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The Reality of Shot Peen Coverage

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ABSTRACT

The statistical nature of surface coverage during shot peening is often misunderstood. In some instances, process and design engineers will specify "200% coverage" or more without a clear definition of what is meant by percent coverage or how to achieve it. This paper will attempt to clarify important aspects of the surface coverage process. A combination of analytical, experimental, and numerical results are presented to illustrate the difference between (1) area of strike ratio, (2) coverage ratio and (3) percent coverage. In addition, a computer program is presented that allows the user to experiment with peening process parameters and observe the effects of the same.

KEYWORDS
shot peening, coverage, simulation, percent coverage, area of strike ratio, coverage ratio

INTRODUCTION

Coverage is an important specification to designers and shot peeners alike. Often, to avoid under coverage of a surface, coverage levels of over 100% will be specified. This additional coverage costs money, and in the extreme, excess coverage can cause damage in the peened surface.

There is a misconception in some places that, at the saturation point, the surface has been completely covered by dimples. In addition, many believe that when the surface has "complete coverage" all areas on the surface have been struck at most a few times by shot particles. This paper will attempt to clarify these points, and demonstrate that neither statement is true.

In reality, there are very real and substantial differences between "complete coverage," the average number of hits at any point on a surface, and percent coverage. Using simulation, some statistics, and experimental verification, this paper will attempt to delineate some of the differences amongst these concepts. Along the way, some of the impractical aspects of requiring completely overlapping dimples are illustrated. This paper does NOT address the (probably more) important questions. How much coverage is "enough" to optimize the beneficial effects of peening? Or how much coverage is "too much?" Both of these concepts are much too application specific to have adequate general answers. However, this paper will discuss the possibility that dimple size alone may not be the best indication of peening coverage and that the plastic zone beneath the dimple covers the surface in a significantly shorter time than the dimples do.

COVERAGE CONCEPTS

Coverage requirements and definitions vary subtly, but as it turns out, these subtle variations have significantly different implications for the coverage process. Here is a selection of three different requirements for coverage from the literature.

- "3.3.7 Coverage. Areas of parts shot peened in compliance with design requirements shall be peened to complete visual coverage." (1)
- "6.1.2.3 Saturation and Coverage - ...Complete coverage by overlapping indentations corresponds to complete saturation if conditions of uniformity are maintained..." (2)
- "4 Coverage:...For practical purposes, 98% coverage is considered complete... A 200% coverage is attained by peening for twice the length of time required to attain 98% coverage." (3)

The first, the MIL-spec requirement, is vague enough to include the other two. The second description is, as will be demonstrated in this paper, vastly different from the third statement even though they are from two publications of the same organization. Experimental data suggests that coverage occurs between 97% and 99% making the third definition appear quite reasonable.

DEFINITIONS

The remainder of this section provides working definitions of some important terms used with respect to coverage in this paper. In addition, some less common terms used in reference to the simulation and the statistical methods applied are described.

Area of Strike Ratio (ASR) (4)- Represents a ratio of the cumulative area of dimples on a surface to the total area of the surface. This number is also equivalent to the average number of impacts per unit area on the surface.

$$ASR = \frac{N \cdot a}{A} \qquad (1)$$

where:
N = number of particle impacts on surface
a = average dimple area
A = total surface area

Coverage Ratio (CR) (4)- Represents the ratio of area that has been struck at least once to the total area under the peening stream. This number approaches but never exceeds 1. Estimates of CR received by the author at saturation range from 0.90 to 0.98 (3) which correspond to ASR values of 2.3 to 3.9 respectively. Experimental data suggests that the correct value is closer to 3.9.

$$CR = 1 - e^{-ASR} \qquad (2)$$

Percent Coverage (%Cov)- Represents the ratio of the current coverage to the coverage present at saturation. At values less than 100%Cov, the incremental %Cov is controlled by the probability of a dimple hitting unpeened area. By definition, at values >100%Cov, the %Cov represents how many times 100%Cov has been achieved.

$$\%Cov = \begin{cases} \frac{CR}{CR_{saturation}} & CR \le CR_{saturation} \\ \frac{ASR}{ASR_{saturation}} & CR > CR_{saturation} \end{cases} \qquad (3)$$

Cumulative Probability - The percent probability that a given value or less will be measured during any single observation.

