EVOLUTION OF SHOT PEENING EXPERIMENTAL TECHNIQUES

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ABSTRACT

A wide variety of experimental techniques have evolved which greatly enhance our knowledge and understanding of the shot peening process. Four technique categories are discussed relating to peening intensity, surface coverage simulation, shot properties and peened surface properties respectively. Peening intensity techniques include interactive intensity measurement and computer-fitted saturation curve procedures. Mathematical models have been developed for the prediction of surface coverage, the incidence of multiple impacting and indent diameters. Image analysis techniques have evolved for the quantification of shot properties such as size and shape variation. Surface property techniques include those for measurement and prediction of residual stress distributions, indentation size prediction and surface heating analysis. Examples are presented for each of the technique categories to illustrate the advantages and limitations of procedures that have been adopted.

Peening intensity, surface coverage, shot properties, surface properties.

INTRODUCTION

Experimental techniques have evolved continuously since the first introduction of shot peening. This paper covers the period from ICSP1 (1981) to the present. Most of the techniques described here would not have been possible without the explosion of computing power and sophisticated software that has occurred during the same period. Graphing of data has changed dramatically from the manual curve-fitting prominent at ICSP1 to the 'least-squares' computerised procedures that are currently used. Mathematical modelling is emphasised because it allows realisation of solutions to a wide range of shot peening problems. The overall objective is to present a coherent account of selected techniques. These techniques relate primarily to the three most important peening parameters: intensity, coverage and surface properties. It would impossible to present a comprehensive account of all techniques without being far too superficial.

PEENING INTENSITY

Almen intensity, derived from saturation curves, remains the industry-standard for quantifying the 'indent ability' of impacting shot particles. Individual Almen strips have their induced curvature measured using gauges whose accuracy has evolved considerably. Digital monitors, which can be connected directly to computers, have largely replaced dial gauges. Manual curve-fitting to the corresponding data points is being replaced by computerised techniques. Curve-fitting, however, requires assumptions about the shape of the 'best-fitting' mathematical equation. In order to investigate the true shape of Almen saturation curves it is necessary to look at a large collection of data that has been obtained using carefully controlled peening variables. One such collection (Wieland, 1993) relates to arc heights from 388 Almen strips. Wieland's collection has been used (Kirk, 2002) to derive an equation that accurately describes the shape of Almen saturation curves. That equation, (1), has both exponential and linear components and involves four constants (***a, b, c*** and ***d***).

$$y = a\,(1 - \exp(-\,b\cdot x^{c})) + d\cdot x \tag{1}$$

Wieland's data averages have been plotted in fig.1 and a best-fitting version of equation (1) applied. The ***y*** values are the Almen arc heights and the ***x*** values are the corresponding peening times. Having established the values of the four constants for equation (1) a shortest time, T, has been deduced mathematically such that the y-values for T and 2T differ by 10%. Substituting T for x and the four constants into (1), yields the Almen saturation intensity value, in this case 0·319mm.

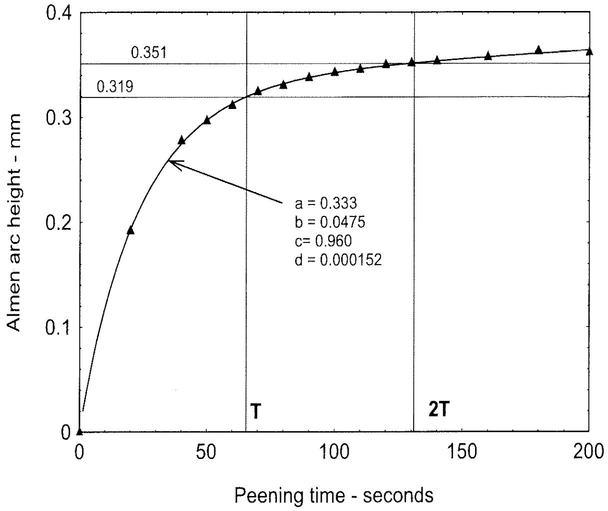


Fig.1 Curve fit of equation (1) to published data (Wieland, 1993).

The excellent fit achieved by equation (1), $r^2 = 0.999$, indicates that it is a good representation of the true shape. Fitting of equation (1) to numerous other sets of saturation data has shown that it is extremely effective in predicting shape.

