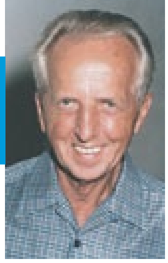

ACADEMIC STUDY
by Dr. David Kirk | Coventry University

Quantification of Shot Peening Coverage

INTRODUCTION

Shot peening is essentially a surface metalworking process. A stream of high-energy shot particles does work on the surface of components. The work done manifests itself in the form of dents. Coverage with dents increases with peening time. The progress of coverage is illustrated in fig.1. The rate of increase in coverage slows down with increase in the amount of peening – following the "Law of Diminishing Returns." An important practical requirement is that the applied shot stream must achieve a required degree of coverage in an economical time. As coverage increases a surface layer of work-hardened, compressively-stressed component material is generated. It is this "magic skin" that promotes improvement in service performance.

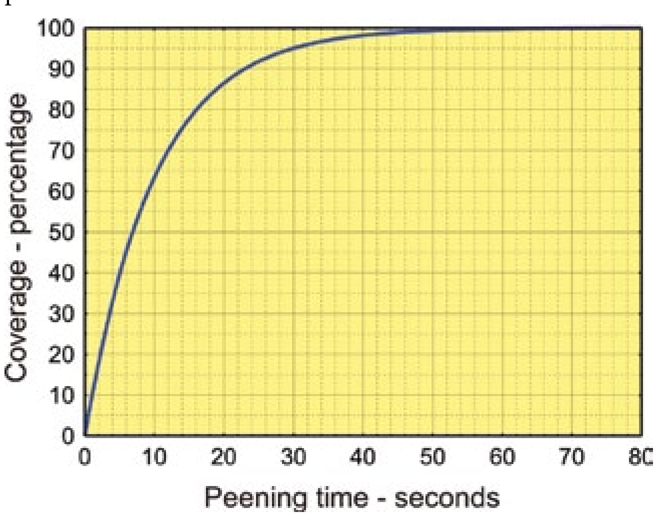

Fig.1. Typical Coverage/peening time curve.

The shot stream itself must have a specified intensity level, e.g., N254 (Almen N strip deflecting by 0.254 mm at a particular time of peening, T). This is an identifying parameter. There is, however, currently no specified parameter that quantifies a shot stream's ability to achieve required coverage levels.

This article considers, in quantitative terms:

(1) Particle Work Capability,

(2) Dent formation,

(3) Coverage evolution and

(4) Coverage versus Peening Intensity.

A suggested identifying parameter for a shot stream's ability to achieve required coverage levels is described in some detail.

1 PARTICLE WORK CAPABILITY

Each effective shot particle has some capability for doing work on a component's surface. This capability depends upon the kinetic energy possessed by the particle. It is not commonly recognized that work units and kinetic energy units are identical, i.e.:

The units for work can be expressed as either N*m or $kg*m^{2}*s^{-2}$.

Work is force (in Newtons) multiplied by distance (in meters) so that:

$$\textbf{Work units} = N*m \qquad (1)$$

Kinetic energy, $\frac{1}{2}mv^2$, has units of **kg** (for the mass, **m**) and of $m*s^{-1}$ (for the velocity, **v**). Hence by inserting these units we have that:

$$\textbf{Kinetic energy units} = kg*m^{2}*s^{-2} \qquad (2)$$

Force, which has the unit of Newtons, **N**, is equal to mass (in **kg**) multiplied by acceleration – which has units of $m*s^{-2}$. Hence we get that:

$$\textbf{Force}, N = kg*m*s^{-2} \qquad (3)$$

If we multiply both sides of equation (3) by **m** we get that for work units:

$$N*m = kg*m^{2}*s^{-2} \qquad (4)$$

(2) and (4) are identical. It therefore follows that the work capacity for an individual shot particle can be expressed as either N*m or $kg*m^{2}*s^{-2}$.

