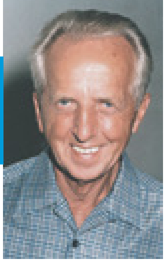

ACADEMIC STUDY

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Back to Basics: Dent Formation and Coverage

INTRODUCTION

The aim of this mini-series is to cover the basic scientific principles of shot peening. Fundamental principles are presented together with relevant theoretical explanations. You do not need to understand the mathematics—they are only needed to justify the ways in which quantification and prediction can be achieved.

A necessary feature of shot peening is that dents are produced on the surface of the component. It is these dents that induce the beneficial effects of surface work-hardening and compressive residual stress to form the "magic skin." This article deals only with dent formation and coverage, leaving these beneficial effects of dents for later articles.

Dent formation requires work being done. A very important scientific principle is that energy is indestructible—it can only be transferred. In our case we have the kinetic energy of a flying shot particle available to carry out the work needed to create a dent. During dent formation two types of kinetic energy transfer are involved: plastic and elastic.

Kinetic energy and work energy are identical in terms of units. Every impacting shot particle has a kinetic energy—$\frac{1}{2}\mathbf{Mv^2}$ where **M** is mass and **v** is velocity. Work done is force times distance so that its units are **Nm** where **N** is force and **m** is distance. Mass can also be expressed as **kg** and **v** as $\mathbf{ms^{-1}}$ so that $\underline{\mathbf{Mv^2}}$ becomes $\mathbf{kgm^2s^{-2}}$. One Newton, **N**, can also be expressed as $\mathbf{kgms^{-2}}$ so that $\underline{\mathbf{Nm}}$ becomes $\underline{\mathbf{kgm^2s^{-2}}}$—the same as $\underline{\mathbf{Mv^2}}$.

Shot peening induces vast numbers of dents. These dents give us progressive coverage. The greater the number of dents per unit area the greater will be the coverage. Because coverage is a specified requirement it has been thoroughly analyzed. This article includes a summarized version of the relevant theoretical explanations of coverage evolution.

DENT FORMATION

PLASTIC AND ELASTIC ENERGY TRANSFER

Imagine dropping a tennis ball onto a steel plate. The ball will rebound but not to the same height indicating a loss of kinetic energy. No dent is formed so that all of the kinetic energy loss has been elastic. A steel ball bearing dropped from a height of several meters will also rebound but will form a dent. Kinetic energy loss is now a mixture of plastic and elastic energy transfer. The higher the ratio of plastic to elastic energy transfer the greater is the efficiency of kinetic energy usage.

DENT DIAMETER

The controllable variables that influence indent diameter are well-known to shot peeners. For a given type of shot they are shot diameter, shot velocity and component hardness. These variables influence three interrelated factors: the volume of the indent, **V**, the amount of work done by the shot particle, **W**, and the amount of work, **B**, that has to be done to create each unit of indent volume. A simple equation connects the three variables:

$$\mathbf{V = W/B} \tag{1}$$

As a "hole digging" example for equation (1), if **W** represents 80 man-hours of digging work and **B** represents a situation where 10 man-hours of work are needed to create 1 cubic metre of hole, then 8 cubic metres of hole are created.

DENT VOLUME, V

Shot particles are almost spherical so that dent shape is close to what mathematicians call a "spherical cap". The volume of a spherical cap, see fig. 1 on page 30, can be represented by the following equation:

$$\mathbf{V = \pi d^4/32D} \tag{2}$$

WORK, W, DONE IN CREATING DENT

A flying shot particle has a kinetic energy, E, given by the expression $E = \frac{1}{2}Mv^2$ where M is the mass of the particle and v is its velocity. The mass of a sphere is its volume, $D^2\pi/6$ multiplied by its density, ρ. Hence:

$$\mathbf{M = D^2 .\pi. \rho./6} \tag{3}$$

Therefore:

$$\mathbf{E = D^2 .\pi.\rho.v^2/12} \tag{4}$$

After the shot particle has struck the component it bounces off at a lower velocity thereby losing some of its kinetic energy. The proportion, P, of energy lost is the work, W, done in creating the dent. W is therefore given by W = P.E.

