Peening Indent Dimensions

Dr. David Kirk 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 Visiting Professor in Materials, Faculty of Engineering and Computing at Coventry University.

INTRODUCTION

Indent size really matters! It has a direct effect on both peening intensity and coverage. Peening intensity is directly proportional to the size of the indents. Coverage increases with indent size (other things being equal). The size of indents is, therefore, of primary importance. Control of indent size depends on knowing (a) the size, (b) the factors affecting size and (c) implementing methods of influencing indent size.

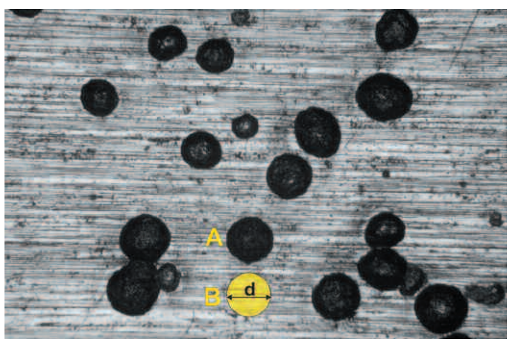

Fig.1 Indent shapes at low coverage.

Typical indents are illustrated in fig.1. The shapes are approximately circular. One indent, highlighted at **A**, has had an 'equivalent circle' created at **B** whose diameter is **d**. Equivalent circles are generally assumed when modeling coverage and indent depth.

This article is a quantitative analysis of the several factors that affect indent size. It is hoped that readers who dislike mathematics will not be put off by the necessary equations that are introduced. Widely-available computer programs, such as Excel, allow such equations to be employed by simply inserting known values. For example, the depth of an indent can be calculated using Excel by entering a known shot diameter into cell A1, a known indent diameter into cell A2 and the following formula into cell A3: =(A1-(A1^2-A2^2)^0.5)/2. This formula is the same as equation (1) presented later.

SHOT SIZE VERSUS INDENT DIAMETER

There is a linear relationship between indent diameter and the diameter of the shot causing the indent – other things being equal. This is confirmed by both actual observation and theoretical analysis. Standard shot peening will produce indents whose diameter is a substantial percentage of that of the shot particles – say 30 to 50%. We can, therefore, predict a standard size range of indents - because we already know the diameter of the shot particles being used.

Fig.2 is a graphical representation of these predicted ranges of indent diameters, **d**, that we might encounter when using cast steel shot of diameter, **D**. SAE nominal shot size has been indicated as this is the most familiar size parameter. It can be seen that there is a huge range of indent diameters that we may come across. A useful 'memory aid', based on assuming that **d** is 40% of **D**, is that:

Indent diameters in microns are roughly the same as the SAE number of the shot being used.

For example, S110 shot produces indents of roughly 110 microns diameter whereas S460 shot commonly produces indents of roughly 460 microns diameter – 1 micron being the same as 1µm.

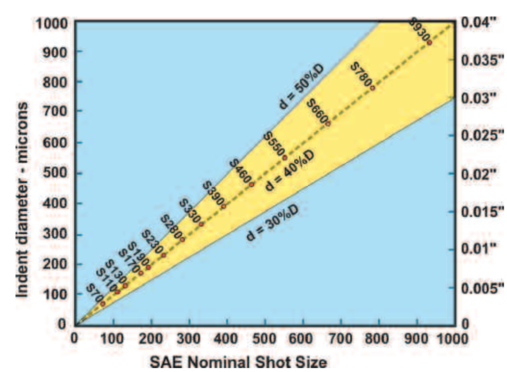

Fig.2 Common range of indent diameters induced using cast steel shot.

INDENT DEPTH, h

Indent depth, **h**, depends on both the shot diameter, **D**, and the indent diameter, **d**. If we assume that the indent is circular and that the shot particle is spherical then the relationship between **h**, **d** and **D** is that:

$$h = [D - (D^2 - d^2)^{0.5}]/2 \qquad (1)$$

where $d < D$

For example: if **D** = 110μm and **d** = 44μm then **h** = 4.6μm. **h** is then 11% of **d**. Fig.3 is a universal representation of how indent depth varies with indent diameter. **D** is fixed as '100'' so that **h** is then a percentage of **D**. If the indent diameter is 20% of **D** then the depth is only 1% of **D**! Even if the indent diameter is 60% of D then the indent depth is only 10% of **D**. The percentage values for **d/D** as 30, 40 and 60% have also been highlighted.

