed to accelerate the air. For a given nozzle, shot and peening intensity, $P_{shot}$ is almost linear function of the feed rate whereas $P_{air}$ is almost constant. If the feed rate is zero then the power usage efficiency is also zero—we are simply blowing air! As the feed rate increases so does the power usage efficiency up to the rate at which the nozzle becomes choked.

In order to increase the coverage rate beyond the choke rate, we have to use a larger diameter nozzle. Estimating the effect of nozzle diameter on power usage efficiency requires consideration of how nozzle diameter affects $P_{air}$. For a given maintained air pressure the air flow is proportional to the cross-sectional area of the nozzle. This cross-sectional area is $\pi D^2/4$ where **D** is the nozzle's diameter. The power needed to produce the air flow is therefore proportional to $D^2$. Power needed to accelerate the shot to its emergent velocity is still (almost) a linear function of the feed rate, **F**. Fig. 3 is one example of the effect of nozzle diameter on air-blast power usage efficiency ratio. For this example, feed rates having a range of 0.8 to 8 has been combined with nozzle diameters having a range of 1 to 10 mm.

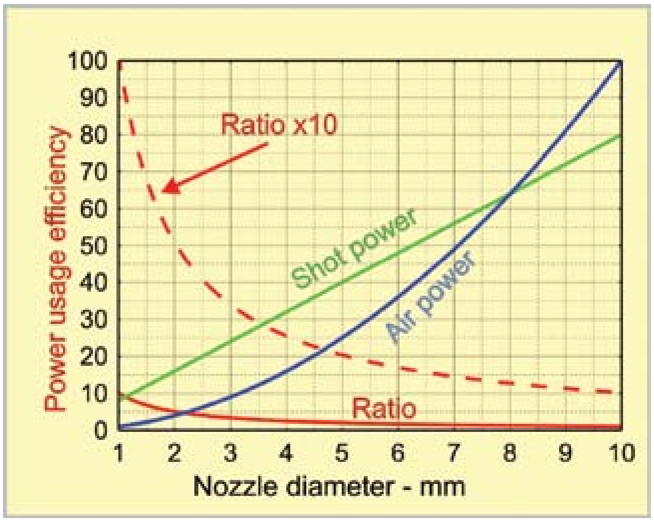


*Fig. 3. Effect of nozzle diameter on power usage efficiency ratio.*

## UNIFORMITY OF COVERAGE

It must be stressed that:

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

As a simple illustration, if one dent was being produced per unit area per second then 10 dents would be produced per unit area in 10 seconds. If, however, the coverage rate was doubled to two dents per second then 20 dents would be produced in 10 seconds or 10 dents in five seconds. These actual times of peening are only true if the shot stream is stationary over the component which hardly ever is the case.

In practice, perfect coverage uniformity is impossible to achieve—it can only be approached. Peeners have to contend with two major variables: (a) coverage rate variability within the indenting area and (b) the actual time of peening.

### Coverage Rate Variability within the Indenting Area

Fig. 4 is a pictorial representation of coverage rate variability within the indenting area. The darker shade at the center represents higher coverage rate.

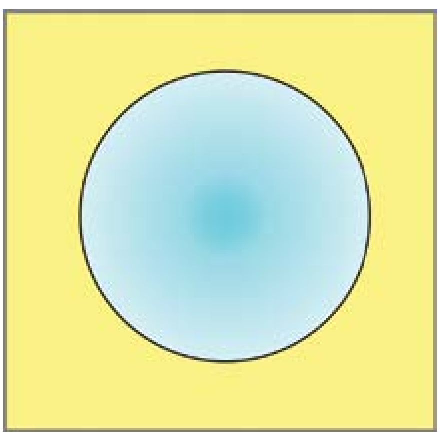

*Fig. 4. Coverage rate variability within indenting area.*

### Actual Time of Peening

If we move a circular-section shot stream in a straight line across a flat component's surface, the coverage of the peened area varies from zero to a maximum. This is because the actual time of peening varies from zero at the top and bottom of the shot stream/component interface to a maximum at the center. Fig. 5 illustrates the variability of coverage produced. This is a very important phenomenon and full details of the science involved appeared in *The Shot Peener* article "Coverage Variability", Winter, 2017.

Consider next the effect of using several offset parallel passes in order to cover a larger area of a component. If the offset is equal to the diameter of the shot stream's indenting area then coverage will take the form of separate individual stripes, as indicated in fig. 6. Reducing the offset will result in a more uniform, but still stripy, coverage, as indicated in fig. 7.

Science can be employed in order to predict the achievement of maximum coverage uniformity. For a single pass, it can be assumed that coverage is zero at the edge of the shot stream's indentation area and rises sinusoidally to a maximum at the centre of the indentation area. If we offset two parallel passes by precisely half of the shot stream indentation area we get, theoretically, the situation presented in fig. 8.

