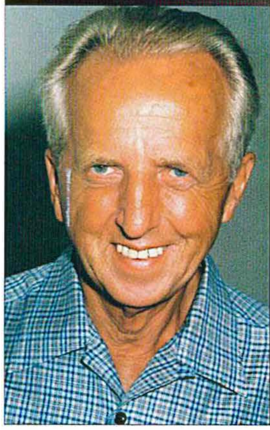
Theoretical Principles of Shot Peening Coverage



by Dr. David Kirk, Coventry University, U.K.

Dr. David Kirk, our "Shot Peening Academic" is a regular contributor to ***The Shot Peener***. Since his retirement, Dr. Kirk has been an Honorary Research Fellow at Coventry University and still supervises their Shot Peening and X-ray Stress Analysis facilities. He is currently writing a book "The Science of Shot Peening". We greatly appreciate his contribution to our publication.

INTRODUCTION

Coverage is arguably the most important variable in shot peening. It is defined as the percentage area of a surface that has been impacted. This paper examines the major factors that influence the increase in coverage that occurs as peening progresses. A secondary objective is to stimulate debate on the vexed question of "What is 100% coverage?"

In the 19th century investigators recognized the need to reduce information to numerical values in order to avoid the ambiguity of verbal description. Even with numerical description there is room for ambiguity. Lewis Carroll's Governor was on firm ground when he said, "Surely Her Radiancy would admit that ten is nearer to ten than nine is – and also nearer than eleven is." Less firm would be a shot peener's assertion that "100% coverage is nearer to 100% coverage than is 300% coverage."

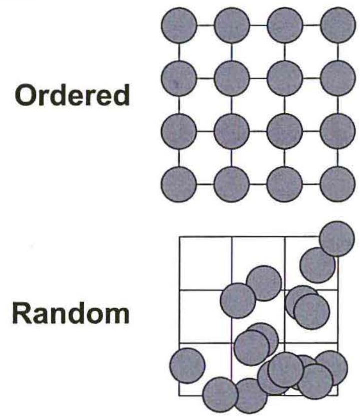


Fig.1 Perfectly-ordered and perfectly-random indentation distributions.

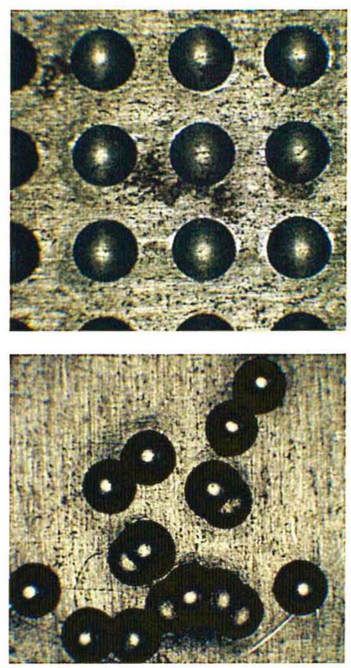


Fig.2 Laboratory-generated ordered and random indentation distributions on mild steel.

RANDOMNESS OF INDENTS

If we assume that shot produces a distribution of constant-diameter, circular indentations then mathematical models for coverage generation are relatively simple. Several authors have used such models. Fig.1 shows a representation of the two extremes of indentation distribution. One type of perfect order is shown, where indentations are placed at each intersection of a square grid. Using a 'uniform random number generator' for the x and y coordinates of each indentation centre simulates perfect randomness. Normal peening, using air-blast or wheel machines, creates a distribution that is almost, but not quite, random. 'Flapper wheel' peening generates rather less randomness than does normal peening. At the other extreme, 'tramp peening' (designed for peen forming operations) creates a nearly uniform distribution of large indentations. Virtually perfect uniformity and randomness can be achieved on a laboratory scale, by using a precisely-located single indenter. Such an approach is illustrated in fig.2 for which a flat mild steel block has been controlled by an x-y table located under a fixed-load single indenter.