Automatic calculation of indent depth, **h**, is included in the Excel spreadsheet described in the next section.

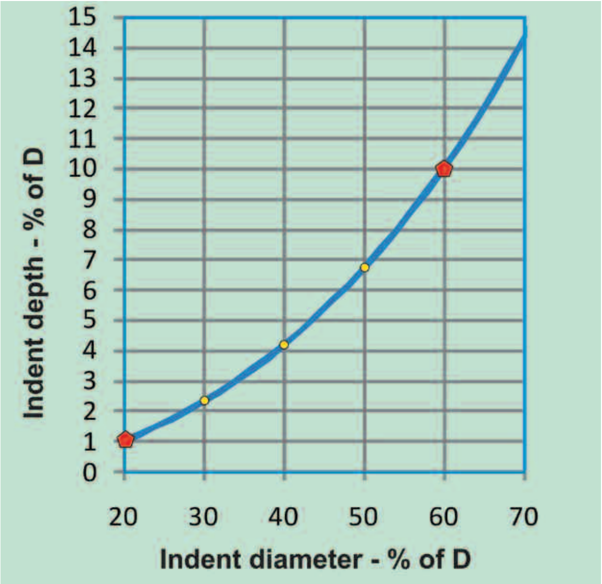

Fig.3 Universal representation of indent depth as a percentage of indent diameter.

PREDICTION OF INDENT DIAMETER AND DEPTH

We can predict the indent diameter and depth that will be induced by shot peening – provided that we know the magnitude of the several controlling factors. These are: **shot diameter**, **velocity** and **density**, together with **component hardness** and **coefficient of restitution**. All of the factors are more or less familiar - with the exception of 'coefficient of restitution'.

Coefficient of restitution is, arguably, the most important parameter in shot peening! It determines how much energy is retained when a shot particle bounces off a component. Imagine a particle being dropped from a certain height, **h1**, onto a flat plate component. It will bounce up to a height, **h2**. The coefficient of restitution, **e**, is given by:

$$e = \sqrt{(h2/h1)} \quad (2)$$

If **h2** is half of **h1** then the shot particle has lost half of its energy. **e** is then equal to 0.71. If **h2** equals **h1** (e = 1) then the shot particle has not lost any energy on impact so that no indent could have been produced.

Equation (3) predicts the effects of the several factors controlling indent diameter.

$$d = 0.02284 * D * (1 - e^2)^{0.25} * \rho^{0.25} * v^{0.5} / B^{0.25} \quad (3)$$

where: **ρ** is shot density, **v** is shot velocity and **B** is the component's Brinell hardness.

The factor 0.02284 is appropriate when using metric units – **v** in ms^{-1} and **ρ** in kgm^{-3}.

A	B	C
4	K	0.02284
5	Shot Diameter - mm	0.100
6	Coefficient of Restitution - e	0.71
7	Density - kgm^-3	7860
8	velocity, v - ms^-1	85
9	B.H.N.	300
11		
12	Indent diameter, d - mm	0.040
13	Indent depth, h - mm	0.0042

Fig.4 Spreadsheet for prediction of indent diameter and depth.

Equation (3) is too complicated to visualize quantitatively. A simpler approach is to incorporate that equation into an Excel spreadsheet. The quantitative effect of changing factor magnitudes then appears on simply pressing a button. Such a spreadsheet is shown as fig.4, which also incorporates an indent depth calculation based on equation (1). Known values are entered into the yellow boxes and required answers then appear in the green boxes. The factor **K** is fixed, as is **e** (unless a different, measured, value is available). A value of 0.71 for **e** is reasonable for steel shot bouncing from steel components. Free copies of the spreadsheet are available on request.

The advantages of using a spreadsheet-calculation approach are that the effects of different factor magnitudes can easily be quantified. This is facilitated by having copies of fig.4 side by side on the same spreadsheet. As an example, consider the indents shown in fig.1, which vary in diameter by a factor of approximately 2. Component hardness, coefficient of restitution and shot density are virtually constant (for the given specimen). That only leaves shot diameter and shot velocity as possible causes of indent diameter variation. Using the initial values given in fig.4 the velocity would have to be reduced from $85ms^{-1}$ to $21ms^{-1}$ in order to halve a predicted indent diameter. Shot diameter would only have to be halved (in order to halve the predicted indent diameter). Cast steel shot specifications allow for diameter variations much greater than a factor of 2. It is, therefore, reasonable to argue that the observed indent diameter variation in fig.1 is largely due to shot diameter variation.