Interactive intensity measurement has continued to evolve since its introduction (Kirk, 1993). Several authors (e.g. Kirk, 1996 and Sharma *et al*, 2002) have contributed and commercial exploitation of the concept is now a reality. Initial work involved the use of rectangular strips, but rounds have now become the preferred shape.

The angle of impingement between shot and component surface, θ, has a significant effect on peening intensity. It is generally assumed that there will be a simple **sin**θ relationship between intensity at an inclined angle, I_θ, and intensity for perpendicular impact, I_p:

$$I_\theta = I_p \cdot \sin\theta \tag{2}$$

This general assumption is based on the argument of resolving the shot energy vector, E, into components normal to and parallel to the impacted surface, as shown in fig.2. That simplistic argument does not allow for the change in morphology of indents with angle of impact. This effect has been studied recently (Kirk, to be published).

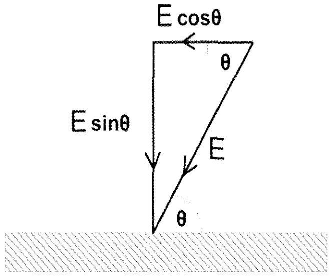
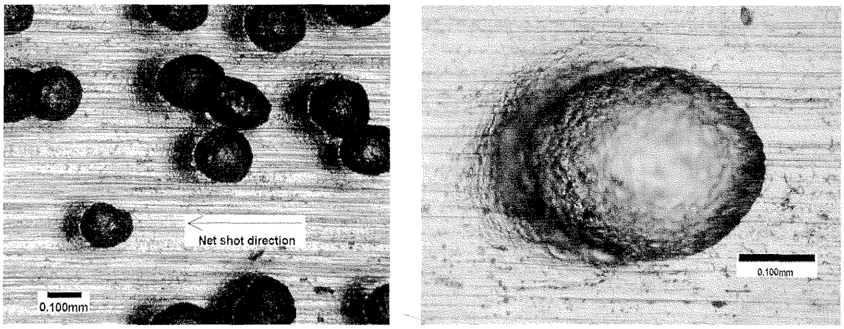


Fig.2 Vector resolution of shot particle energy, E.

Spherical shot particles striking perpendicular to a surface generate a circular indentation in the form of a 'spherical cap'. If, however, the particles strike at an inclined angle, then the indentation will be elliptical. The energy being absorbed by the surface will therefore be spread over a larger area, and therefore to a lesser depth, than would be the case for perpendicular impact. Elliptical indentations are illustrated in fig.3. A noticeable feature is the generation of 'pile ups' of heavily cold-worked material ahead of the impacting shot particles.



(a) (b)

Fig.3 Impact morphology for partially-peened aluminium using S170 steel shot. Impingement angle 45° for (a) and 30° for (b).

Ellipticity increases with decrease in impingement angle. For an ellipse we have an area $\pi \cdot a \cdot b$, where a and b are the major and minor axial lengths. The area of an elliptical section of a circular cone of radius, r, is $\pi r^2/\sin\theta$ (to a close approximation). It follows that the peening intensity will be reduced by some function of $\sin\theta$ - due to increased area of indent and therefore reduced depth of indent. Combining the two $\sin\theta$ factors that reduce peening intensity gives:

$$I_\theta = I_p \cdot \sin^n\theta \qquad (3)$$

where **n** lies between 1 and 2.

Fig.4 summarises measurements made using sets of A and C Almen strips, S170 shot, and a device for holding the strips at a variable impingement angle. The trends indicate that the value for the n of equation (3) is close to 1·5. It has also been shown, by indentation measurements, that the ellipticity follows a $\sin^{0.5}\theta$ function.