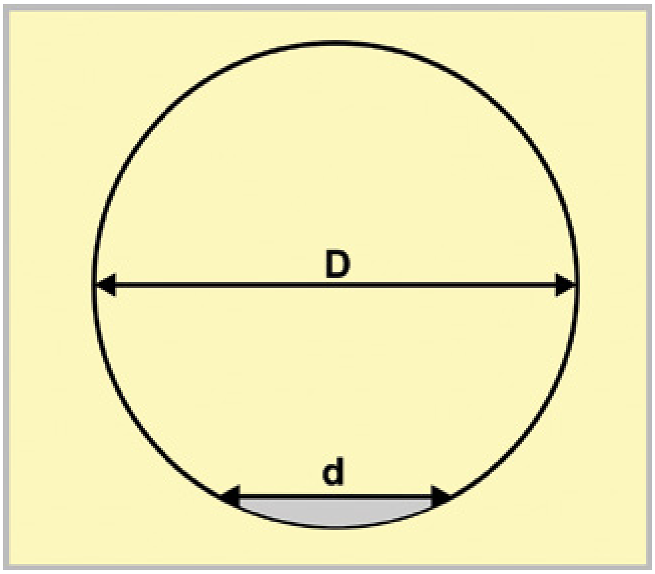

Fig. 1. Indent of diameter d, created by sphere of diameter D.

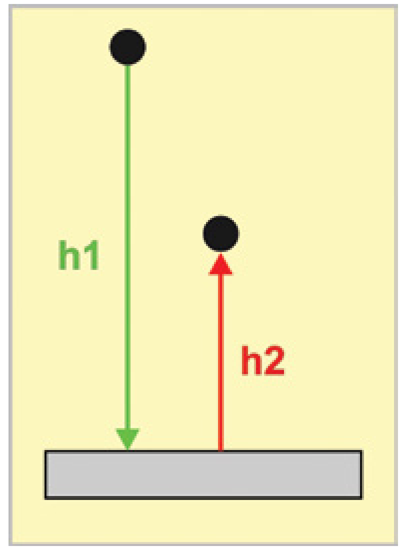

Fig. 2. Ball dropped from height h1 and then rebounding to height h2.

The proportion of energy lost varies with the hardness of the component. If the component was made of modelling clay it would not rebound at all! A very simple experiment to find a value for P is illustrated in fig. 2. A ball bearing is dropped from a known height, h_1, onto a metal plate. The rebound height, h_2, is measured using a rule held vertically and monitored using the video function of a smartphone. P is then given by:

$$\mathbf{P = (1 - h_2/h_1)} \qquad (5)$$

If $h_2 = h_1$ then $h_2/h_1 = 1$ so that $P = 0$. This means that no kinetic energy has been lost at all—perfect elasticity. More realistically if $h_2/h_1 = ½$ then $P = 0.5$.

Knowing, or assuming, a value for P we can incorporate it into equation (4) to give that:

$$\mathbf{W = P.\ D^2 .\pi.\rho.v^2/12} \qquad (6)$$

WORK DONE PER UNIT VOLUME OF INDENT, B

The indent strength, B, is equivalent to the work done during a Brinell hardness test. Brinell hardness values are normally quoted in kgf/mm^2 but can be converted into MPa by multiplying by 9.8. A Brinell hardness value for mild steel of 200 kgf/mm^2 is equal to 1,960 MPa. The theoretical basis for assuming indent strength to be equal to the Brinell hardness value is described in a previous article (TSP, Spring, 2004, "Prediction and Control of Indent Diameter").

EQUATION FOR PREDICTION OF INDENT DIAMETER

Combining equations (1), (2) and (6) gives that:

$$\mathbf{d = 1.278D.P^{0.25}.\rho^{0.25}.v^{0.5}/B^{0.25}} \qquad (7)$$

Equation (7) is absolutely fundamental to shot peening control. Experienced shot peeners already know that the factors in the equation are important. Indent diameter does increase with shot diameter, shot density and particularly shot velocity but decreases as the hardness of the component increases—other factors being kept constant.

Science is based on a combination of theory and experimental verification. Experimental verification of equation (7) was presented in a previous article (TSP, Summer, 2004, "Actual and Predicted Shot Peening Indentations"). Fig. 3 illustrates one factor, velocity, that was investigated. A 2 mm weighted ball bearing was dropped from different heights onto mild steel. The diameters of the indentations produced were measured optically and then plotted as a function of drop height. Indentation diameter was found to be proportional to the fourth root of the drop height. Impact velocity, v, is proportional to the square of the drop height. This means that the data proves that indentation diameter is a function of $v^{0.5}$ as given in equation (7).