The mass of a particle is its volume multiplied by its density, ρ. The volume of a spherical particle is $\pi*D^3/6$ (D being diameter) so that its mass is $\pi*D^{3}*\rho/6$. Substituting this expression for mass into $\frac{1}{2}mv^2$ gives that a spherical particle's kinetic energy is $\pi*D^{3}*\rho*v^{2}/12$. Now a particle's kinetic energy is the same as its capability for doing work on a component, W_P. Hence $W_P = \pi*D^{3}*\rho*v^{2}/12$. Dividing by 10^6 (to give D in mm and W_P in Nmm) gives:

$$W_P = \pi*D^{3}*\rho*v^{2}/(12*10^{6}) \qquad (5)$$

Where W_P is particle work potential in Nmm, **D** is particle diameter in mm, **v** is particle velocity in ms^{-1} and **ρ** is particle density in kgm^{-3}.

Equation (5) can be used to estimate the work capability of individual shot particles e.g. as in fig.2. A 'mental picture' of the magnitude of the capabilities can be gained from the following example. Imagine an average-sized apple – it has a mass of approximately I Newton (remember that Sir Isaac Newton supposedly devised the Law of Gravity after seeing an apple fall in his orchard). Lifting this average-size apple by 100 mm (4 inches) requires 100 Nmm of work to be done on it.

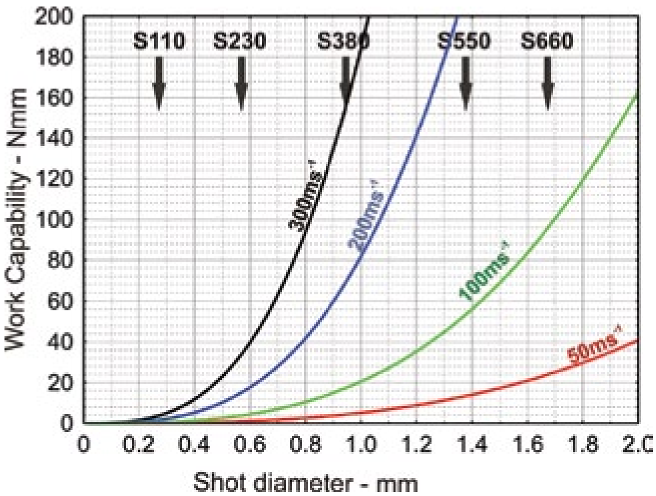

Fig.2. Steel shot work capability variation with diameter and velocity.

2 DENT FORMATION

Having quantified the work capability of an individual shot particle we can now estimate its ability to form a dent. When a high-velocity particle strikes a component's surface it loses a large part of its work capability. The greatest loss is caused by heat generation. Less than a tenth of the work capacity is used up in creating a dent. The previous section showed how the particle's work capacity can be calculated. This section shows how the amount of work needed to create a given dent can be estimated.

On initial contact with the surface the force being exerted on the surface by the impacting particle is zero. That is because force is stress multiplied by the area of contact – which initially is zero. The stress being applied is the compressive yield strength of the component. As the particle forces its way deeper into the surface the contact area grows. As a consequence the force grows. When the particle has its forward movement stopped the contact area is at its maximum so that the force being exerted is at its maximum. Fig.3 illustrates this progression from initial contact at (a) to maximum contact area at (b) when the dent depth is H.

The area, A, of contact between a spherical shot particle and a flat surface is given by:

$$A = \pi * D * h \quad (6)$$

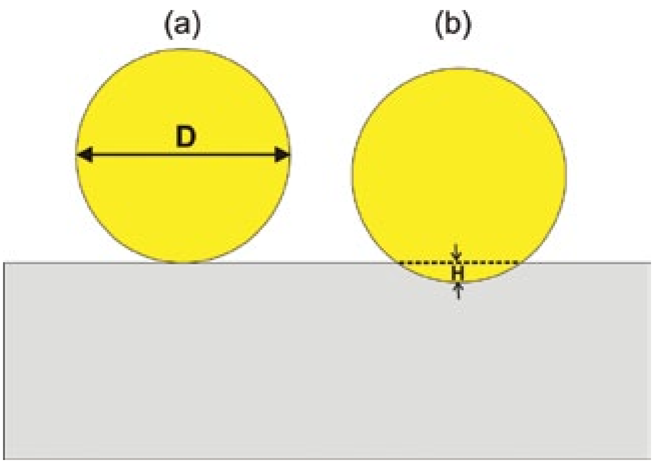

Fig.3. Progressive indentation by a shot particle to create a dent.

