ACADEMIC STUDY

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Optimization of Shot Peening Coverage

INTRODUCTION

Shot peening coverage of components is, of course, very important. The importance of coverage optimization is emphasized in SAE J2277 with its: "Effectiveness of shot peening is directly dependent on coverage. Inadequate or excessive coverage may be detrimental to fatigue."

Unfortunately, many users still believe that "More is Better" and require huge amounts of coverage, e.g., "300%". This approach ignores the importance of the other factors that govern optimum coverage.

Property optimization normally relates to fatigue life. Variation of fatigue life with coverage depends on component design, material and stressing. For every combination there is a corresponding coverage/property-improvement curve. Fig.1. is a simple type of coverage/property-improvement curve illustrating two important features. Firstly, that the maximum property improvement normally occurs below 100% coverage. Secondly, that the property improvement varies only slightly on either side of the optimum coverage—as indicated by the double-headed arrow. If we can control peening variables to somewhere near the optimum then there will be only a small variation of maximum improvement value.

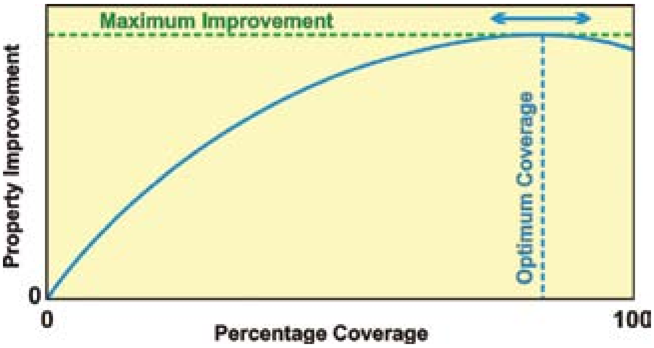

Fig.1. Example of a Property Optimization Curve.

Process control of coverage can only be achieved if the level of coverage can be measured with some degree of accuracy. 98% peening coverage is the maximum level that is recognized as being measurable with any degree of accuracy. It follows that less than 98% should normally be specified if coverage level is to be consistently applied.

Shot peening produces surface dents, work-hardens the surface and also induces compressive residual stress in the surface layer. Three types of coverage can, therefore, be identified:

Dent Coverage,
Hardening Coverage and
Stress Coverage.

Dents in the surface do not normally improve service performance. Hardening and compressive residual stress, on the other hand, do improve service performance. The three types of coverage are illustrated in fig.2.

Fig.2. Generation of different types of coverage by shot peening.

The three types of coverage develop at different rates during shot peening. This article considers each type separately and indicates their effects on coverage optimization. Coverage is a quantity and therefore has to have ways of quantifying it. Several equations are included in the article. There is no need to be a mathematician to use these equations. Programs such as Excel will do all the work!

DENT COVERAGE

Dent coverage is the one type universally recognized by shot peeners. Its great advantage is that it is a visible indication of the amount of shot peening. The SAE J2277 definition of dent coverage is: "The percentage of a surface that has been impacted at least once by the peening media." This definition embraces two important features of dent coverage:

1 Dent coverage increases with amount of peening and

2 The probability of multiple impactions.

The quoted definition is, unfortunately, followed by: "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 peening impressions (dents)." This statement is misleading as it implies that with a sufficient amount of peening, 100% dent coverage can be assured. It also implies that 100% coverage may be advantageous. Both of these are incorrect.

Prediction of increasing dent coverage with increasing amount of peening.

The prediction of increasing dent coverage with increasing amount of peening is well-documented. Prediction techniques are, however, normally based on two simplifying assumptions. These are (1) that every dent is circular and (2) that every dent has exactly the same radius. Given those assumptions, we have a coverage/time curve that has a simple shape. This shape has been analyzed and discussed in previous TSP and ICSP articles and is included in SAE J2277.

The mathematical equation that describes the shape of the conventional dent coverage curve is:

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

C is dent coverage, **r** is the fixed radius of the circular dents, **R** is the rate of dent creation per unit area and **t** is the time of peening.