Uniform Distribution - All values within a range have equal probability. Also known as a flat distribution.

Normal Distribution - Often referred to as a bell curve distribution.

Pixel - A single "picture element" on a computer display. i.e. The smallest dot that can be displayed and controlled.

COVERAGE SIMULATION PROGRAM

A computer program (5) has been developed that can be used to simulate several aspects of the coverage process. The essential feature of this program is that it can randomly place dimples on a simulated surface and keep track of the number of times each pixel in the simulated area has been "under" a dimple. It also keeps account of relevant coverage parameters and can produce spreadsheet-compatible data files for further analysis.

For the purposes of this paper, an abbreviated description of how the program operates follows. The program will, as stated above, place randomly distributed dimples on a simulated area of surface. The dimple size characteristics can be set explicitly or the user can allow the program to estimate the dimple size based on the shot/workpiece properties (4). The size of the simulated area can be manipulated to, in effect, control the magnification of the simulated area. Finally, the program can be set up to stop when specific values of several coverage related parameters (e.g. CR, %Cov, ASR, and total mass flowed) are achieved. For a more thorough description of this program and how to use it, see the manual that accompanies the software.

It is important here to describe certain assumptions that must be kept in mind relative to this program.

- All dimples are circular but only to the extent of the pixel resolution.
- The dimple sizes are described by a normal distribution.
- The dimple placement is a random, uniform distribution over the simulated area.

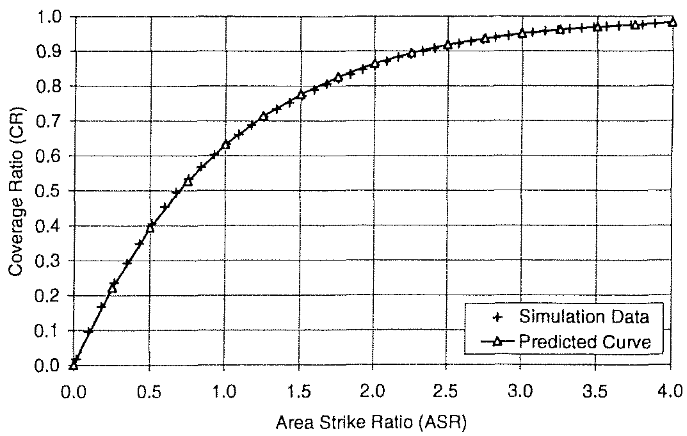

Figure 1. An example simulation run to compare simulation with predicted behavior of CR and ASR

