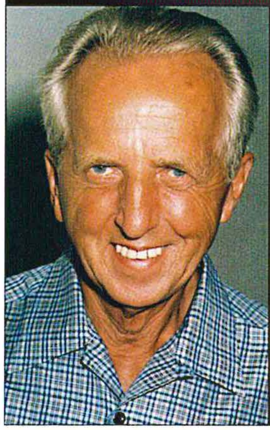

Effects of Varying Shot Impact Angle

by Dr. David Kirk, Coventry University, U.K.

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 and still supervises their Shot Peening and X-ray Stress Analysis facilities. He is currently writing a book "The Science of Shot Peening". We greatly appreciate his contribution to our publication.

INTRODUCTION

It is commonly assumed that Almen saturation intensity, I_θ, varies directly as the sine of the shot impact angle, θ. Hence, $I_\theta = I_{90}.\sin\theta^{1.0}$ where I_{90} is the intensity for 90° impacting. Some specifications therefore preclude the use of low impact angles. A second common assumption is that Almen saturation intensity is directly proportional to the depth of the indents being produced by the impacting shot particles. This paper examines the validity of those two closely-related topics. It is shown that both depth and intensity vary as $\sin\theta^{1.5}$ - rather than as simply $\sin\theta^{1.0}$.

Shot must always impact at some angle to a component's surface. Very rarely will that angle be 90°. The impact angle will depend on a number of factors including: normal spread from air-blast nozzles or centrifugal wheels and inclination of the surface to the mean direction of the shot stream. Occasionally the shot will impact over the full range of from 0 to 90°, as in fig.1.

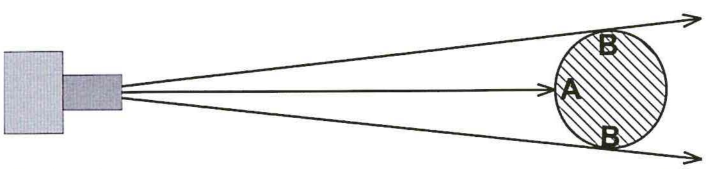

Fig.1 Rod component receiving 90° impacts at A and 0° impacts at B.

Every impacting shot particle has a kinetic energy, E, where $E = \frac{1}{2}mv^2$, m is mass and v is velocity of the particle. Part of that kinetic energy is lost on impact and part is retained as the particle rebounds from the component surface. The proportion of energy lost varies between 0 and 1. Zero loss of energy is equivalent to a 'perfect bouncing ball', which rebounds to the same height as that from which it is dropped. Unit loss of energy is the complete loss of kinetic energy that occurs when the ball does not rebound at all – for example, a steel ball dropped onto a soft clay block. Some of the lost energy in peening is used to produce a permanent indent and some is used elastically and translated into heat. The greater the loss of kinetic energy the greater is the volume, V, of the permanent surface indent produced by a particular shot particle.

PERPENDICULAR IMPACT

With perpendicular impact, a circular indent will be produced by a spherical impacting shot particle. This has a volume, V, where $V = \pi \cdot d^4/32D$ (to a first approximation), d being the indent diameter and D the particle diameter. Now V = W/B, where W is the work done by the indenting shot particle and B is the work that has to be done to create each unit of volume of indent. The work done by the indenting particle is given by $W = (1 - e^2).E$, where e is the coefficient of restitution.

Combining the foregoing relationships gives that $d^4 = \frac{1}{2}mv^2.32D(1 - e^2)/\pi.B$. For a given combination of shot and component material we can assume that m, D, e and B are effectively constant. Hence we then have that:

$$\mathbf{d = v^{0.5}.K} \qquad (1)$$

where K is a constant, $(16mD(1 - e^2)/\pi.B)^{0.25}$

The relationship between indent diameter, d, ball diameter, D, and indent depth, h, is that $h = d^2/4D$ (again to a first approximation). Substituting for d in equation (1) gives that:

$$\mathbf{h = v.C}$$

where C is a constant, $(m(1 - e^2)/\pi.D.B)^{0.5}$ (2)

Equations (1) and (2) show that the diameter and depth of an indentation are directly proportional to the square root and velocity of the particle respectively (for a given combination of shot size and material hardness). Hence, for example, if we double the shot velocity we will double the indent depth but only increase the indent diameter by a factor of $\sqrt{2}$.