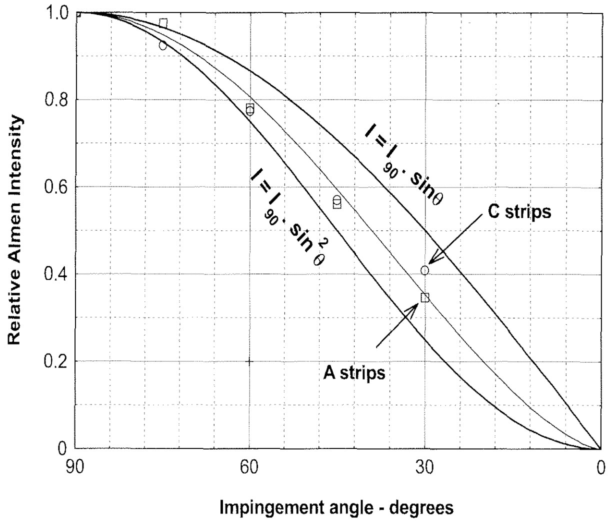


Fig.4 Effect of impingement angle on Almen intensity.

SURFACE COVERAGE SIMULATION

Surface coverage is arguably the most important variable in shot peening. It is defined as the percentage area of a surface that has been impacted. Computer-controlled techniques have evolved which minimise macroscopic variations in coverage received by commercial components. The amount of coverage that should be applied is the subject of considerable debate. There is a danger with high coverages of exhausting the ductility of components because of multiple, superimposed, plastic deformations. That is in spite of the tri-axial compressive stressing that is a characteristic of indent formation. If we assume that the impacting shot produces a distribution of constant-diameter, circular, indentations then mathematical models for coverage generation are relatively simple. Several authors have used such models. Traditional peening, using air-blast or wheel machines, creates a distribution that is almost, but not quite, random. 'Flapper wheel' peening generates rather less randomness than does normal peening. At the other extreme, 'tramp peening' (designed for peen forming operations) creates a nearly uniform distribution of large indentations.

The theory of coverage development for random indentations is well-established. The simplest model is based on assuming statistically-random shot particles arriving at the component's surface at a constant rate and creating circular indents of a constant size. Given those assumptions, an Avrami equation appropriate to the situation (Abyaneh and Kirk, 1993) is:

$$C = 100\{1 - \exp(-\pi r^2.R.t)\} \qquad (4)$$

where ***C*** is the percentage coverage, ***r*** is the radius of each indentation (so that πr^2 is the area of each indentation), ***R*** is the rate of impacting (number of impacts per unit area per unit time) and ***t*** is the peening time.

It is important to note that the predicted coverage, *C*, given in equation (4) is only exact for an infinitely-large sample. When plotted using specific combinations *K*, of *r* and *R*, equation (4) gives continuous curves that are exponential towards 100% coverage, as shown in fig.5. That does not mean that we cannot possibly achieve 100% coverage with a real, finite, sample. In practice we have a rapidly-increasing possibility that 100% coverage will be achieved for a real component.

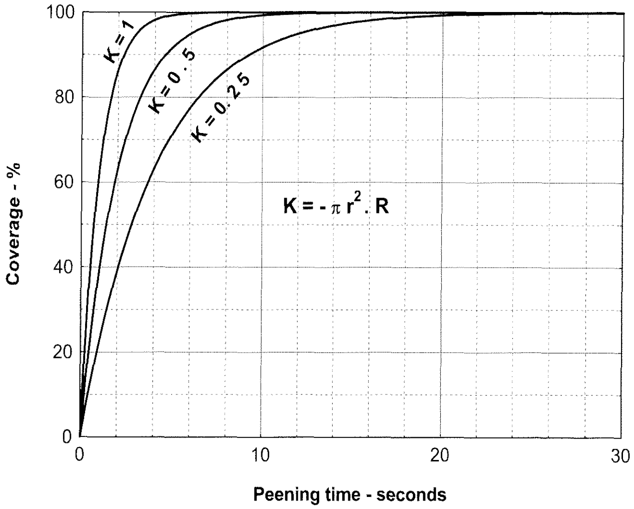


Fig.5 Coverage curves for different peening rates, *K*.

Static models have been used (Abyaneh and Kirk, 1996) to simulate different stages of coverage. Fig.6 shows a typical example, which depends upon the use of uniform random numbers for the coordinates of the circle centres. An excellent dynamic model of coverage generation has been demonstrated (Lombardo and Bailey, 1996).