COVERAGE FOR RANDOM INDENTATIONS

The theory of coverage development for random indentations is well-established. The simplest model is based on assuming statistically-random shot particles arriving at the component's surface at a constant rate and creating circular indents of a constant size. Given those assumptions, an Avrami equation appropriate to the situation is:

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

where **C** is the percentage coverage, **r** is the radius of each indentation (so that πr^2 is the area of each indentation), **R** is the rate of impacting (number of impacts per unit area per unit time) and **t** is the peening time.

It is important to note that the predicted coverage, C, given in equation (1) is only exact for an infinitely-large sample. When plotted using specific combinations, **K**, of r and R gives continuous curves that are **exponential towards 100% coverage**, as shown in fig.3. That does **not** mean that we cannot possibly achieve 100% coverage with a real, finite, sample. In practice we have a rapidly-increasing **possibility** that 100% coverage will be achieved for a real component.

The following exercise shows how shot peening can be simulated and coverage findings compared with theoretical predictions.

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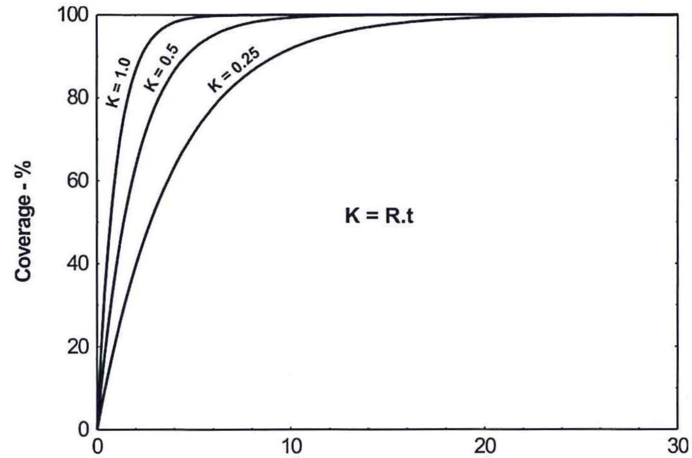

Fig.3 Coverage curves for different peening rates, K.

Exercise on Coverage Generation

This exercise utilizes a standard modelling procedure. This procedure involves a 'picture frame' around a 'picture' that accurately simulates random coverage by identical circular 'indentations'. The 'picture frame' width is always the radius of the simulated indentations.

A total of fifty circular indentations, all of unit radius, were randomly sited such that their centres lie on or within a square that has a side of six units. Twenty-five indentations were situated first, followed by the remaining twenty-five indentations. That corresponds to doubling the peening time for a model situation of constant peening intensity and rate. The two corresponding coverages were compared with those predicted by equation (1).

Generating fifty pairs of random centre coordinates simulates random siting of the indentations. Fifty uniformly random numbers were generated using Mathcad® for the x-coordinates together with a different fifty numbers for the y-coordinates. The first twenty-five pairs were accurately plotted as circles, using AutoSketch®, as shown in fig.4. Only the inner four by four square can be considered as representative of coverage. That is because contributions would be made within the 'picture frame' by indentations placed in adjacent 'six by six' squares.

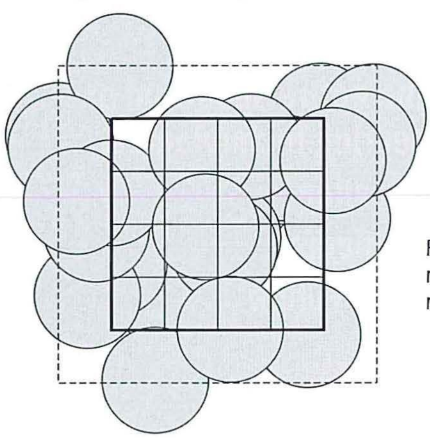

Fig.4 Twenty-five randomly-sited unit radius circles.

