Peening Intensity Curves

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INTRODUCTION

Two parameters dominate shot peening effectiveness: COVERAGE and PEENING INTENSITY. Coverage is two-dimensional, easy to define (percentage of surface covered by indentations), visible and can be measured directly. Peening intensity, on the other hand, is three-dimensional, difficult to define, invisible and can only be measured indirectly.

Indirect measurement of peening intensity is achieved by exposing Almen strips to the shot stream for different periods (of time or its equivalent in terms of either number of passes or feed rate). When one major face is shot peened, each strip develops a convex curvature whose arc height, h, can readily be determined using an Almen gage. The variation of arc height with peening 'time', **t**, is a peening intensity curve (commonly called a "saturation curve"). "Saturation intensity" is a particular arc height on the curve, **H**, for which doubling the corresponding peening time, **T**, gives a 10% increase in arc height, see fig.1. This parameter is used to quantify differences between peening intensity curves and has become the industry-standard quantitative measure of a shot stream's indentation ability.

A peening intensity curve is a 'continuous function' and has a corresponding equation relating arc height to peening time. Standardized gages and procedures are used to monitor the change of arc height with peening time. Gage measurements can then be used to estimate the peening intensity curve parameters and hence "saturation intensity".

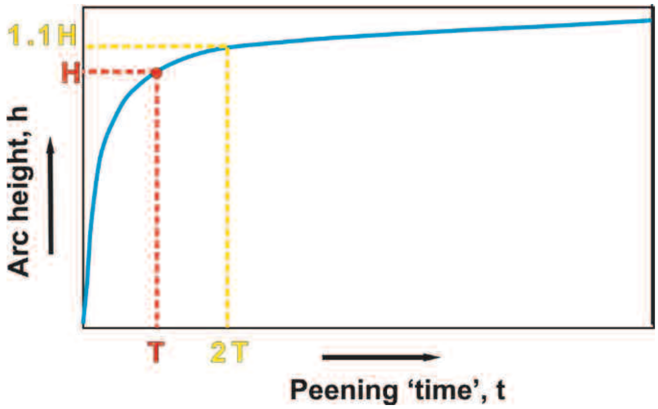

Fig.1 Peening Intensity Curve ("Saturation Curve")

Each impacting shot particle produces a minute amount of plastic stretching parallel to the strip surface. This stretching induces a corresponding minute strip deflection, **δh**. The plastic deformation is **tensile** so that convex curvature occurs. In this respect the situation is very similar to peen-forming.

GAGE MEASUREMENTS

Every measured arc height, h, is the sum of a very large number of individual **δh** contributions. We therefore have features in common with a rain gage. Fig.2 shows the principle involved in rain measurement. Each raindrop will make a tiny contribution, **δh**, to a measurable height, **h**, of rainwater collected over a time period, **t**. The measured height will also depend on the rate, **r**, of drops entering the gage. Hence:

$$h = r.\ \delta h.t \qquad (1)$$

If both **r** and **δh** are known to be constant then equation (1) can be written as:

$$h = a.t \qquad (2)$$

where **a** is a constant (**r. δh**)

Equation (2) is a straight line. Estimation of that straight line could be achieved by taking measurements of **h** at different times, **t**, as shown in fig.2. Measurements have statistical variability and can therefore only be indicators of a known, behavior pattern. In 1805, Legendre introduced the procedure of "least squares" as a method for arriving at a 'best' estimate for a known pattern. Since then, up until the computer era, generations of engineers endured the tedium of having to determine, manually, the 'normal equations' that defined the best-fit equation for each data set.

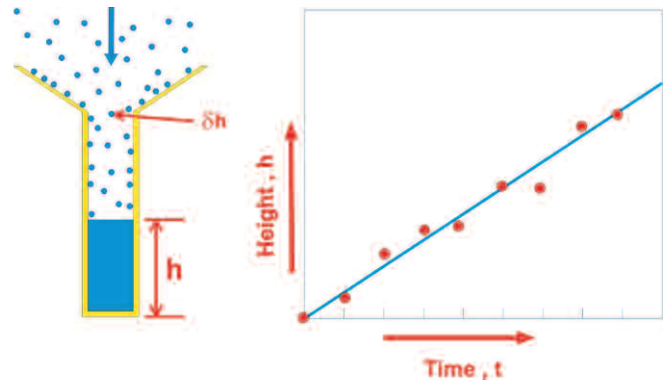

Fig.2. Standard rain gage with hypothetical data set and fitted linear curve.