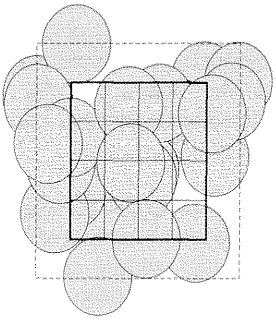


Fig.6 Twenty-five randomly-sited unit radius circles.

Image analysis techniques are available which permit greater objectivity in assessing coverage. There is an evolving consensus that 98% coverage, as defined by equation (4), is a realistic maximum that can be accurately measured.

SHOT PROPERTIES

In 1981 shape assessment was based on visual inspection and comparisons were made with drawings specifying "acceptable shapes" and unacceptable "deformed" and "broken" shapes', see fig.7.

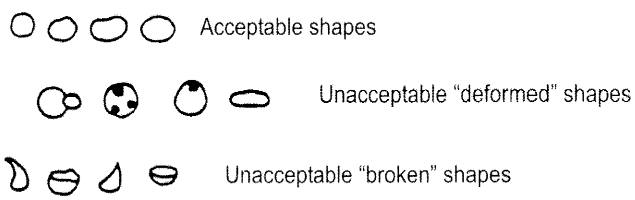
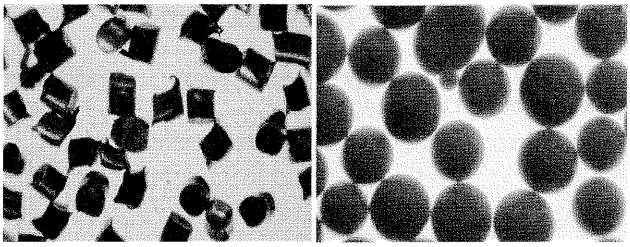


Fig.7 Specified acceptable and unacceptable shot shapes.

Shape and size assessment of shot particles have since been improved by the introduction of image analysis techniques (Gillespie, 1996 and Kirk, 2001).

Techniques involving digital cameras linked to computers allow rapid, objective, quantitative measurements to be made on shot samples. Two extreme shape examples are illustrated in fig.8. Image analysis quantifies shape and size in terms of parameters such as roundness, area, and diameter. Digitised data is readily stored and transmitted.



(a) (b)

Fig.8 Extremes of shot shape, illustrated by as-cut wire (a) and ceramic (b).

X-ray residual stress measurement techniques were already well-established in 1981. Alternative techniques have since been proposed, but these have not been generally adopted. Commercial computer programmes are available for predicting residual stress profiles. User-based programmes can also be constructed (Kirk, 2004). Micro hardness testing has been widely used to examine the depth and degree of work hardening induced by shot peening. Modelling techniques for residual stress distribution are described (Kirk and Hollyoak, 2005) in another paper presented at this conference.

Techniques for predicting indentation diameters have been developed (Kirk, 2004). Diameter predictions can be made using information about shot size, density and velocity and component material strength, see equation (5). Such predictions are important because of the relationship that exists between indent diameter/depth and peening intensity.

$$\boldsymbol{d = 1{\cdot}278.D.(\tfrac{1}{3}P)^{0.25}.\rho^{0.25}.v^{0.5}/B^{0.25}} \qquad (5)$$

where $\boldsymbol{d}$ is the indent diameter, $\boldsymbol{D}$ is the shot diameter, $\boldsymbol{P}$ is the proportion of kinetic energy absorbed on impact, $\boldsymbol{\rho}$ is the shot density, $\boldsymbol{v}$ is the shot velocity and $\boldsymbol{B}$ is the Brinell hardness of the component material.

Commercial developments have taken place employing high-intensity peening in order to thermally-induce surface structural changes. A technique, for predicting the very large temperature rises required, has been developed (Kirk, 2004). The temperature rise during peening, ΔT, is given by an equation of the form:

$$\boldsymbol{\Delta T = K(1 - \exp(-a{\cdot}t)) + c{\cdot}t} \qquad (6)$$

where $\boldsymbol{K}$ is a constant (proportional to the product of mass of shot striking a unit area per unit time multiplied by the square of the shot velocity and divided by the shot diameter), $\boldsymbol{t}$ is the peening time and $\boldsymbol{c}$ is a constant that depends on the thermal conductivity of the component.