As an example, consider 14 dents per second (on average) being produced within a square 10 mm by 10 mm, with each circular dent having a radius of 1 mm. Therefore $\mathbf{r^2}$ is 1 mm^2, **R** is 0.14 per mm^2 per second and **t** is in seconds. The units in equation (1) cancel each other out. The product, $\mathbf{\pi.r^2.R}$, is the "coverage rate factor." For this example, $\mathbf{\pi.r^2.R}$ is 0.44. Fig.3 uses 0.44 as this factor. Therefore, after 1 second, an area of 100 mm^2 will have received, on average, 14 dents. Equation (1) then predicts an average coverage of 36%.

The theoretical curve, shown as fig.3, has exactly the same shape as the example given in SAE J2277. It is important to note that these curves are only accurate for average dent coverage. This point is illustrated in fig.4 which comprises 14 identical dents of precisely 1 mm radius – equivalent to peening for 1 second. These dents have been placed randomly within a square 10 mm by 10 mm – their centers having been chosen using computer-generated random numbers. For the example shown in fig.4 the measured dent coverage (within the yellowed square) is 42%, shown as "T" on the graph, (measured using several techniques which all gave the same value). Equation (1), however, predicted that the average dent coverage would be 36%. The difference between the measured 42% and the predicted 36% is due to statistical variation. The value of 42% has been included in fig.3 to emphasize statistical deviation. We should, therefore, note that there is a difference between statistically-variant coverage for a restricted area and average coverage (coverage over a very large area).

Coverage curves of the type shown in fig.3 (and in SAE J2277) are very useful for predicting and controlling average dent coverage. Optimization of dent coverage requires, however, that we consider both the coverage achieved and the amount of peening needed to achieve that coverage.

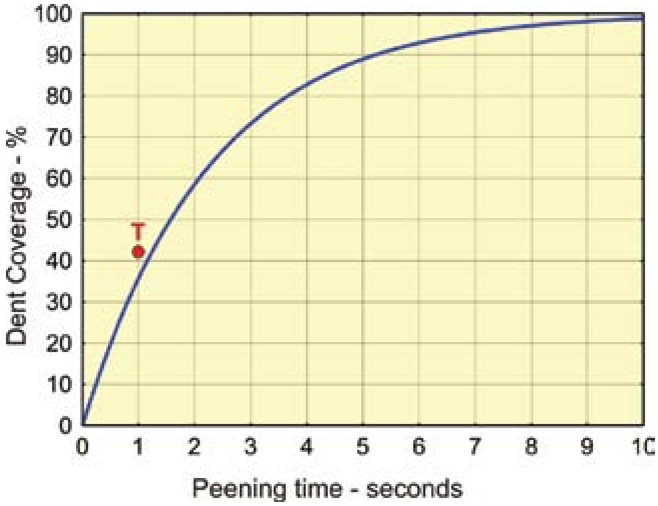

Fig.3. Theoretical average dent coverage curve for dents of 1 mm radius generated at a rate of 14 per 100 mm^2 per second.

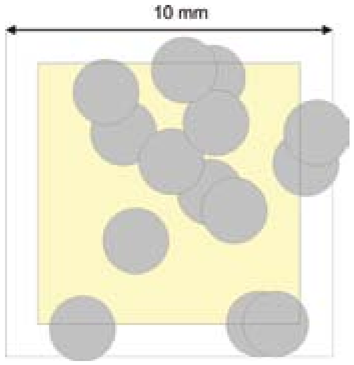

Fig.4. Precision drawing of 14 circular dents randomly distributed with centers within a square having an area of 100 mm^2.

Fig.5 uses three different values of the peening rate, $\mathbf{\pi.r^2.R}$, and reverses the coverage axes usually employed. This axis reversal is designed to emphasize taking a different view of achieving desired coverage levels. At the lowest peening rate (shown in black) 86% coverage is predicted to be achieved in half of the time required to achieve 98% coverage. For a desired 98% coverage small changes in the amount of peening will only produce small changes in the induced dent coverage. On the other hand, if the desired level is 86%, small changes in the amount of peening will produce much larger changes in the induced dent coverage.