A simple visual assessment of fig.4 indicates that the 'unpeened' areas add up to approximately one of the sixteen unit squares. We therefore have a coverage of 'fifteen out of sixteen', which is equivalent to **C = 93.8%**. Image analysis carried out on an 'image-friendly' version of fig.4 gave a coverage of **C = 94.2%**. Substitution of r = 1 and R.t = 25/25 in equation (1) gives that C = 100(1- exp (-π. 25/25)) or **C = 95.8%**. The denominator of 25 corresponds to a 'five by five' square that is the true representation of the average area of simulated peening.

Fig.5 shows the corresponding effect of plotting all fifty circles. In this example all sixteen unit squares have 100% coverage, which is equivalent to **C = 100%**. Substitution of r = 1 and R.t = 50/25 in equation (1) gives that C = 100(1-exp (-π. 50/25)) or **C = 99.8%**.

This exercise illustrates the difference between coverage generated by a *finite* sample of indentations and coverage predicted for an *infinite* number of indentations. Repeating the exercise with different sets of x-y coordinates would yield slightly different values for coverage. Infinite repetition of the exercise using 50 'indentations' would give an average value for coverage of the theoretical 99.8%. The single example used here only simulates a tiny area of a peened component. If the indents had a diameter of 0.1mm then the 50 indents would have covered an average area of only 0.25 of a square millimetre. A 50mm by 50mm square area of a component would require 500,000 indents to achieve the average 99.8% coverage. The larger the peened area being considered the greater is the possibility that there will be some minute areas that have not been impacted. It is worth noting that with only the 94.2% coverage represented in fig.4, the'unpeened regions' are small relative to the indentation diameter. It should also be noted that random placement of 'indentations' involves multiple overlapping well before even 80% coverage is achieved.

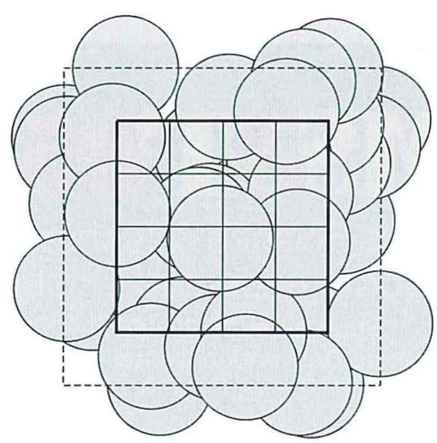

Fig.5. Fifty randomly-sited unit radius circles.

COVERAGE FOR UNIFORM INDENTATIONS

Coverage calculations for uniform peening involve simple geometry. Fig.6 shows how different coverages can be achieved using a 'square-packed' arrangement of indentations. Imposing one square-packed arrangement yields 78.5% coverage, whilst imposing a second, precisely offset, arrangement gives 100% coverage. It may be noted that, for the inner four by four square, the 'density' of unit radius indentations required is 0.25 and 0.5 per unit area for 78.5 and 100% coverage respectively. That compares with only 54.4 and 79.2% coverages achieved using random indentation and the same densities of indentation.

Whilst uniform peening may be regarded as a 'laboratory curiosity', it is simple to achieve for test specimens. Commercial exploitation would require, for example, a system of multiple captive balls in a flexible mount that could be dynamically loaded using pulsed hydraulics.

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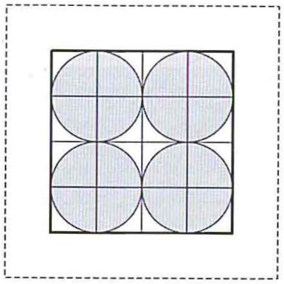

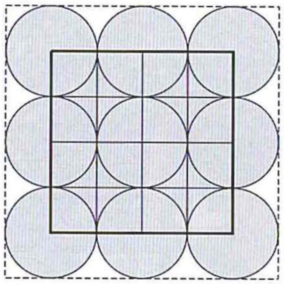

Fig.6. Coverages of 78.5 and 100% achieved using "square-packed" indentations.