Where **D** is the particle's diameter and **h** is the depth of the dent.

h in equation (6) has a value of zero on initial contact and rises to a maximum of **H** (see fig.3).

Exerted force is yield stress, **Y**, multiplied by area over which that stress is applied, **A**. Hence the force, **F**, being exerted by the particle during impact is given by:

$$F = \pi * D * h * Y \quad (7)$$

The amount of work, W_D, which has to be done to create a typical dent, is the area of the blue right-angled triangle in fig.4. Area of a right-angled triangle is half the product of the base length multiplied by its perpendicular height. For the example shown, the area would be 126*0.08/2 N*mm or 5 N*mm.

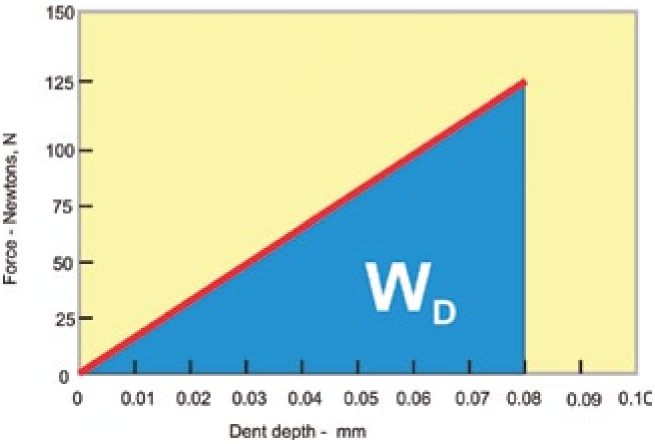

Fig.4. Example of force variation with dent depth - indicating work done.

The following example shows the calculations needed to determine the values shown in fig.4.

Example of work done in creating a dent

Assume that a spherical particle has a diameter of 1 mm and produces a dent 0.08 mm deep in component material that has a constant yield strength of 500 Nmm^{-2} (500 MPa). Substituting these values into equation (7) gives that the maximum force, F_{max}, is given by:

$F_{max} = \pi * 1mm * 0.08mm * 500\ Nmm^{-2}$ so that
$F_{max} = \pi * 1 * 0.08 * 500\ N$ giving
$F_{max} = 126\ N$

The work done in creating the dent, W_D, is the area of a triangle whose height is F_{max} and whose base is the depth of the dent. Hence we have that:

$W_D = 126N * 0.08mm/2$ giving that
$W_D = 5\ N*mm$.

As stated previously, less than a tenth of a particle's work capability can be translated into the work of dent creation. The particle must therefore have a work capacity at least ten times the magnitude of the dent creation work requirement. We can now compare the dent creation work requirement with the work capacity of a flying steel shot particle – using fig.2. If we assume that the particle is S380 then it would have to be travelling at about 180 $m*s^{-1}$ in order to have 50 N*mm of work capacity – the amount required to produce a dent about 0.08 mm deep.

There is a quantitative relationship between the work capability of a single shot particle and the diameter of the indent produced on striking a component. That relationship was originally presented by the author in a previous TSP article – Spring, 2004. In terms of work capability that relationship can be expressed as:

$$d^4 = D^4 * P * W * 1000/B \quad (8)$$

Where **d** is the indent diameter in mm, **P** is the proportion of the work potential used in dent creation, **W** is the work potential in N*m, **D** is the particle diameter in mm and **B** is the Brinell hardness of the component in MPa. The usually-quoted kg/mm^2 value for **B** has to be multiplied by 9.8 to give its MPa equivalent.

Equation (8) is useful in several ways: for predicting the separate effects of particle diameter, particle work capability and component hardness on indent diameter.