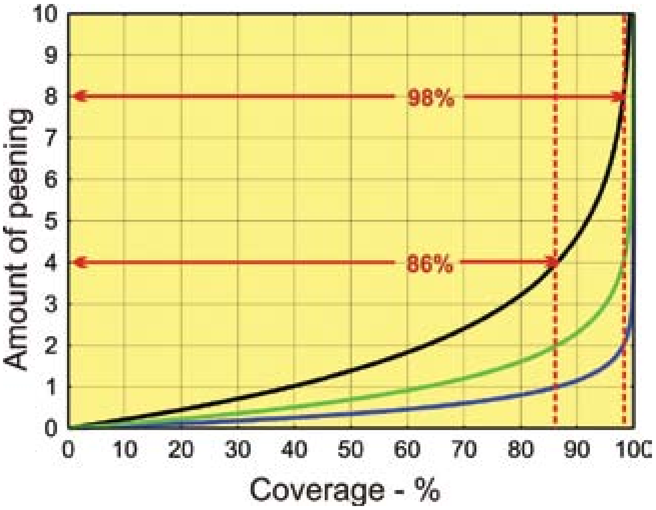

Fig.5. Coverage curves using reversed axes.

Prediction of multiple impactions with increase in amount of peening.

A multiple impaction is defined as the part of a surface where dents have overlapped – either once or more than once. Fig.6 identifies double impaction at A and triple impaction at B.

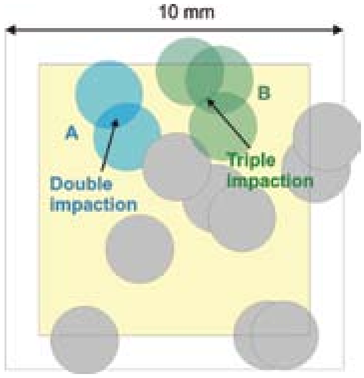

Fig.6. Multiple impaction examples with only 42% coverage.

As the average coverage increases so does the probability of greater and greater multiple impaction.

The mathematical equation that describes the contribution to coverage by **n** overlapping impactions is:

$$C_n\% = 100[(\pi.r^2.R.t)^n/n!]*\exp(-\pi.r^2.R.t \qquad (2)$$

C_n is the contribution to total coverage by **n**-impacted areas, **r** is the radius of the dents, **R** is the rate of dent creation per unit area, **n** is the number of impacts that a particular area has received, **t** is the time of peening and **n!** is the factorial of **n**. Factorial **n** is 1*2*3…*n, so that, for example, when n = 4 then factorial n = 24 (1*2*3*4).

Fig.7 uses equations (1) and (2) to give a graphical representation of multiple impaction contributions to total coverage. The plots are those for which **n** has values ranging from 1 to 9, **r** equals 1 mm and **R** is equal to 0.14 dent per mm^2 per second (as for fig.3).

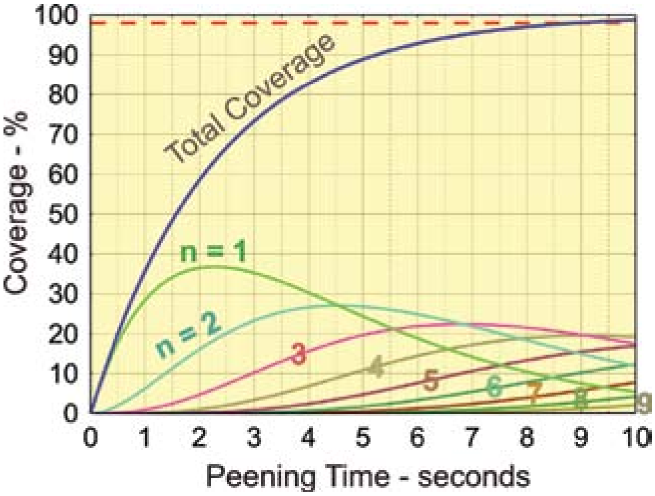

Fig.7. Contributions of multiple overlaps to total coverage.

Table 1 presents calculations (made using equations (1) and (2) of percentage coverage contributions for different amounts of peening and of overlapping.