Fig.3 shows the parallel situation for Almen strip arc height evolution. Each rebounding shot particle has caused a tiny amount of plastic stretching of the peened surface with a corresponding contribution, **δh**, to the arc height, **h**. A data set is shown - fitted to a 'known curve'.

One obvious difference between the curves shown in figs.2 and 3 is their shape. Peening of Almen strips must therefore involve a reduction of **δh** with increase of peening time.

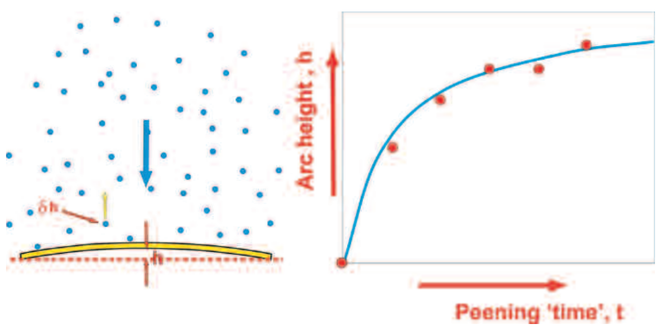

*Fig.3. Almen arc height, **h**, as the sum of individual contributions, **δh**, with hypothetical measurement points and fitted 'saturation' curve.*

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REDUCTION OF ARC HEIGHT CONTRIBUTION, δh, WITH PEENING TIME

The reduction of arc height contribution with increased peening time determines the shape of peening intensity curves. This reduction is primarily associated with the plastic deformation behavior of the surface. The deformed surface layer of a peened Almen strip is made up of innumerable overlapping deformation zones. These deformation zones contain a variable degree of work-hardening. As peening time increases, individual deformation zones progressively overlap and work-hardening accumulates. Fig.4 is a simplified representation of the effect of peening time, together with a corresponding peening intensity curve. The shape of the intensity curve mirrors the development of the deformed surface layer. The final outcome is a fully work-hardened surface layer of thickness, t. That thickness is directly related to the peening intensity, **H**, of the shot stream being used.

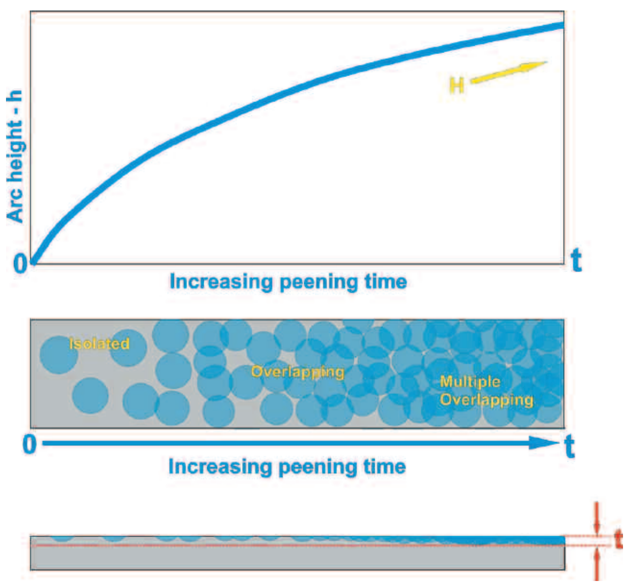

Fig.4. Progressive overlapping of deformation zones to produce a deformed layer of thickness, t.

As peening progresses we work harden the surface, reducing its ductility, so that it becomes progressively more difficult to produce surface stretching.

QUANTIFICATION OF REDUCTION IN δh WITH INCREASE IN PEENING TIME

The reduction in arc height contribution with peening time can be quantified by modifying equation (1) to give:

$$h = r.\sum_{0}^{t} \delta h.dt \qquad (3)$$

The Greek letter Σ simply implies 'sum'– of contributions **δh** that vary in size in minute intervals of time, **dt**, spread over a range of time from **0** to **t**. Peening an Almen strip over a time period, **t**, is therefore a practical application of integral calculus! The strip integrates (sums) the effects of a large number of indentations imposed over a known period of time.

The shape of any curve is defined by its corresponding equation. For peening intensity curves we can invoke a series of equations, of increasing complexity. A 'first approximation' to observed curve shapes is a two-parameter exponential equation of the form:

$$h = a\,(1-\exp(-b^*t)) \qquad (4)$$

where **a** and **b** are the two parameters.