Multiple impacting is a necessary consequence of conventional shot peening. A technique has been presented (Abyaneh and Kirk, 1996 and Lombardo and Bailey, 1996) which quantifies the contribution, $\boldsymbol{C_n}$, of $\boldsymbol{n}$ multiple impacts to the total coverage. The quantifying equation (Abyaneh and Kirk, 1996) is that:

$$\boldsymbol{C_n = (\pi r^2 At)^n{\cdot}\exp(-\pi r^2 At)/n!} \qquad (5)$$

where $\boldsymbol{r}$ is the indent radius, $\boldsymbol{A}$ is the rate of indenting per unit area, $\boldsymbol{n}$ is the number of multiple impacts and $\boldsymbol{n!}$ is the factorial of $\boldsymbol{n}$.

Fig.6 is a graphical representation of equation (6) showing how multiple impacting becomes predominant above 80% coverage.

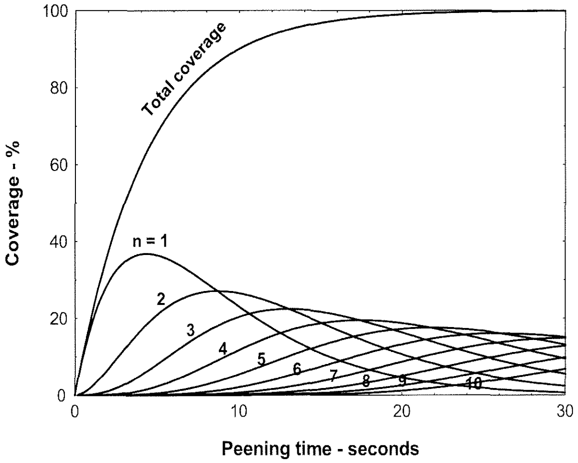


Fig.6 Contributions to total coverage by different numbers, *n*, of multiple indentations.

The danger with very high coverages is that the component's surface ductility becomes exhausted and the surface structure is increasingly thermodynamically unstable – leading to greatly reduced stress relief temperatures.

DISCUSSION AND CONCLUSIONS

Mathematical models for describing experimental observations have been emphasised throughout this paper. Models have the advantage of objectivity and also reveal underlying controlling mechanisms. These models would not have been feasible without the ready availability of enormous computing power and sophisticated computer programmes.

The evolution of experimental techniques, both physical and mathematical, has allowed the development of what can be termed the 'science of shot peening'. The corresponding growth of understanding of the principles that govern shot peening has facilitated a transformation of a 'blacksmith's art' into a precisely-controlled surface enhancement process. This growth of understanding has built on the studies undertaken using techniques established before 1981.

It should be noted that the techniques described in this paper are only a fraction of those that have been evolved since 1981. The selection is justified on the basis of avoiding superficiality.

REFERENCES

[1] Abyaneh, M Y and Kirk, D, Fundamental Aspects of Shot Peening Coverage Control, Part 3, Proc. ICSP6, 1996, 456.
[2] Gillespie, B, Image Analysis of Shot Peening Media, Proc. ICSP6, 1996, 213.
[3] Kirk, D, Interactive Shot Peening Control, Proc. ICSP5, 1993, 9.
[4] Kirk, D, and Abyaneh, M Y, Theoretical Basis of Shot Peening Control, Proc. ICSP5, 1993,183.
[5] Kirk, D, Image Analysis and Computer Microscopy of Shot Particles, The Shot Peener, 2001, **15-3**, 4.
[6] Kirk, D, Curve Fitting for Shot Peening Analysis, The Shot Peener, 2002, **16-1**, 6.
[7] Kirk, D, Developments in Interactive Control of Shot Peening Intensity, Proc. ICSP6, 1996, 95.
[8] Kirk, D. Prediction and Control of Indent Diameter, The Shot Peener, 2004, **18-2**, 18.
[9] Lombardo, D and Bailey, P G, The Reality of Shot Peening Coverage and Dimple Interactions, Proc. ICSP6, 1996, 493.
[10] Sharma, M C et al, Virtues & Limitations of Almen Round, Proc. ICSP8, 2002, 83.
[11] Wieland, R C, A Statistical analysis of the Shot Peening Intensity Measurement, Proc. ICSP5, 1993, 27.