EFFECT OF IMPACT ANGLE ON INDENT SHAPE

Shot particles rarely strike a component perpendicularly. In general they strike at some other angle, θ, to the surface - see fig.5 on page 30. Shot stream divergence, component surface curvature and angling of shot stream to the surface all combine to induce values of θ that are less than 90˚. The impact angle has an important effect on both peening intensity and indent size. When θ does equal 90˚ spherical shot will produce a circular indent. If θ is less than 90˚ the indent will be elliptical.

Fig.6 (on page 30) shows the elliptical indent shape produced by a real shot particle striking a mild steel surface at θ = 45˚ (travelling from right to left). Mild steel is very useful as a research material because it highlights plastic deformation zones – as on the left of the indentation in fig.6.

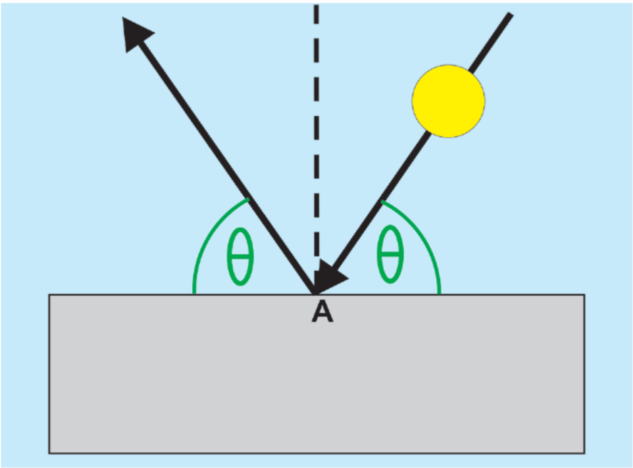

Fig.5 Shot particle destined to impact at A making an angle, θ, with the component surface.

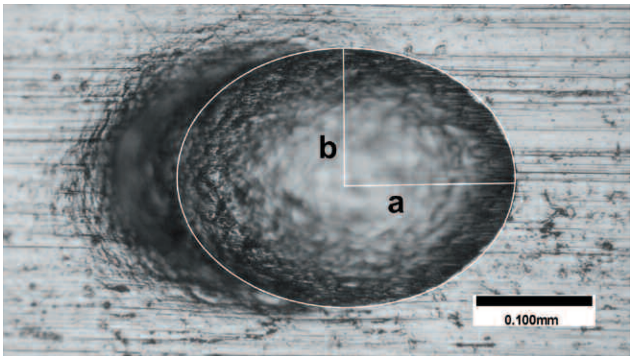

Fig.6 Elliptical indent created by 45° impact with a flat mild steel surface.

Ellipticity is defined by the ratio of the major and minor axes, **a/b**. The origin of elliptical indents has been described previously (TSP vol. 19, No.3, 2005).

Effect of Impact Angle on Peening Intensity

Empirical studies have shown that both peening intensity and indent depth vary with impact angle in the same way – as illustrated in fig.7. They are both inversely proportional to $\sin\theta^{1.5}$.

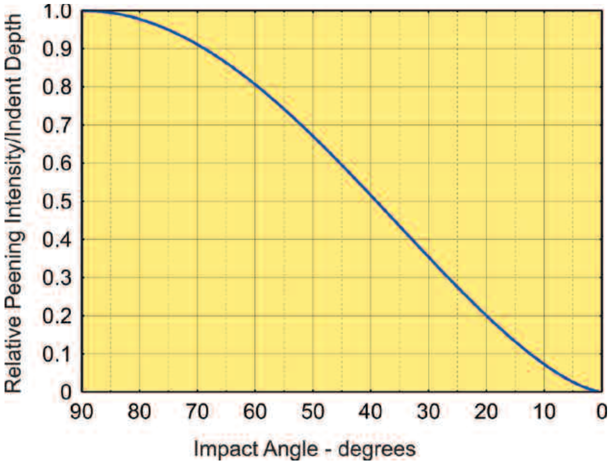

Fig.7 Variation of Peening Intensity and Indent Depth with Impact Angle.