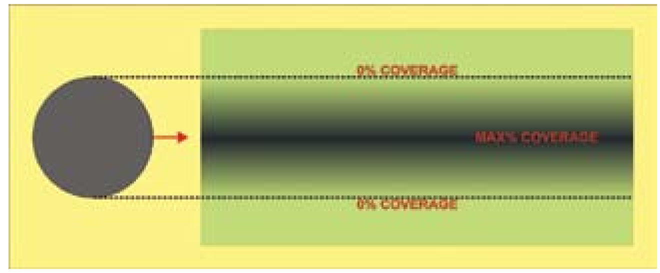


*Fig. 5. Variability of coverage produced by a single linear pass.*

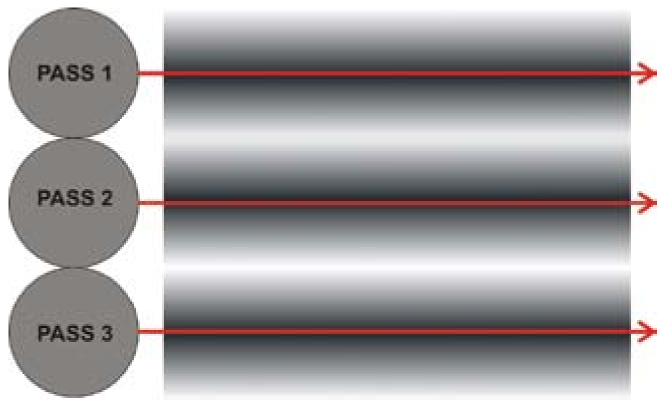


*Fig. 6. Stripe coverage imparted by passes offset by the indenting area's diameter.*

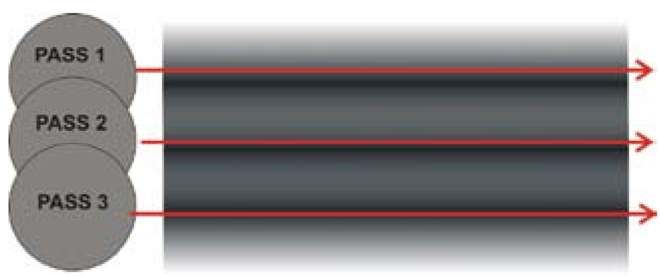


*Fig. 7. Reducing pass offset improves uniformity of coverage.*

This predicts perfect coverage uniformity! Such perfection would, however, require perfect shot stream positioning and a constant coverage rate over the whole of the shot stream's indentation area. As indicated previously, coverage rate varies substantially over this area (see fig. 4). Notwithstanding these limitations:

**Optimum coverage uniformity is predicted to be achieved with a pass offset of half of the shot stream's indentation area diameter.**

An alternative approach, when seeking uniform coverage, is to use a thin-slit nozzle. Fig. 9 illustrates the difference between round- and slit-orifice shot streams' indentation areas. Fig. 10 is a schematic representation of their comparative coverage uniformities with (a) for a round cross-section and (b) for a rectangular cross-section of impacting areas. Consider, as an analogous situation, painting a flat wall. A rectangular brush is always preferable to a round brush for achieving uniform coverage.

**Available methods of coverage prediction are fundamentally flawed. This is because they are all based on the assumption of uniform coverage being applied at each pass to a fixed point on the surface.**

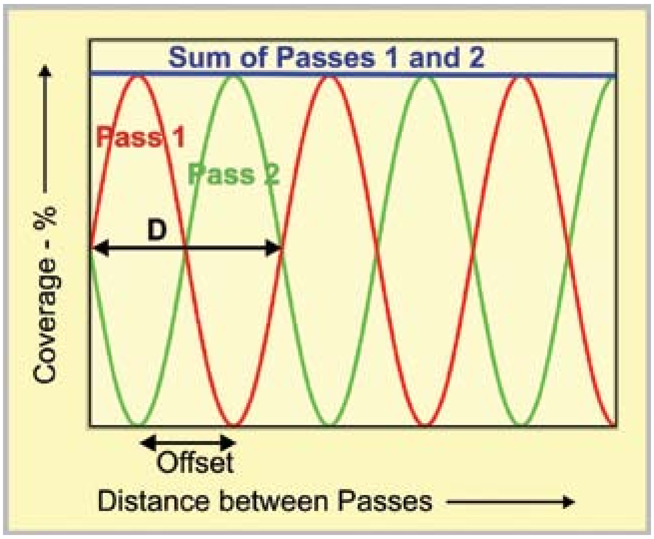


*Fig. 8. Predicted optimum coverage using an offset half of the shot stream's indenting area diameter, D.*