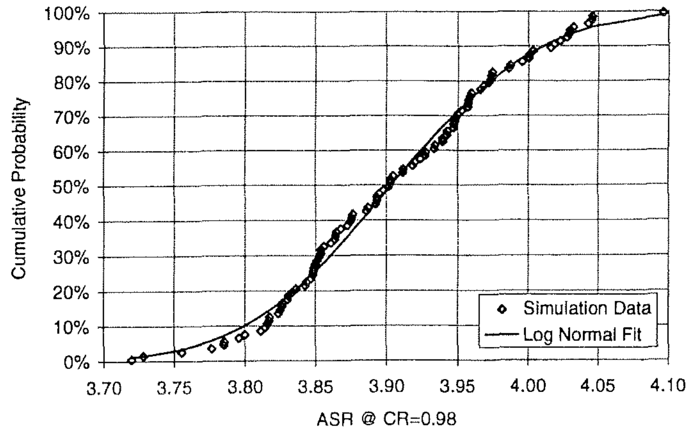

Figure 2. Results of 100 simulation runs to CR=0.98

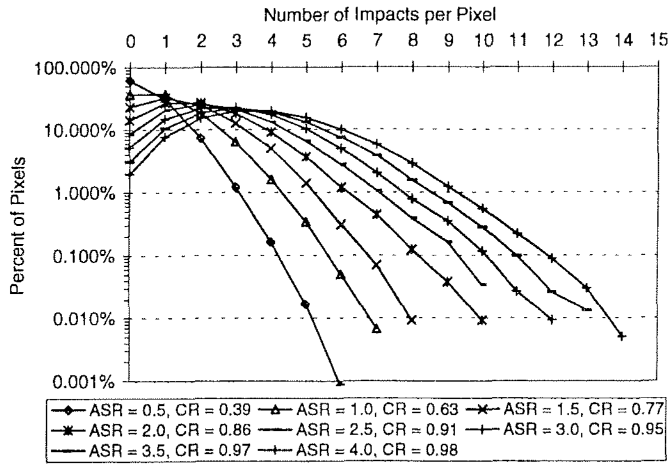

Figure 3. Family of histograms illustrating the frequency of specific numbers of impacts during a simulation. (See the legend for the corresponding ASR and CR for each curve.)

SIMULATED COVERAGE EXPERIMENTS

The first tests done were performed to validate the simulation. One of these tests involved running the program 100 times to verify the validity of eq.(2). The program does not use eq.(2) internally; CR and ASR are calculated purely from the resulting random dimples. These runs were setup to have the program stop automatically as soon as a coverage ratio ≥0.98 was reached.

Fig. 1 shows an example simulation run compared to the predicted behavior. To investigate the run to run variation Fig.2 shows the CR=0.98 point for all 100 simulation runs that were made. The results are plotted as cumulative probability vs. ASR @ CR=0.98. Then a log normal distribution curve was fitted to the data. The fit curve predicts that 98.2% of the time, ASR will be within 5% of the predicted value.

The simulation program also maintains a histogram of the number of hits on the simulation area. Fig. 3 shows a plot of these histograms for the same run as in Fig. 1. Histograms are plotted for approximately each 0.5 ASR. Each curve can be viewed as a snapshot of the distribution at a particular point in the simulation. Although the maximum ASR on this plot is 4.0, the histogram illustrates that there are many pixels that have received 10 hits or more in the last histogram.

Mathematically, a coverage ratio of 1.0 is impossible because according to eq.(2) CR approaches 1 but never quite reaches it. However, in the real world as in the simulation, the surface **will** eventually become totally covered by dimples. This is a result of the fact that Eq.(2) does not account for two important aspects of peen coverage (a) the peened surface is finite and (b) the dimples have a defined shape.

Where eq.(2), reality, and simulation agree is that it can take a long time to achieve CR1. Refer to Fig.4. In the test runs for that figure, the program ran 100 trials to record when CR=1 was achieved. A log normal distribution fit the test data best. What is immediately apparent is that the variation in completion times is significantly larger than for CR=O.98. The average ASR for CR=1.0000 was 11.6, for 0.98 the average was 3.9. This represents a threefold increase in the average number of hits on the surface (which translates directly into a 3x increase in peening time) for only a 0.02 increase in CR!

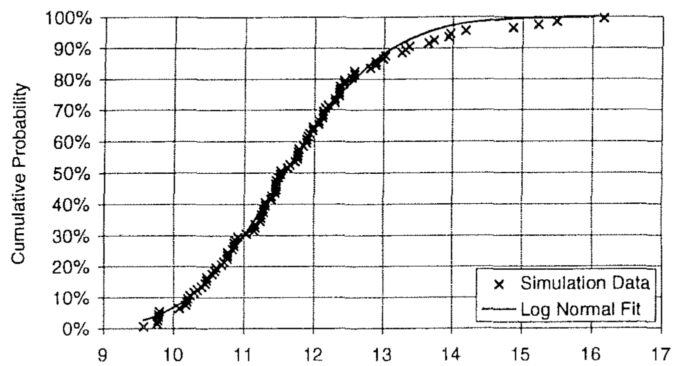

Figure 4. Simulation from 100 runs showing ASR for CR=1.000

In addition, Fig. 4 shows that the spread in the distribution has gone up dramatically. Instead of 98% of the runs falling within 5% of the average value, only 39% of the CR=1.0 runs will fall within 5% of the average value of 11.6.

To put this into typical shot peen terms, the following simulation parameters were used.