Table 1. Effect of Peening Time on Multiple Dent Overlap Contributions to Coverage.

Time - s	1	2	3	4	5	6	7	8	9	10
n = 1	28.34	36.50	35.26	30.28	24.38	18.84	14.16	10.42	7.55	5.40
n = 2	6.23	16.06	23.27	26.65	26.81	24.87	21.80	18.34	14.95	11.88
n = 3	0.91	4.71	10.24	15.63	19.66	21.88	22.38	21.52	19.73	17.43
n = 4	0.10	1.04	3.38	6.88	10.82	14.44	17.23	18.93	19.53	19.17
n = 5	0.01	0.18	0.89	2.42	4.76	7.63	10.62	13.33	15.47	16.87
n = 6	6.49E-04	0.03	0.20	0.71	1.74	3.36	5.45	7.82	10.21	12.37
n = 7	4.08E-05	3.36E-03	0.04	0.18	0.55	1.27	2.40	3.93	5.78	7.78
n = 8	2.24E-06	3.70E-04	0.01	0.04	0.15	0.42	0.92	1.73	2.86	4.28
n = 9	1.10E-07	3.62E-05	8.96E-04	0.01	0.04	0.12	0.32	0.68	1.26	2.09
>9	5.03E-09	3.46E-06	1.34E-04	1.61E-03	0.01	0.04	0.13	0.34	0.76	1.49
TOTAL	**35.60**	**58.52**	**73.29**	**82.80**	**88.92**	**92.86**	**95.40**	**97.04**	**98.09**	**98.77**

As examples: At 35.6% coverage, single impact (i.e., no overlapping), predominates although more than 1% of the surface has received at least triple impacting. At 88.9% coverage, the largest contribution is now of double impacted areas followed by single impacting, but also with more than 2% having been impacted at least six times.

HARDENING COVERAGE

Work-hardening is one of the two beneficial effects of shot peening—the other being surface compressive residual stress development. A zone of work-hardened material surrounds each dent as shown schematically in fig. 8 in cross-section.

In plan view the diameter at the surface of the work-hardened zone, 2d, is approximately double that of the dent, d.

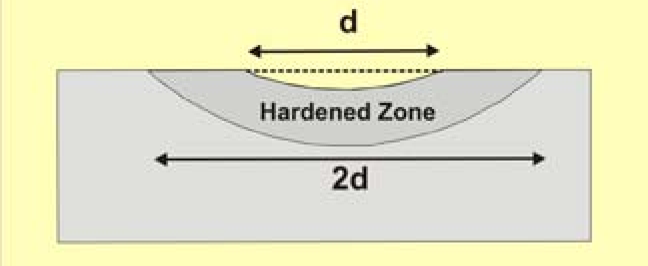

Fig.8. Cross-section indicating zone of work-hardening surrounding dent.

Work-hardening necessitates that the applied stress exceeds the yield point, meaning that the zone has a definable limit.

The equation that describes the shape of the hardening coverage curve is:

$$\mathbf{WH\% = 100(1 - exp\ (-\pi.r^2.R.t))} \qquad (3)$$

WH is work hardening coverage, r is the fixed radius of the circular hardening zones, **R** is the rate of zone creation per unit area and **t** is the time of peening.

Doubling the radius, **r**, of any zone multiplies the coverage rate factor, $\pi.r^2.R$, by a factor of four (e.g., to 1.76 when dent coverage has a factor of 0.44). Note that **R** is the same for both dents and work-hardening zones for a given rate of impaction. Hardening coverage increases at a much faster rate than does dent coverage. Comparative rates are included in the Discussion at the end of this article.

Equations (1) and (3) can be used to quantify the difference between dent coverage and hardening coverage. Equation (1) predicts that 98% coverage will be achieved in 8.9 seconds using 0.44 as the coverage factor. Substituting 8.9 and 1.76 into equation (3) predicts that the hardening coverage would then be 99.99999%. This means that we have virtually complete hardening coverage—a desirable parameter—when the dent coverage has reached 98%.