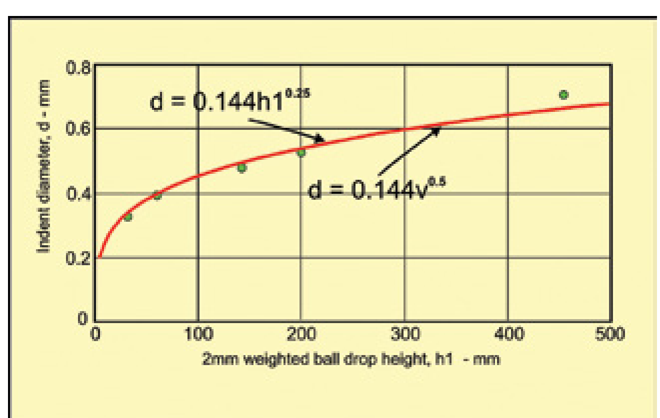

Fig. 3. Effect of drop height on indent diameter using 2 mm diameter weighted ball.

COVERAGE

INDENT RATE

A key factor in coverage control is the number of dents that are being produced per unit area per unit time, i.e., rate of denting. The rate of denting is controlled by the shot feed rate and the average size of the dents. As an example, assume that an average of 50 dents, with each dent having an area of $1mm^2$, are being produced every second for each area of $100mm^2$. The rate of denting is therefore $50 \times 1mm^2 \times s^{-1}/100mm^2$ or $0.5s^{-1}$. Note that the units for area cancel each other out.

The rate of denting can easily be measured. A polished strip of the same hardness as the component can be peened for a short time so that individual dents can be counted. For a known area of strip, the number and average size of dents can therefore be measured and converted into a denting rate.

COVERAGE

Coverage is generally defined as "The percentage area of the peened surface that has been dented." This sounds very simple but "the devil is in the detail." As a definition, it is incomplete! On a microscopic scale, coverage is a mixture of 100% and 0%—either dent or not a dent. A more precise definition would therefore be: "For a specified area of a peened surface, coverage is the percentage of that area that is comprised of dents." If the defined area is reasonably large, statistical variation of denting will then be averaged out. Estimation of high levels of coverage is so tricky that the term "Full Coverage" has been included in specifications as corresponding to 98%.

A major practical problem is to define the precise area of each dent. Life becomes much simpler when using models with clear defined edges. Coverage is then commonly explained using a model based on the random distribution of identical circular dents. Fig. 4 is a typical example. Seven and forty-two circular dents have been distributed randomly with their centers all inside the outer square. In order for the model to be accurate, coverage has to be measured using the amount of "greying" inside the specified red square. Coverage then becomes:

% Coverage = 100 x total "greyed" area/specified "red" area

The larger the number of dents within the specified area the greater will be the coverage. This will correspond to either an increase in the length of the peening time or an increase in shot flow rate.

Fig. 4 illustrates the characteristic features of increasing coverage. At a low coverage level, individual dents can be identified and there is only a small proportion of dent overlap. As coverage level increases there is a much greater chance of dent overlap and also of multiple overlapping. There is also a much greater chance of tiny uncovered areas being present. These features can easily be seen using this type of model but difficult to identify for real peened components.

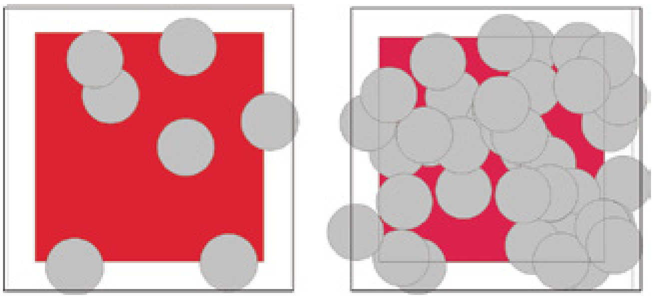

Fig. 4. Seven and forty-two "craters" distributed randomly.

COVERAGE ESTIMATION

In the author's opinion, coverage can only be estimated. It cannot be measured with a high level of accuracy. Estimation techniques fall into three categories: **manual comparison**, **manual measurement** and **computer-based image analysis**.

Manual comparison involves simply comparing an image of a peened area with reference images that span a range of coverage levels. Fig. 5, copied from J2277, is a typical example of this useful, quick, but rough method. There is, obviously, a subjective element to this technique. An image of a selected peened area can be photographed, via say a smartphone, and then downloaded to a computer for side-by-side comparison with stored reference images.