If we differentiate equation (4) with respect to **t** we get the equation for indentation contributions:

$$\delta h/dt = a^*b^*\exp(-b^*t) \qquad (5)$$

Equation (5) is an 'indentation contribution curve'. That is to say it shows how the contribution, **δh**, of individual indentations changes with peening time. Fig.5 shows a peening intensity curve based on equation (4), together with the corresponding indentation contribution curve given by equation (5). It is clear that the contribution to arc height by successive impacts falls rapidly to a very small value.

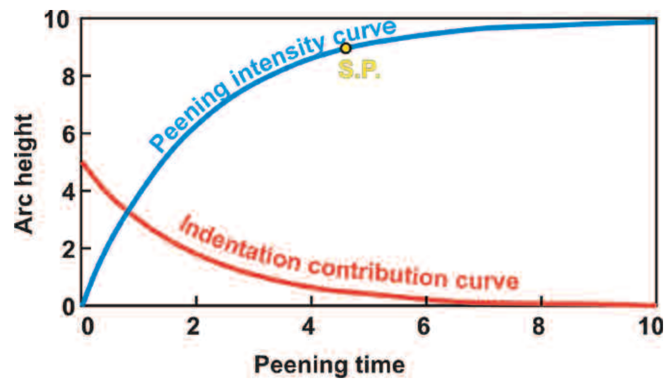

Fig.5. Two-parameter exponential peening intensity curve with corresponding indentation contribution curve and saturation point, S.P.

Table 1 lists four generally-recognized equations that simulate peening intensity curves, together with the corresponding first-differential indentation contribution equations.

Table 1. Peening Intensity and Indentation Contribution Curve Equations

Peening intensity Curve	Indentation Contribution Curve
$h = a(1 - \exp(-b^*t))$	$dh/dt = a^*b^*\exp(-b^*t)$
$h = a(1 - \exp(-b^*t^C))$	$dh/dt = a^*b^*c^*\exp(-b^*t^C)$
$h = a(1 - \exp(-b^*t^C) + d^*t)$	$dh/dt = a^*b^*c^*\exp(-b^*t^C) + a^*d$
$h = a^*t/(b + t)$	$dh/dt = a^*b/(b + t)^2$

If we use a two-parameter equation for peening intensity curves then one parameter, **b**, reflects the rate of generation of deformation zones and the other, **a**, reflects the contribution made by those indentations. Since we have only one parameter relating to indentation contributions that implies that only one primary height-generation mechanism is involved – plastically-deformed surface layer formation. The *form* of the equation indicates how the contribution of the indentations decreases with time. It is known, however, that three- and four-parameter equations are rather more accurate expressions of the 'known shape' of saturation curves. The extra parameters accommodate the secondary mechanisms involved in arc height generation.

COMPARISON OF PEENING INTENSITY AND COVERAGE CURVES

In plan view the indentations that contribute to coverage are smaller in surface area than those of the deformation zones that surround them. We might, therefore, expect that a coverage curve would take longer to reach a nominal 100% than would a peening intensity curve.

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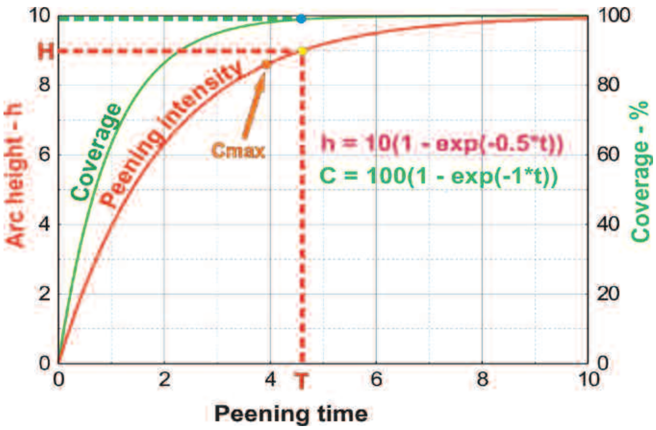
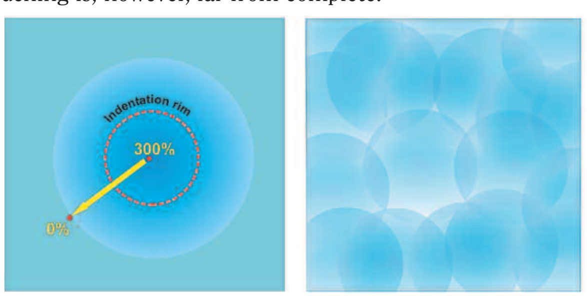


Fig.6. Comparison of Coverage and Peening Intensity curves for the same shot stream.