Work-hardening zones overlap in the same way as do dents. The effect of multiple overlapping is that there are corresponding multiple work-hardenings. More and more hardening is generally beneficial. The exception is when the ductility of the component material becomes exhausted. The mathematical equation that describes the contribution to hardening coverage by n overlapping impactions is:

$$\mathbf{WH_n\% = 100[(\pi.r^2.R.t)^n/n!]*exp(-\pi.r^2.R.t)} \qquad (4)$$

$\mathbf{WH_n}$ is the contribution to total hardening coverage by **n**-impacted areas, **r** is the radius of the hardened zones, **R** is the rate of zone creation per unit area, **n** is the number of impacts that a particular area has received, **t** is the time of peening and **n!** is the factorial of **n**.

Equation (4) can be used to construct an equivalent table to that for dent coverage. For comparison purposes only the hardening coverage values at 98% dent coverage are reproduced in Table 2.

Table 2. Comparison of Coverage Contributions when Dent Coverage is 98%.

	Multiple Hardenings Contribution	Multiple Dents Contribution	Multiple Stress Contribution
Time - s	9	9	9
n = 1	0.00	7.55	1.0011E-39
n = 2	0.00	14.95	4.9555E-38
n = 3	0.01	19.73	1.6353E-36
n = 4	0.03	19.53	4.0474E-35
n = 5	0.11	15.47	8.0138E-34
n = 6	0.29	10.21	1.3223E-32
n = 7	0.66	5.78	1.8701E-31
n = 8	1.30	2.86	2.3142E-30
n = 9	2.28	1.26	2.5457E-29
>9	95.32	0.76	100
TOTAL	100.00	98.09	100

The values given in Table 2 substantiate the previous comment: "This means that we have virtually complete hardening coverage—a desirable parameter—when the dent coverage has reached 98%." When dent coverage has just reached 98%, less than 1% of the surface has had more than 9 overlaps. That compares with 95% having more than 9 overlapping hardening zones. Values are also included for multiple stress zone contributions and are discussed in the next section.

STRESS COVERAGE

At the risk of repetition, "Dents in the surface do not normally improve service performance. Hardening and compressive residual stress, on the other hand, do improve service performance." The work-hardening of the surface by peening induces beneficial compressive residual stress at the surface. Each isolated dent is surrounded by a zone of compressively-stressed material. This zone is illustrated in fig.9. Unlike dents and work-hardening zones, the induced surface compressive residual stress does not have a clearly-defined limit—it just goes 'on and on'.

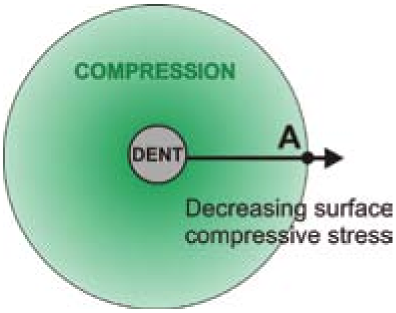

Fig.9. Schematic representation of effective compressively stressed zone surrounding a dent.

The level of surface residual stress decreases with distance from the edge of a dent. Fig.9 shows a compressed zone extending to five times the diameter of a corresponding dent. Relevant evidence was presented at ICSP9 (Kirk and Hollyoak, *Relationship between Coverage and Surface Residual Stress*, pp 373-378). This quantified surface residual stress variation with distance from the edge of dents. Fig.10 relates to measured surface stress variation for 0.67 mm diameter dents in mild steel. Induced surface compressive residual stress adds to any pre-existing surface stress. For this example the pre-peening surface stress was found to be tensile - + 20 MPa. Point A on the curve, 1⅓ mm from the edge of the dents, indicates that compressive surface residual stress is within 20 MPa of its maximum level – 120 MPa. Point A corresponds to five times the diameter of the dent and is included in fig.9. Point A could be regarded as representing the maximum radius for effective compressive stress coverage.

Equation (5) is the equation, presented at ICSP9, which predicts surface compressive stress variation (for the mild steel specimens that had been studied).

$$\boldsymbol{\sigma} = -140\,(\exp(-d^2)/10) + S \qquad (5)$$

where **σ** is residual surface stress in MPa, **d** is distance from dent edge and **S** is the stress level of the unpeened surface.