3 COVERAGE EVOLUTION

Peening involves vast numbers of particles impacting the component's surface. These particles progressively cover the surface with dents. Users specify the extent of the coverage that they require for particular components. For every specified peening operation the coverage achieved is determined by two factors (a) the coverage factor, K, of the shot stream on impact and (b) the time of peening.

Coverage Factor, K

K is A multiplied by N where A is the average projected area of each dent and N is the rate of dent creation per unit area of the component being peened. For example: assume that the average area of each dent, A, is 0.01 mm^2 and that the rate of dent creation, N, is 10 dents per mm^2 per second. The value of K (A multiplied by N) is then 0.1 per second (the mm^2 cancelling each other).

An equation relating dent creation rate to coverage was presented at ICSP5 by Kirk and Abyaneh. Expressed in terms of the coverage factor this equation is that:

$$C = 100(1 - \exp(-K*t)) \quad (9)$$

Where **C** is the coverage percentage, **K** is the coverage factor and **t** is the time when dents are being created (actual peening time).

Substituting 0.1 for **K** in equation (1) gives that $C = 100(1 - \exp(-0.1*t))$. Fig.5 represents the form of this equation. One useful feature of this exponential coverage curve relates to the peening time, T, that gives 90% coverage. If we double that time to 2T we get 99% coverage, 3T gives 99.9% coverage, 4T gives 99.99% coverage and so on. When $K = 0.1s^{-1}$ 90% coverage occurs at 23 seconds and 99% at 46 seconds and so on. So-called "full coverage" is defined as 98% or greater - based on measurements above 98% not being of acceptable accuracy and repeatability. When $K = 0.1s^{-1}$ 98% coverage occurs at a time of 39.1 seconds.

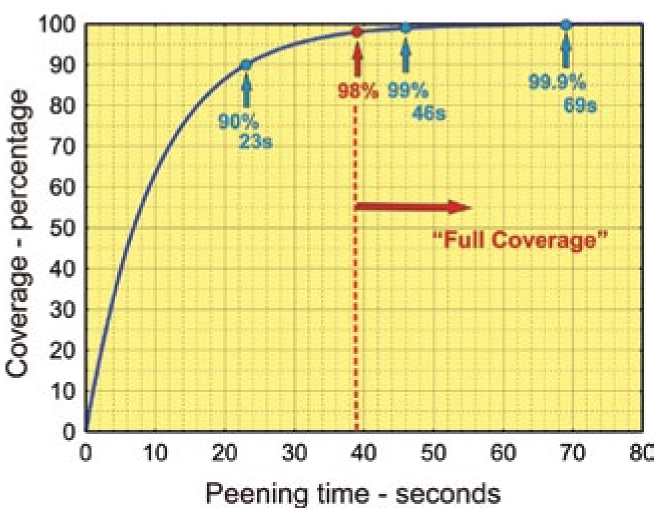

Fig.5 Coverage curve when Coverage Factor equals $0.1s^{-1}$.

When coverage reaches a very high value any further peening is generally wasteful. K can also be expressed as "per pass" rather than "per second." In this case the N is determined per pass rather than per second.

Reasonable maxima can be assumed for either the time of peening or the number of passes that will be employed on a given component. Assuming that these are 100 seconds and 10 passes respectively the effect of different coverage factors can be expressed graphically – as shown in figs. 6 and 7.

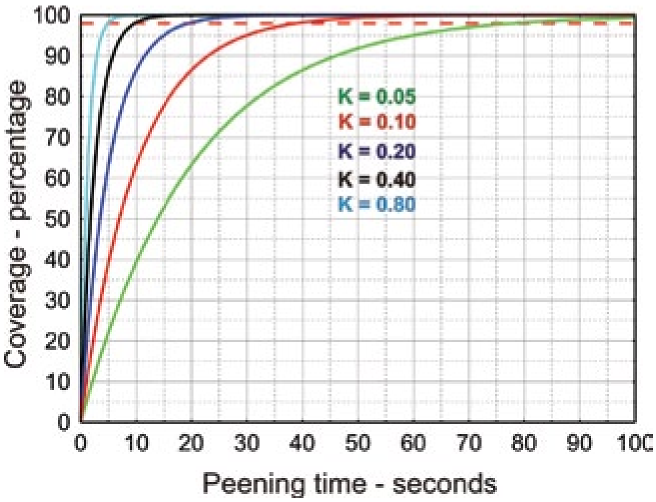

Fig.6 Effect of Coverage Factor on coverage/ peening time curve.