In fact the reverse is the case – which is paradoxical. The real situation is *modeled* in fig.6. At the ''saturation point' the peening intensity is shown as **H** at a time **T**. At **T** the coverage is shown as being approximately 99%. Peening intensity at **T** is only 90% of its value at **2T** when the deformed surface layer is approaching its maximum thickness. The coverage at **2T** will be 99.9%.

The key to unlocking the paradox lies in a consideration of the variation of deformation within a deformation zone. This variation is modeled for two dimensions in fig.7. Most of the deformation zone, shown in (a), has only had a very small amount of plastic deformation! That means that multiple impacting, shown in (b), will be required to exhaust the material's hardenability. For the model illustrated in fig.7(b) the degree of multiple impacting would correspond to 99.9% coverage but work-hardening is, however, far from complete.



(a) (b)

Fig.7. (a) Deformation zone surrounding an indentation and (b) multiple overlapping of zones.

PEENING INTENSITY

Peening intensity is a parameter that is deduced for each peening intensity curve. It is the arc height, **H**, that occurs at a 'characteristic point' of the curve. This characteristic point has long been associated with the so-called "knee" of the peening intensity curve. The definition (and specification) of the characteristic point has evolved somewhat erratically over a period of more than fifty years. Originally curves were hand drawn and subjective judgment was needed to pick a point where the "knee" occurred. In 1984, SAE adopted a mathematical approach – ostensibly in order to eliminate subjectivity. The 2003 version of J443 clarified the mathematical aspect ("10% rule") but is also ambiguous. The "knee" of a peening intensity curve evokes a mental picture of the region that has maximum curvature. Curvature, **C**, is the reciprocal of curve radius, **r**. Hence:

$$C = 1/r \qquad (6)$$

The smaller the radius the greater is the curvature. A straight line has no curvature - because r = ∞ and 1/∞ = 0. A circle has a constant curvature because the circle radius is constant. *All* other curves have a variable curvature. The "knee" of a curve can be defined, quantitatively, as *the point at which the curve has a maximum curvature*. For curves such as peening intensity curves the curvature is given by:

$$C = d^2h/d^2t/[1 + (dh/dt)^2]^{1.5} \qquad (7)$$

where **dh/dt** and $\mathbf{d^2h/d^2t}$ are the first and second differentials of the curve equation.

As an example, if h = a(1-exp(-b*t)) then dh/dt = ab*exp(-b*t) and $d^2h/dt^2 = -ab^2exp(-b*t)$ so that:

$$C = -ab^2exp(-b*t)/[1 + a^2b^2exp(-2b*t)]^{1.5} \qquad (8)$$

The point of maximum curvature occurs when **C** has its maximum (absolute) value. "Absolute" comes in because convex curves have positive curvature and concave curves have negative curvature. A straightforward way of obtaining the maximum value for **C** is to insert the r.h.s. of the equation into an Excel spreadsheet together with values for **a**, **b** and a 'guess' value for **t**. 'Solver' can then be invoked to 'minimise' the r.h.s. value by changing **t**. The derived 'minimized value' for **C** is a negative quantity - because the curve is regarded as being concave.

For illustration purposes if **a = 10 and b = 0.5** then equation (8) yields **h = 8.59** at **t = 3.91** as the point of maximum curvature. This point is shown in fig.6 as **Cmax**. It can be seen that the 'conventional' and 'mathematical' definitions for the knee location are close to one another.

The great advantage of curve-fitting is that it allows us to determine objectively a unique, fixed, quantity that characterizes the peening intensity of a shot stream.

DATA POINTS AND PEENING INTENSITY CURVES

Peening intensity curves are *derived* from sets of data points. Each data point is subject to variability – either random or systematic. If we only have random errors then they can be 'smoothed' by using a curve-fitting procedure. A typical situation, using real data (SAE Data Set 10), is illustrated in fig.8. The fitted curve has smoothed out the variability displayed by the data points. Looking at the box insert the measured arc height at **t=1** is slightly lower than that at **0.75**. This sort of situation would be expected with the random errors that are inescapable in strip testing. None of the data points lies *exactly* on the best-fitting curve. Similarly the derived peening intensity of **5.47** occurring at **t=0.55** does not coincide exactly with any of the data points.