The residual stress coverage equation for multiple overlapping zones is:

$$S_n\% = 100[(\pi.r^2.R.t)^n/n!]^{*}\exp(-\pi.r^2.R.t) \qquad (6)$$

S_n is contribution to total compressive stress coverage by **n**-impacted areas, **r** is the radius of the 'Point A' zones, **R** is the rate of zone creation per unit area, **n** is the number of impacts that a particular area has received, **t** is the time of peening and **n!** is the factorial of **n**.

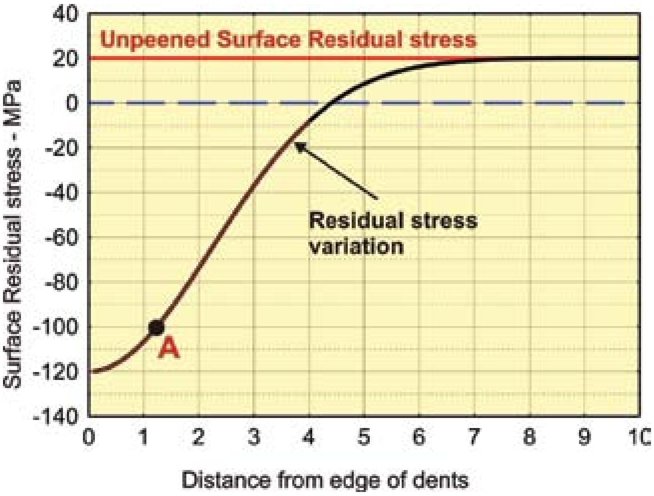

Fig.10. Surface residual stress variation with distance from dents.

Estimates based on equation (6) quantify residual stress coverage in the same way as those derived for dent coverage and hardening coverage. Such estimates confirm that stress coverage approaches 100% very, very rapidly - as illustrated in fig.12. The values given in Table 2 are astronomically small for any region receiving less than 9 overlapping compressively-stressed zones. A pictorial representation is given as fig.11 where just four dents (of the fourteen that generated 42% coverage in fig.4) have been surrounded by induced effective compressive residual stress zones five times the diameter of each dent. Here we have 100% coverage together with general overlapping of these beneficial compressive stress zones (shown green).

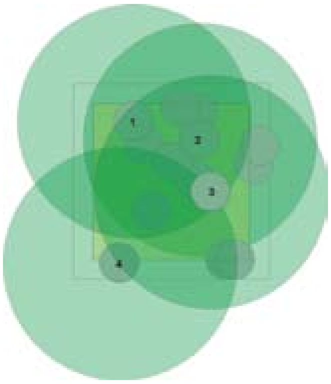

Fig.11. Complete stress coverage with just four dents.

DISCUSSION

Optimum dent coverage occurs when desirable service properties reach their maximum. It is not, however, the dents themselves that contribute to property improvement. Work-hardening and the development of compressive surface stress are the principal factors that generate property improvement. Dent, hardening and stress coverage proceed together but at vastly different rates as illustrated in fig.12.

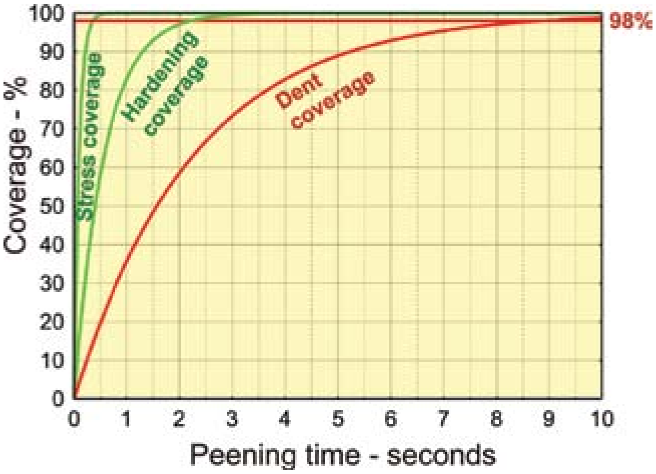

Fig.12. Relative coverage rates for dents, hardening and surface residual stress.