- 0.787mm (0.031in) diameter steel shot
- a dimple size of 0.127mm (0.005in)
- shot stream area of 51.6cm^2 (8.0in^2)
- simulated surface area of 0.207cm^2 (0.032in^2)

Assuming that the simulation area is under the shot stream 10% of the time, ASR=3.9 (CR=0.98) is equivalent to 31.3Kg (68.9 lbs) of shot flowed and ASR=11.6 (CR=1.00) corresponds to 93.2Kg (205 lbs) of shot.

Using ABAQUS™, a simulation of a single dimple was run as an example case to estimate the subsurface size of the plastic zone. An elastic model of a steel shot particle indenting an IN718 workpiece was used. A coefficient of contact friction of 0.15 was assumed, and the particle was assumed to be traveling normal to the workpiece surface. This resulted in a plastic zone (measured as ≥0.2% e_p) with a diameter slightly more than 2 times the dimple diameter. These results were then used in the graphical simulation program. The first series of 100 runs used the dimple size in the simulation, and the program was set to stop after a specific amount of simulated mass flow which was selected to coincide with approximately CR=0.98. Then the same 100 runs were repeated using the average of the dimple size and the plastic zone size as the "dimple" size, thus creating an estimated effective dimple size. The coverage ratio results of these runs are shown in Fig.5. You can see clearly that the additional area under the plastic zone promotes the CR to very nearly 1.0. As a matter of fact, 90% of the dimple-only runs fall within

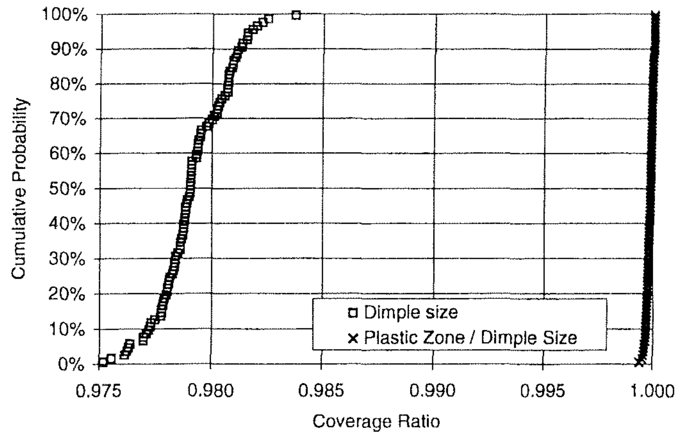

Figure 5. Comparison of coverage ratios using dimple size and estimated effective dimple size.

.9764≤CR≤.9816, and 90% of the effective dimple runs fall within .9996≤CR≤1.0000.

EXPERIMENTAL RESULTS

In order to substantiate some of the simulation results, an experiment was designed to look at coverage in the terms of this paper while creating an Almen saturation curve. The experiment uses a specialized Almen fixture with three Almen strips located around the periphery of a disk. Each run is then controlled to a specific time interval. By controlling the size of the shot stream, maintaining a 90 degree impingement angle, and knowing the mass flow rate, it is possible to estimate the number of particles that strike the Almen strips. With a measurement of the dimple size, ASR can be estimated. Table 1 provides the summary data from this test.

Table 1. Results of Almen experiment

% of Time to Saturation	Arc Height (A scale)	ASR		% of Time to Saturation	Arc Height (A scale)	ASR
10	2.4	.38 - .42		90	7.0	3.38 - 3.75
20	**3.5**	**.75 - .83**		100	7.2	3.71 - 4.12
30	4.5	1.13 - 1.25		**120**	**7.5**	**4.50 - 5.00**
40	5.3	1.50 - 1.67		133	7.8	5.00 - 5.56
50	5.7	1.88 - 2.08		150	7.8	5.63 - 6.25
60	6.4	2.25 - 2.50		200	8.0	7.50 - 8.34
70	**6.5**	**2.63 - 2.92**		250	8.2	9.38 - 10.42
80	6.7	3.00 - 3.33		300	8.4	11.25 - 12.51

The saturation time was calculated by definition. The arc heights shown are in mils and represent the average reading of the three strips for each time increment. The estimates of ASR include a range. The range indicates the result of an assumed 10% error in calculating the total number of dimples on the strip.