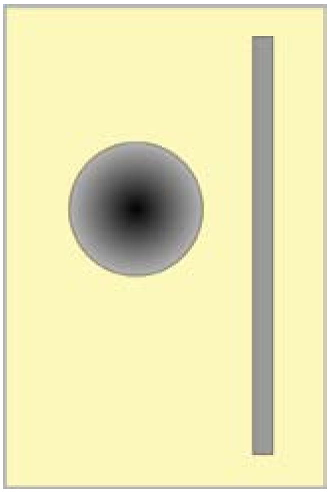

*Fig. 9. Indentation areas for circular and slit peening nozzles.*

## COVERAGE MEASUREMENT

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

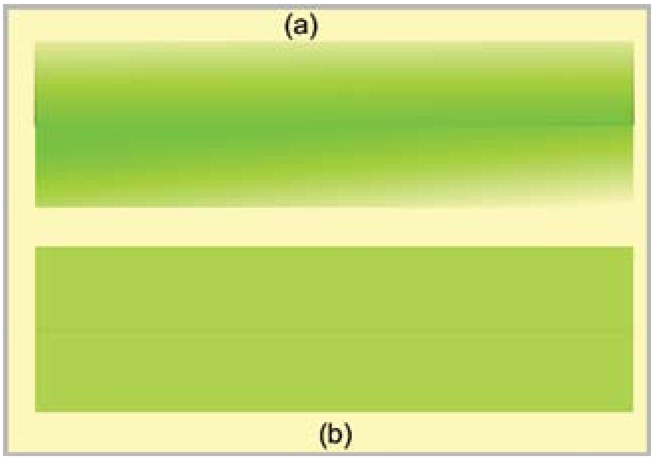


*Fig. 10. Non-uniform (a) and uniform (b) coverages produced by round and narrow slit nozzles respectively.*

**(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. 11. 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. 12.

As an exercise, printing fig. 12 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. 12 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. 12 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.

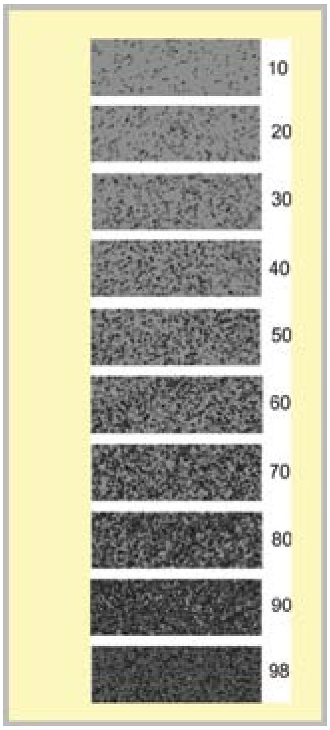


*Fig. 11. Standard Comparison images for Coverage Assessment.*

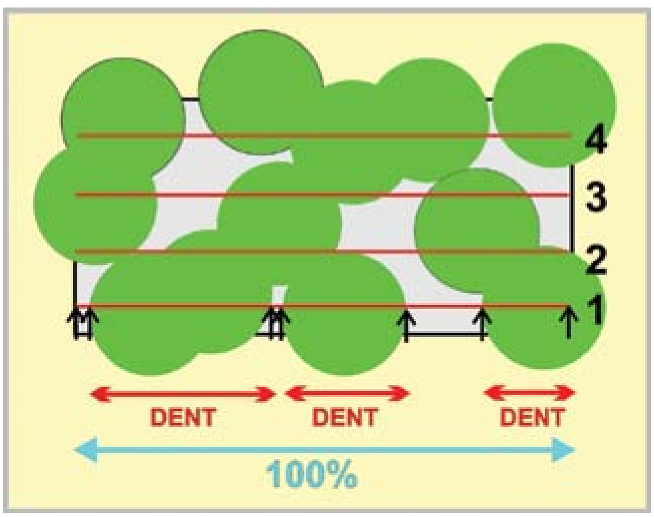


*Fig. 12. Identifying dent lengths for a fixed length of measurement.*

**(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. 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

The main aim of this article was to show how scientific principles can be applied to coverage. Traditionally, shot peeners have relied on manual estimates of percentage coverage. This, necessarily, involves a degree of subjective judgement. The human brain is, however, an excellent image analyser. Computer-based image analysis shares with manual analysis the problem of distinguishing between dented and undented regions of a peened surface. The lineal measurements at the heart of computer-based image analysis can also be carried out manually.

A secondary aim of this article was to present a condensed version of the author's coverage-related articles that have appeared in previous editions of *The Shot Peener*.*

The obvious variability of coverage over the surface of peened components is not generally recognized. Attempts to predict coverage based on repeated passes are only relevant if applied to the same point on the component's surface.

**Previous articles by Dr. Kirk can be found at www.shotpeener.com/library/kirk_articles.php.*