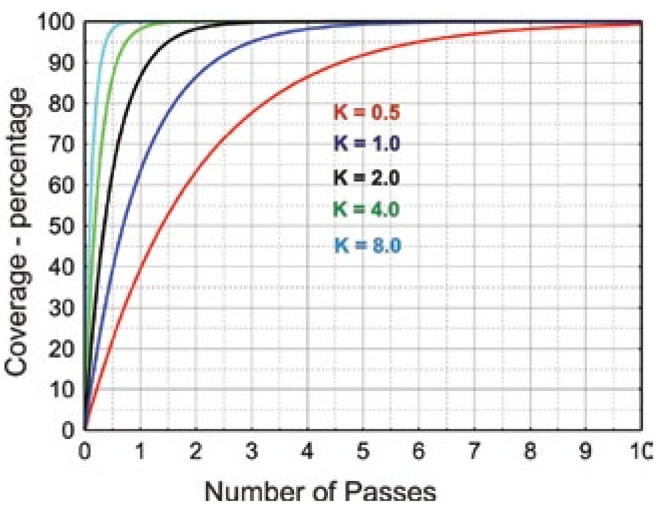

Fig.7 Effect of Coverage Factor on coverage/ number of passes curve.

Commercial values of K depend on the type of peening operation and its parameters. K values can be either measured or predicted for particular operations. The following is an example of the steps involved for air-blast peening.

Example of Coverage Factor Estimation for Air-blast Peening

For this example it is assumed that a conical shot stream is striking a flat component producing a circular impact zone whose diameter is **D** and whose area is **Z**. It is further assumed that the shot stream is being traversed linearly at a rate **TR**, that the feed rate of shot is **FR** and that the shot particles produce indents whose average area is **A**. Fig. 8 illustrates the variables.

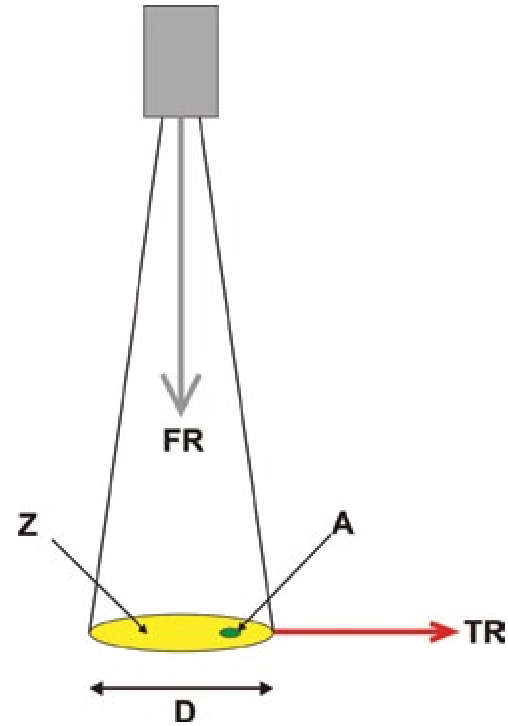

Fig.8. Coverage Factor variables.

The coverage factor for stationary peening (i.e. zero traverse rate) can be estimated using the following expression:

$$K = FR*A/(m*Z) \qquad (10)$$

Where **m** is the average particle mass.

As an example, assume that: a feed rate of 50 $g*s^{-1}$ is used to feed S170 shot; the impact area, **Z**, is 1300 mm^2 (**D** being 50 mm) and impact dents have an area, **A**, of 0.01 mm^2. The average particle mass, **m**, for S170 shot is $0.33*10^{-3}$g. Substituting these values into equation (10) gives that:

$$K(s^{-1}) = 50*0.01/(0.33*10^{-3}*1300) \text{ so then:}$$

$$K = 1.2\ s^{-1}$$

The average coverage factor, K_{AV}, for a stream that is moving relative to the component can be estimated using a modified form of equation (10):

$$K_{AV} = FR*A*D/(m*Z*(TR + D)) \qquad (11)$$

Where **TR** is the transfer rate per second.