At θ = 60°, for example, the peening intensity has dropped to 80% of the value that would have been obtained if θ had been 90°. At 20° it is only 20%. This underlines the practical importance of ensuring that the average impact angle is reasonably close to 90°.

Effect of Impact Angle on Indent Size and Coverage Rate

The size of an indent can be quantified as the flat area defined by its rim. For a circular indent, size is then the area of a circle - $\pi d^2/4$. For an elliptical indent, size is the area of an ellipse – $\pi ab/4$. The empirical studies mentioned previously yield a relationship between impact angle and area of an indent. This relationship is that indent area varies inversely with sinθ – as shown in fig.8. Relative coverage rate varies inversely with $\sin^2\theta$ – because a given shot stream is striking a larger area as θ decreases.

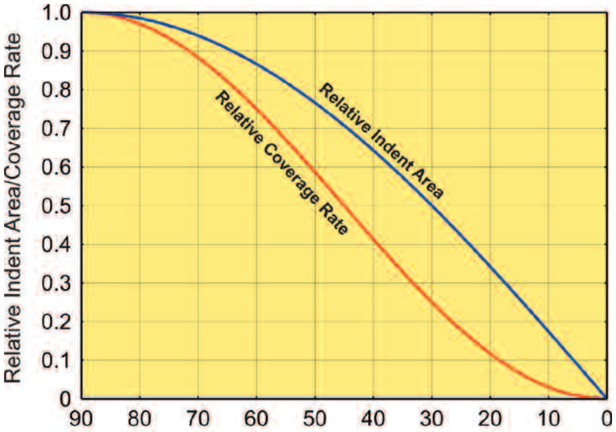

Fig.8 Effect of Impact Angle on Indent Size and Coverage Rate.

The fall in coverage rate with decrease in impact angle is even greater than the fall in peening intensity. Again we have a practical significance – the time for attaining a given coverage percentage will strongly depend on the impact angle.

INDENT VOLUME

Having either estimated or measured the diameter and depth of an indent we can then estimate its volume. Indent volume, v, for a circular indent is given by:

$$v = (\pi/6)(3d^2/4 + h^2)h \qquad (4)$$

Indent volume is important because it represents the amount of work that has been done by the impacting particle on the work piece. The impacting particle has a kinetic energy, $\frac{1}{2}mv^2$, as it impacts the surface. It follows that the greater the particle's kinetic energy the greater will be the volume of the indent produced.

MEASUREMENT OF INDENT DIAMETERS

Peening indents are very small - some 10 to 1000 microns - so that image magnification is essential for accurate measurement. Magnification can either be simply optical or a combination of optical and digital.

We can measure indent diameters either directly - using an optical image - or indirectly - using a digital image. Direct measurements involving a measuring microscope are probably the more accurate. Each human eye has about 125 million rods to detect black-and-white and 7 million cones to detect color. Using two eyes we also have the benefit of stereoscopic vision. A typical digital camera has only about 10 million pixels.

There is a wide range of available measuring techniques each of which has advantages and disadvantages. Every technique relies, however, on a 'graticule'. A graticule is a form of miniature ruler made by using precision engineering to inscribe finely-spaced lines on either a metal or glass plate. A typical graticule is illustrated in fig.9 where one millimeter has been divided into 100 segments.

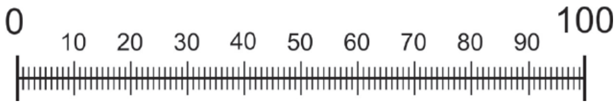

Fig.9 Metric graticule with one millimeter divided into a hundred parts.

Two of the author's favorite techniques are based on using either a measuring microscope or a USB microscope. Fig.10 is a flow chart summarizing the differences between the techniques.

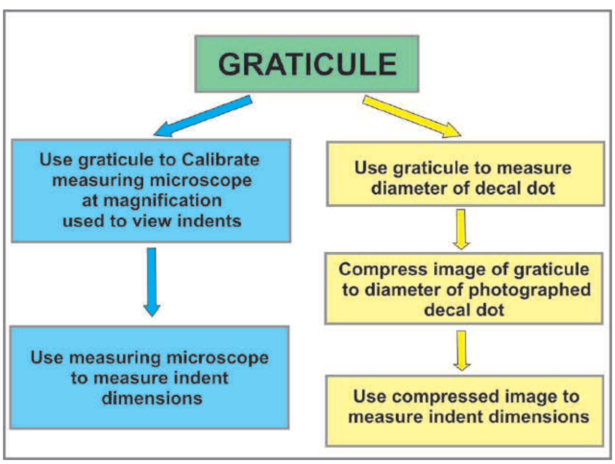

Fig.10 Indent dimension measurement - either directly or indirectly.