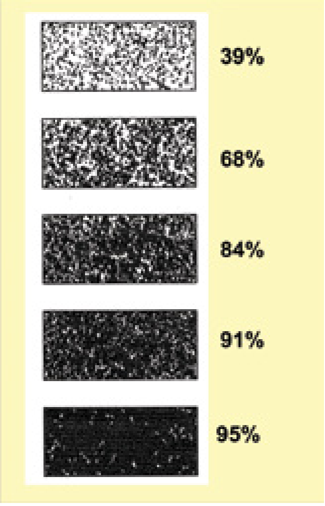

Fig. 5. Manual comparison images.

Manual Estimation

Every shot peener should be capable of carrying out a manual estimation of actual coverage for a shot-peened component. Fig. 6 illustrates the procedure, using identical spherical dents whose centers lie within the defined greyed rectangle. To show how easy it is: photograph fig. 6, download the image to

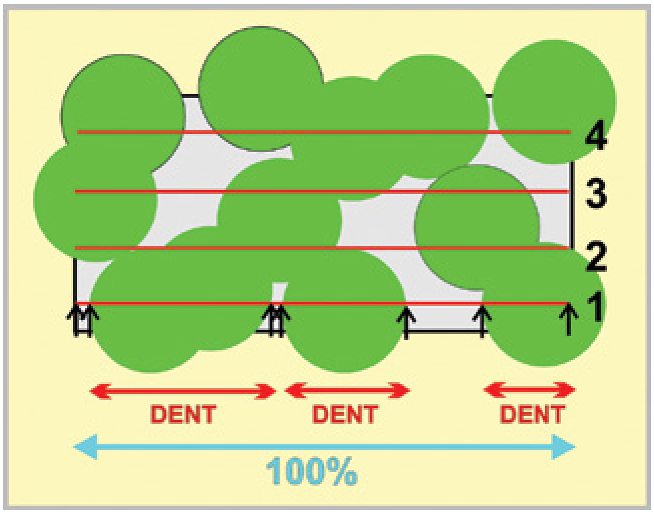

Fig. 6. Manual technique for estimating coverage.

a computer, adjust the image to a width of say 200 mm, print in landscape and then measure and add the green distances between the black arrows using a metric office ruler. I found lengths of 158, 158, 136 and 178 mm for lines 1 to 4. Dividing by two (to allow for 200 mm as the reference length) gives 79, 79, 68 and 89% for coverage. The average is 79%. Variation between test lines inevitably occurs over micro distances.

The lineal manual technique just described does contain a small element of subjectivity. This is mainly due to having to decide where a line intersects a dent. It is, however, much more precise than the manual comparison technique.

Applying the lineal manual technique to actual shot peened components requires a slightly different approach. First photograph a test area of the peened component and paste it into, say, Word. Crop a suitable rectangle after appropriate image magnification. In landscape mode, magnify the cropped area to give a convenient reference width (say 200 mm). Horizontal lines can then be drawn on a printout at convenient equal intervals. Measure (a) the length of the reference line and (b) the intersections of each line with dents. Sum the intersections for each line and divide by the length of the reference line. Multiply by 100 to obtain percentage coverages.

Fig. 7 illustrates the use of manual lineal analysis for an actual peened specimen. For the lines L1 to L4 the coverages were 31, 30, 34 and 42%, giving an average of 34%. Nine dents appear on the photograph, together with two artefacts—marked X. The artefacts should be ignored as not corresponding to actual dents.

Computer-Based Image Analysis

Computer-based image analysis is very similar in principle to the manual technique just described. The main difference is that thousands of lines can be measured very quickly.

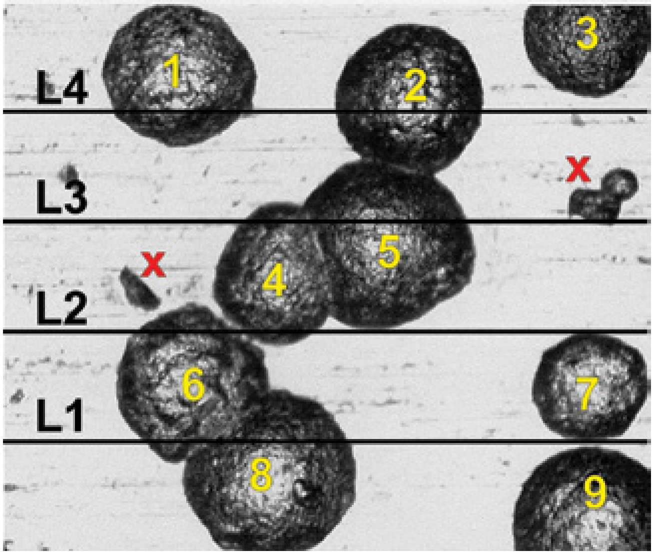

Fig. 7. Lineal coverage analysis of a shot-peened specimen.