Using the same values as in the previous example, together with a transfer rate per second of 50 mm, we have that:

$$K(s^{-1}) = 50*0.01/(0.33*10^{-3}*1300*(50 + 50)) \text{ so then:}$$

$$K = 0.6\ s^{-1}$$

This result indicates, as would be expected, that coverage would then occur at half the rate of an equivalent stationary shot stream.

Equations (10) and (11) quantify well-established knowledge of shot peening parameters. Increasing either the feed rate or the average indent area increases the rate of coverage. Increasing the average particle mass, impact area and traverse rate all reduce the rate of coverage.

4 COVERAGE/PEENING INTENSITY RELATIONSHIP

Coverage is defined as the percentage of a surface that has been covered with impact dents. Peening intensity is defined by a point, P, on a 'saturation curve', see fig.9. This point has, of necessity, two coordinates – H and T. H is the 'h-coordinate' value of deflection at a particular 't-coordinate' value of peening time, T. The magnitude of H therefore depends upon the location of T. As an old song says "You can't have one without the other".

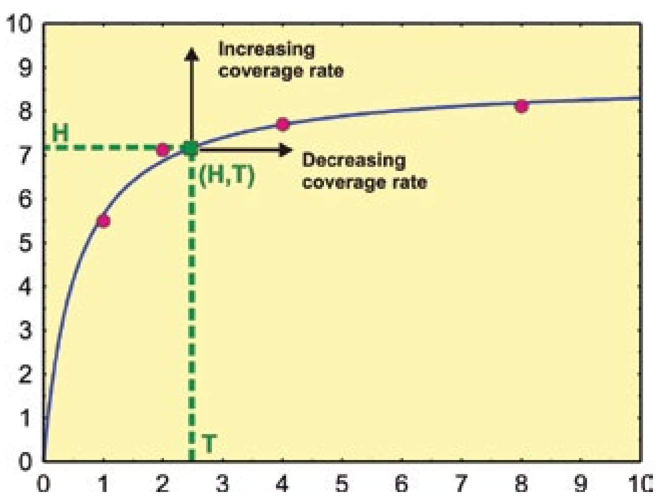

Fig.9 Typical peening intensity curve.

The coverage factor, K, determines the rate at which coverage develops. K is the average area of each dent, A, multiplied by the rate of creation of those dents per unit area of component, N. Now the average area of each dent is directly proportional to the magnitude of H, see fig.9. The value of the H parameter reflects the size of dents – and hence the value of A. Conversely, the time parameter T reflects the rate of creation of dents. It follows that a combination of a low value of H and a large value for T means that coverage (of Almen strips) will progress slowly. Coverage rates achieved for production components will not normally proceed at the same rate as they do for Almen strips. The main reason for this is a difference in the average size of impact dents, A. Components softer than Almen strips will cover faster whereas components harder than Almen strips will cover more slowly. It is, however, possible to allow for the hardness difference – either by prediction or by test measurement.

Some studies have been published for which both coverage and arc height were measured for sets of unpolished Almen strips. Fig.10 gives the first set values from a published study that involved six sets of peened Almen strips. The peening was carried out using a highly-instrumented, highly-controlled, test facility. Simple two-exponent exponential curves have been fitted (by the author) to the first set data. The saturation curve of arc height measurements is a good fit. That indicates that increasing numbers of revolutions increased the amount of work done on the strips in a predictable manner. The curve of coverage measurements is, by way of contrast, not a good fit. Quite surprising is the very small increase in measured coverage between one and three revolutions. The arc height increases substantially, as would be expected, from 0.0081" to 0.0144". Corresponding coverage values only increased from 49 to 52%. The coverage increases (from one to three revolutions) for the other five sets of data were: 48 to 84%, 60 to 83%, 36 to 40% and 67 to 80%. At the 'saturation time' T the measured coverage value was about 75%. Doubling the amount of peening, to 2T, increased the measured coverage value to about a nominal 'complete coverage' level.