Measuring Microscope

The use of a microscope equipped with a measuring eyepiece is well-established and well-documented. Essentially the scale of the measuring microscope is calibrated against a graticule. The scale, calibrated at the magnification to be used for indent examination, can then be used for direct indent dimension measurement. This method is probably the most accurate and reliable of the several available techniques. Its major drawback is a lack of portability so that it has limited application for on-site examination of large components.

USB Microscope

USB microscopes have evolved to a stage where they are sufficiently accurate for indent measurements. When attached to a 'universal clamp', they can easily be focused on peened areas of actual components. A significant problem, however, is posed by the necessary calibration procedure. One solution, employed by the author, is illustrated by fig. 11.

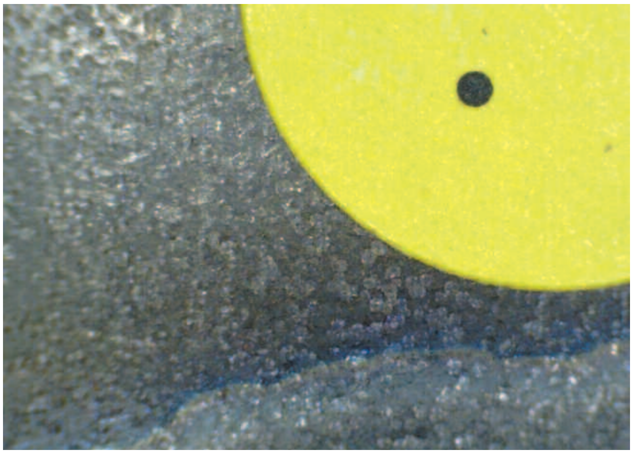

Fig.11 Decal black dot on self-adhesive yellow label stuck to peened component.

Decal black dots (from a dry-lettering range) are manufactured with a high degree of precision. Their diameters can be pre-checked using a graticule and a measuring microscope. One or more dots are rubbed onto a self-adhesive label which is then placed adjacent to the peened area to be photographed. Having selected an appropriate magnification, the dot and peened surface are then photographed - either concurrently or consecutively. The decal dot diameter of fig.11 is 0.450 mm (established using the measuring microscope method). This known diameter is then used as an 'on-screen' reference when examining images on a computer screen. One technique is to compress an image of a 0 - 100 graticule until it is the same length as the diameter of the photographed decal dot. This compressed image is then moved over an indent to effect measurement.

SUMMARY

The diameter, d, of the indent produced by a shot particle can be predicted using equation (3) and hence its area ($\pi d^2/4$). Indent depth can be predicted by using equation (1). These predictions require a knowledge of several shot peening parameters. Shot velocity is not commonly measured directly but can be predicted, for either air-blast or wheel-blast systems, using equations presented previously (TSP volume 21, Nos. 1 and 2, 2007). Observed indent size changes can be related to changes in either operating conditions or component properties.

Indent depth is directly related to the peening intensity that is being used - for a given shot size. There is a current belief that peening intensity depends only on the diameter of indents induced in Almen strips and is independent of the shot diameter being used. For any given indent diameter its depth decreases rapidly with increase of shot diameter - as shown by equation (1). This raises fundamental questions about corresponding depths of plastic deformation. There is an urgent need for experimental verification of the stated belief.

Average indent area, **A**, is one of the three factors that govern coverage, **C**. The others are the rate of indenting, **R**, (number of indents per unit area per unit time) and time of peening, **t**. Equation (5) gives the established connection between the three parameters.

$$C = 100(1 - \exp(-A.R.t)) \qquad (5)$$

It follows that average indent diameter is a prime controlling coverage. Computer programs have been produced that allow predictions to be made of both coverage and indent diameter. One example was presented at ICSP6 by Lombardo. All such programs (and the equations presented in this article) are, however, based on modeling of the peening process. This means that, however useful they may be, they cannot be guaranteed to be precise. ●