At saturation, an ASR of 3.71 to 4.12 corresponds to CR equal to 0.975 - 0.984. This matches very closely with the accepted value 3.91 which corresponds to a CR of 0.98(3).

Example photos from the experimental Almen strips are shown in Fig. 6b. In addition, Fig. 6 shows the comparison of the experimental results to a sequence of simulation runs in Fig. 6a. The simulation program was run to the upper value of the estimated ASR. See bold entries in Table 1. The simulation program predicts that at ASR=0.80, the dimples will mostly be individual

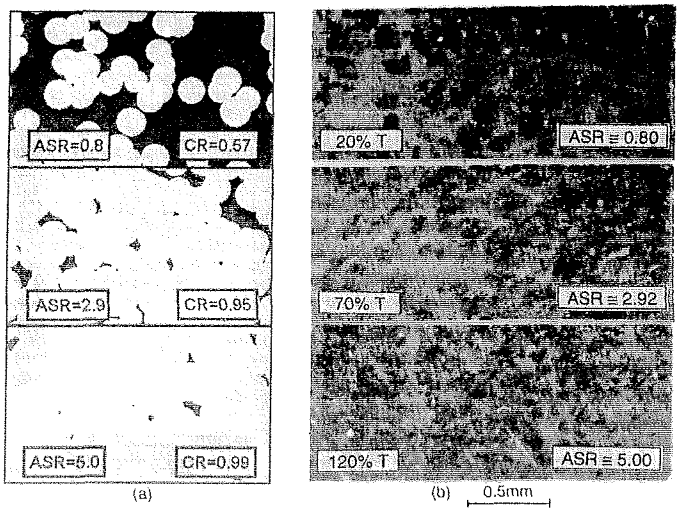

Figure 6. Examples of varying degrees of coverage. (a) Simulation results, black = not peened. (b) Photos of Almen strip, fraction of saturation times = 0.2, 0.7, 1.2 from top to bottom.

or small overlapping groups. At ASR=2.90, the simulation results show a surface that is mostly covered, now with isolated islands of unpeened surface. Finally, at ASR=5.00, the simulation predicts that the surface is almost entirely covered with a smaller number of small isolated unpeened areas.

The photos were taken so that the bottoms of dimples would be in shadow, and the photo magnification is indicated beneath the photos. The photo of 0.2T shows that the dimples are scattered about as single dimples or in small groups. The 0.7T photo shows that the surface is predominantly covered, but uncovered areas are still apparent. Although it is difficult to distinguish the unpeened areas at 1.2T from peened areas in the photos, the experimental photos are qualitatively consistent with the simulation runs. There is no reason to dismiss the simulation program's prediction that there are small isolated areas that have not yet been struck by a particle.

CONCLUSION

This paper presents a simple simulation program for estimating coverage characteristics in the shot peening process. This simulation allows enough flexibility to illustrate several important coverage phenomena. It was also shown that, within its assumptions, the simulation program performs well at approximating real results. The coverage simulations shown in this paper demonstrate that the time to produce a completely overlapping dimple pattern is exceptionally long, and the average number of hits on the surface at that coverage level is high (~10-12).

It is immediately apparent, in the experiment photographs, that distinguishing between peened and unpeened areas becomes very difficult as coverage increases. Only through very painstaking setup and control is it practical to estimate ASR. For these reasons, the most rational definition of coverage is to define the coverage at saturation as 100% which appears to be the intent of SAE J443. In addition, the experimental results presented here support the idea that saturation occurs at 0.98 coverage ratio on the surface.

It appears likely that saturation occurs when the subsurface coverage by plastic zones becomes complete or very nearly so. One difficulty of that approach is that the Almen strip material is different, often substantially, than the workpiece materials. In that case, the dimpling behavior of the shot/workpiece will differ from the behavior of the Almen strip as a result of the differences in material properties. It is conceivable that in some materials, the plastic zone will be substantially smaller and then, saturation of the surface will require more than CR>0.98. This leads one to an intriguing question: "Without making 'Almen' strips out of the workpiece material, how does one know that saturation in the workpiece is achieved?" ❍

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(5) Shotpeen Simulation Program, by Dale Lombardo, © General Electric Company, 1995-1996.