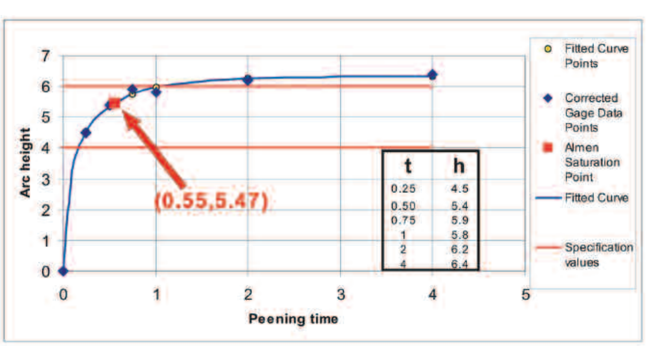


Fig.8. Peening intensity curve derived using six-point data set (shown in box insert).

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For the primary objective of locating the 'knee' of a peening intensity curve it is important to have a data set point distribution that straddles the knee.

DISCUSSION AND CONCLUSIONS

A peening intensity curve is, in effect, an Almen strip peen-forming curve. Tensile plastic deformation within the peened surface induces convex curvature. This induced curvature increases with both the indentation ability of a given shot stream and with the total peening time. Shot stream particles will, of necessity, vary in size, shape and velocity. Almen strip measurements are a remarkably effective, quantitative, means of integrating the indentation effects of the numerous shot particles that contribute to curvature. "Saturation intensity" is a parameter derived from a given peening intensity curve. This has become the industry-standard quantitative measure of a shot stream's indentation ability.

Peening intensity curves are not linear – because of the nature of the mechanisms that are operating. Work-hardening reduces the arc height contribution from individual impacts. The work- hardened surface layer develops more slowly than does coverage – because deformed regions can endure multiple, albeit reducing, plastic deformations. That contrasts with coverage - where each indentation makes a fixed contribution. The depth of the work-hardened surface layer will be proportional to the peening intensity of the shot stream being used.

Individual indentation effects decrease with peening time in a way that can be predicted by differentiating the equation of the corresponding peening intensity curve. This feature allows us to gain an insight into the several mechanisms that co-exist during peening of all materials – not just Almen strips. These mechanisms operate in the three-dimensional surface layer that work-hardens during peening.

Curve-fitting allows the unavoidable variability of individual strip measurements to be smoothed. Consider, for example, the values given in fig.8. *If* the measured arc height at the time 0.50 had been 5.2 (rather than 5.4) then computerized curve-fitting would derive the slightly-changed values of saturation intensity 5.46 at a time of 0.59. A data-point method of determining saturation intensity, on the other hand, would have changed the estimation from 5.4 at 0.50 to 5.8 at 1. In general, *data point definition of peening intensity is a variable quantity* (for any given peening intensity curve) because its value depends on the particular time used for the data point.

With the universal availability of computers and curve-fitting programs the labor previously involved in curve-fitting has been eliminated. Stored curve parameters can provide very useful reference information.

The equation of a peening curve can be used to obtain a unique and objective measure of peening intensity. Peening intensity has always been associated with the "knee" of the peening intensity curve. At least two methods of knee location are available – the "10% rule" and the point of maximum curvature. Both methods are objective and yield similar values. It is not proposed, however, that there is any need to change from the well-established "10% rule". There is, however, a need for greater clarity in the specification of peening intensity.

It is suggested that a primary parameter H_C, is used to specify "the lowest arc height of a fitted peening intensity curve for which doubling the peening time gives a predicted 10% increase of arc height". The use of a capital H incorporates the fact that this is a unique value and the subscript C that it is a position on a curve – not a data point. For the example shown in fig.8, H_C would be 5.47.

There is some justification for allowing the use of secondary peening intensity parameters. This is primarily because of the importance of verification testing involving single test strips being peened for a fixed number of passes/strokes. A secondary parameter such as h_D could be specified as being "the lowest measured arc height that satisfies a '10% or less' rule". The use of a lower-case h would incorporate the fact that it is not a unique value and the subscript D that it is a data point – not a curve point.

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, U.K. and is now a member of their Faculty of Engineering and Computing. We greatly appreciate his contribution to our publication.