COVERAGE CONTROL

Coverage variation on a microscopic scale cannot be avoided for random peening. Sophisticated jigging and computer-control of shot streams minimises macroscopic variations in the average coverage imposed in commercial peening situations. The average coverage achieved relates to the dictates of the particular specification involved. From a theoretical point of view, controlled, repeatable, imposition of *exactly* "100% coverage" over a component then appears to be impossible to achieve, impossible to measure and also undesirable. One realistic approach would be to use the term "Relative Coverage" for the C of equation (1) and to specify a minimum value for Relative Coverage – bearing in mind that values less than 100% are necessary. The use of this term is illustrated in the following examples.

Examples of Coverage Prediction

Assume, for example, that a 99.9% Relative Coverage, C, is specified and has to be produced using four identical passes over each area of a component. At that level of coverage the average of unpeened surface would be just one square millimetre in every thousand square millimetres of peened surface. That one square millimetre would be made up of many thousands of regions too small to be detected. In any case those tiny regions would all have been severely plastically deformed, since they would be very close to indentations. They would therefore contain high levels of compressive residual stress.

Equation (1) can be expressed as:

$$\mathbf{C = 100(1 - exp(- K.n))} \qquad (2)$$

where **C** is the relative coverage, **K** is the average area of each indentation multiplied by the number of indentations per unit area per pass and **n** is the number of passes.

Substituting into equation (2) C = 99.9 and n = 4 gives that K has a value of 1.727. Noting that K is the same for each pass we can now substitute K = 1.727 into equation (2) together with the other three values of n (1, 2 and 3). The resulting relative coverages are given in Table 1; together with a calculation based on using twelve passes instead of four. The value required for one pass, as indicated in Table 1, is easy to assess quantitatively

Table 1
Development of Relative Coverage using Identical Passes.

No. of passes	Relative Coverage -%
1	82.2
2	96.8
3	99.4
4	99.9
12	99.9(999999)

on a real component. Provided that *at least* that value is achieved with one pass then four passes will guarantee reaching therequired 99.9% relative coverage. The figure given for twelve passes is so near to 100% that it would be impossible to detect the difference (from 100%) anywhere on a large peened area. With 99.9999999% coverage the proportion of material impacted more than twenty times would, however, be very high.

An alternative approach to coverage prediction is given in an undergraduate group project summarised as follows: carrying out catch tests to calibrate the throughput via a MagnaValve – to determine mass per second exiting the nozzle; weighing a fixed number of S110 shot particles – to determine the number of particles being thrown per second; peening a static plate for a short period to determine the cross-section of the shot stream and to provide a sample for indent diameter measurements; hence calculating the r and R values for equation (1); estimating the time required for a rectangular polished stainless steel specimen to be slid across the shot stream simulating a single pass yielding 80% coverage; calculating the number of identical passes required to achieve near to a 99.9% coverage, according to equation (1); carrying out that number of passes, trying to assess coverage achieved at each pass and, finally, recommending modifications to the flow rate required to obtain precisely 99.9%. This project was, deliberately, more involved than the pragmatic approach given in the previous example. One outcome was that assessment of high coverages was invariably extremely difficult with no unpeened areas being detectable at 99.9% whereas the 80% (or thereabouts) assessment proved to be both simple and reproducible.

DISCUSSION

The theoretical principles presented in this paper have been applied for more than twenty years in the author's university shot peening laboratory. General experience has indicated that it is always possible to produce peened components that no one could *prove* had not received '100% coverage', using standard specified procedures. Conversely, there was always the knowledge that the components had not actually received precisely 100% coverage - since infinite peening times would have been required and the components would have been subjected to gross overpeening.

The term '100% coverage', as generally interpreted, is ambiguous. Visual inspection with a 10x magnifier cannot guarantee that there will be no tiny unpeened areas. A more realistic approach would be to introduce a specification parameter that *was* measurable and therefore achievable.