Drawbacks are that the identification of artefacts becomes difficult and dent edge location can be imprecise. Image analysis programs are readily available but require training and experience to be effectively employed. At least one company provides a complete unit for coverage estimation.

COVERAGE PREDICTION

Coverage prediction is a jewel in the crown of shot peening science.

As peening progresses, coverage increases but becomes less and less effective as more and more of the surface is already dented. Fig. 8 on page 36 (the figure is copied from a previous article) is a graphical representation of the changes in coverage rate that occur for a constant indentation rate. As is universally recognized, the coverage rate decreases with increase in shot peening time (or number of passes). The mathematical shape of the curve is called "inverse exponential". This shape can be expressed as:

$$\mathbf{C_t\ \% = 100[1 - exp(-A*t)]} \qquad (8)$$

where $\mathbf{C_t}$ **%** is the coverage after a peening time **t** and **A** is the indent rate.

A single measurement of coverage can be used to predict the amount of peening (time or passes) needed to achieve a required level of coverage. An Excel-based program is available free from Shotpeener.com as "Coverage_Predictor.xls". Fig. 9 on page 36 illustrates how the program can be applied. Entering the measured value of coverage after one pass, say 42%, automatically predicts coverage after different numbers of passes. It also calculates the indent rate, A.

DISCUSSION

Experienced shot peeners are well aware of the effects of shot

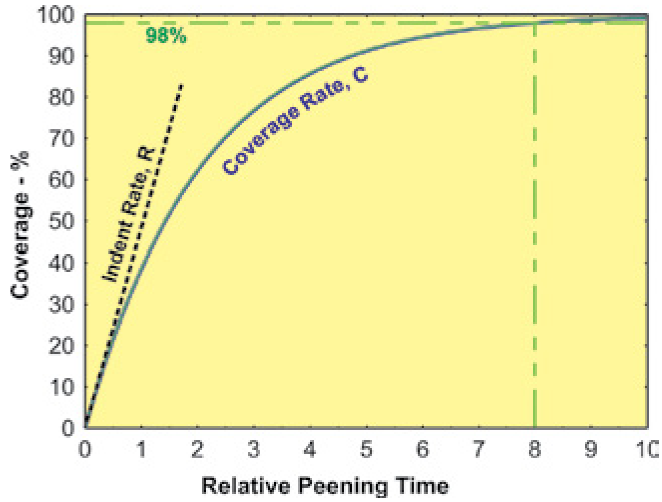

Fig. 8. Variation of coverage rate with peening time.

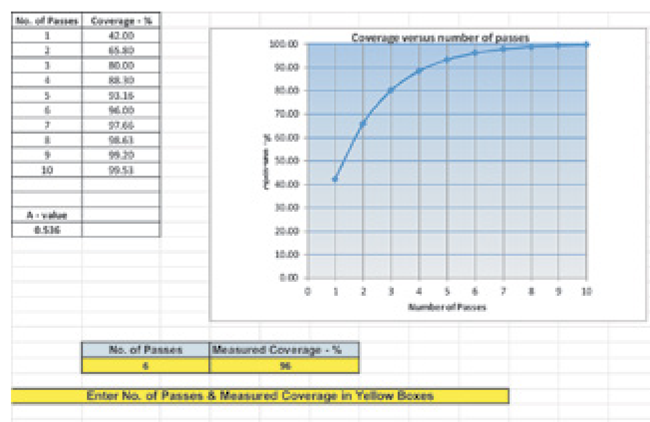

Fig. 9. Example showing application of Coverage Prediction program.

size, velocity, density and component hardness parameters on the dent size that is induced. Semi-quantification is achievable through experience and, importantly, the ability to refer back to stored data. Hopefully, the relationships presented in this article will increase understanding of quantitative parameter effects.

Coverage has a long history of published explanations and has its own standard specification, J2277. One significant feature in this article is the challenge to readers to actually carry out quantitative measurements. The lineal method proposed has been used by the author ever since his undergraduate days. A simple explanation of the method has been included based on that long experience. Somewhat surprisingly, a Google search revealed only very complicated accounts.