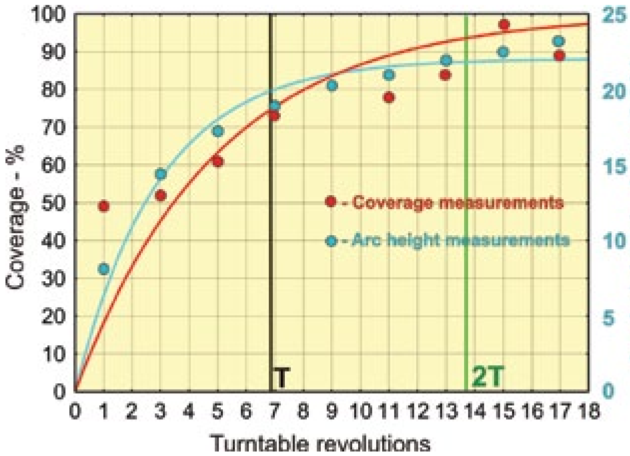

Fig.10. Coverage and arc height measurements on same set of Almen strips.

DISCUSSION

Quantification of coverage is, of course, very important for shot peeners. This article has attempted to show how a Coverage Factor, K, can be used as the basis for controlling applied coverage. This factor can be either predicted or measured.

The progress of coverage with increasing amounts of peening is expected to follow the exponential type of curve shown as fig.1. Experimental verification depends, however, on the accuracy of coverage measurements. The measurements reproduced in fig.10 run contrary to general experience of coverage measurement. The experimental technique used for those measurements should be compared with alternative techniques.

SAE Specification J2277 "Shot Peening Coverage Determination" provides interesting guidance. Equation (1) of that specification gives a quantitative relationship between coverage and shot stream exposure. This equation predicts an identical curve shape to that of equation (9) in this article. Fig.2 of J2277 gives photographs of coverage induced by applying 1, 2 3, 4 and 6 cycles of peening together with corresponding measured coverage values. These five measured values have been plotted in fig.11. The J2277 equation projects the one-cycle measurement in order to predict coverages with increased numbers of peening cycles. A 'best-fitting' curve of the same shape has been included which confirms that the data set conforms to a predicted simple exponential shape.

It is stressed that the only direct application for Almen strips is to enable the peening intensity of a shot stream to be determined. That does not prevent them from being used for other, 'academic', purposes. Their great advantages for coverage analyses are (a) that they constitute readily-available examples of progressive coverage and (b) that they are of a convenient size and shape for coverage measurements. Actual peened components with different levels of applied coverage are rarely both available and of a convenient size and shape.

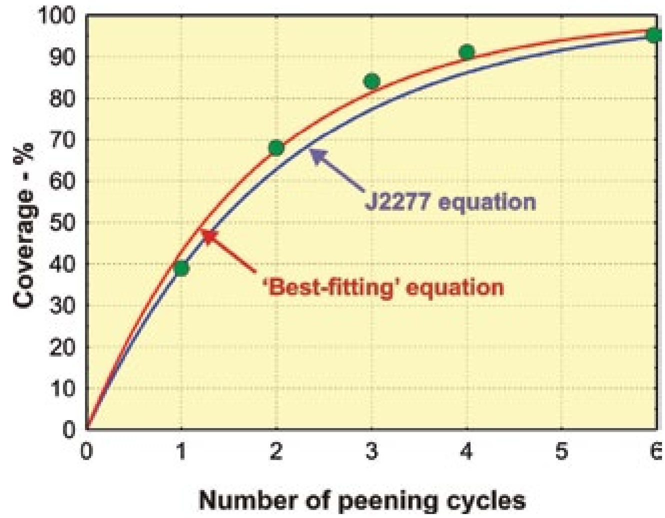

Fig.11. J2277 Coverage measurements