OBLIQUE IMPACT

The mechanics of indent formation with oblique impact are much more complicated than those for perpendicular impact – to say the least! The particle velocity relative to the surface is no longer that of the particle itself, indents are no longer circular in outline, and the proportion of energy lost, $1 - e^2$, is not constant. In effect we have three variables, which we can term relative velocity, shape and restitution factors.

Relative velocity factor

We can represent the velocity and direction of a shot particle as a vector quantity (a vector is something that has both magnitude and direction). Shot velocity can then be resolved into vector components, perpendicular to and parallel to the impacting surface, see fig.2. θ is the angle between the shot direction and the component surface. The velocity vector perpendicular to the surface is shown as v_N and the velocity vector parallel to the surface as v_P. The relationship between the three vectors is known as a 'vector diagram'. v_N and v_P are given by:

$$\mathbf{v_N = v \cdot \sin\theta} \text{ and} \qquad (3)$$

$$\mathbf{v_P = v \cdot \cos\theta} \qquad (4)$$

Shape factor

On impact, the energy vector associated with v_N pushes the shot particle <u>into</u> the surface whereas the energy vector associated

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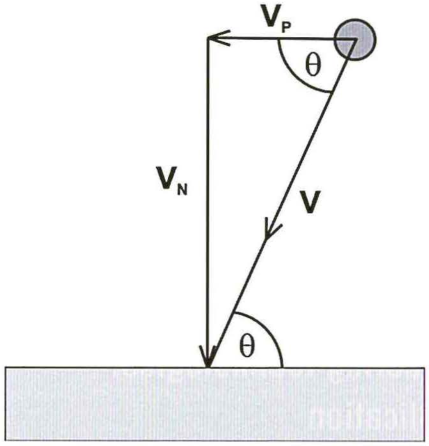

$v_N = v{\cdot}\sin\theta$ and
$v_P = v{\cdot}\cos\theta$

Fig.2 Resolution of shot velocity, v, perpendicular to and parallel to the component surface.

with v_P pushes the shot particle along the surface. When θ does not equal ninety degrees the indentation will therefore resemble an ellipse, as shown in fig.3. The shot particle involved traveled from right to left relative to the sample surface. A perfect ellipse, having 'semi-axes' of a and b, has been superimposed to show the indent outline. The 'shadow' to the left of the indent is caused by massive compressive plastic deformation of the coarse-grained aluminum specimen.

Although the outline produced by oblique impact is elliptical, the indent itself is not ellipsoidal. That is because the cross-section of the indent is circular and not elliptical. The nearest geometrical description is that of a 'stretched spherical cap' where the degree of stretching is a/b. The approximate volumes of a spherical cap of radius r and a stretched spherical cap are given by $\frac{1}{2}\pi r^2 h_{90}$ and $\frac{1}{2}\pi ab h_\theta$ respectively. For a given volume of indent, the depth ratio $h_\theta/h_{90} = r^2/ab$. h_θ/h_{90} is also equal to b^2/r^2. Combining the two expressions for depth ratio gives that:

$$h_\theta/h_{90} = (b/a)^{0.5} \quad (5)$$

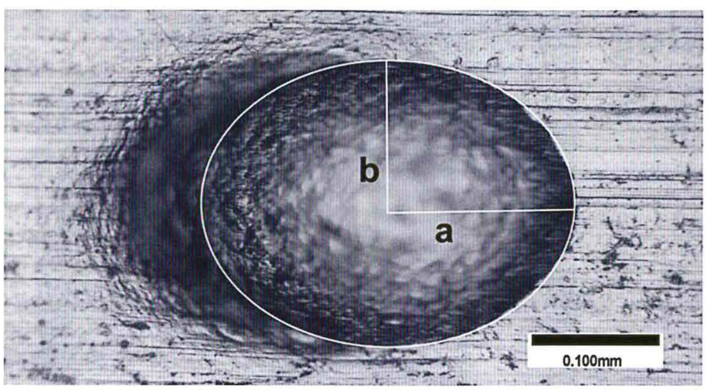

Fig.3 Elliptical indent in aluminum impacted at θ = 30° by an S170 particle.

The sequential positions of a shot particle impacting into the component surface at an angle θ are indicated in fig.4. A path ABC is the locus of the particle center travel.

The non-concentric circles represent successive positions of the moving shot particle that is striking at an angle, θ, to the component surface. When the particle is at the position represented by the grayed circle, massive deformation is occurring in the region marked H. That results in the metallographic feature noted in fig.3.

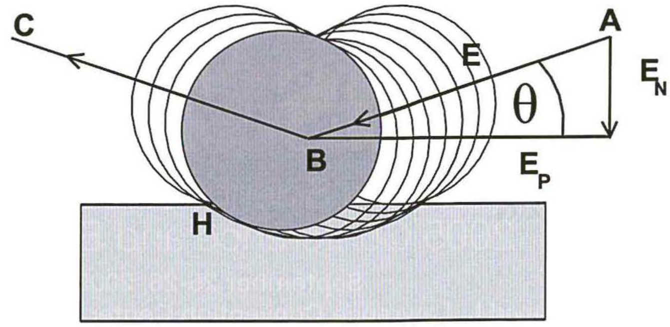

Fig.4 Schematic representation of shot particle movement.

Restitution factor

This is a relatively esoteric factor. Energy transfer is partially plastic and partially elastic. It is the plastic energy transfer component that creates the permanent indentation. With reduction of impact angle the plastic component proportion decreases. The effect of this decrease is to reduce the volume of the indentation.

EXPERIMENTAL STUDIES

The simplest way to study the effect of impact angle on indent shape and depth is to drop ball bearings from known heights onto inclined flat specimens. Fig.5 summarizes measurements involving steel ball bearings dropped from a fixed height onto aluminum strip specimens. Indent diameters were measured using a measuring microscope and converted into depths using the intersecting chord theorem. Surface probe measurements on selected indents confirmed the efficacy of the conversion. Comparisons of indent axes indicated that the reverse ellipticity (b/a) was, to close approximation, a $\sin\theta^{0.3}$ function.

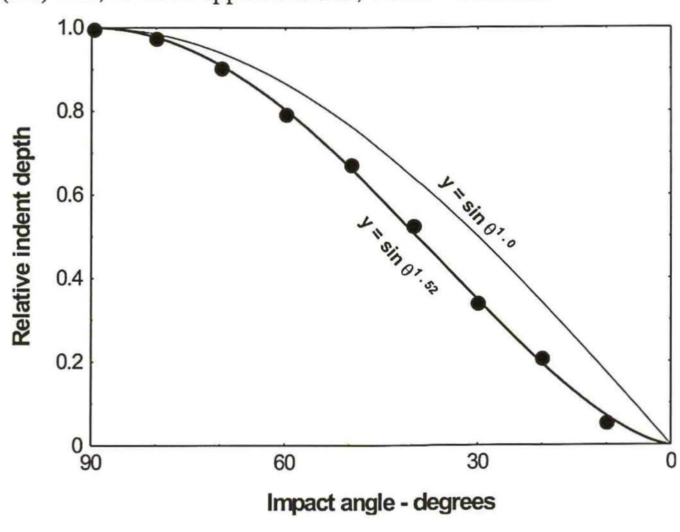

Fig.5 Effect of impact angle on indent depth.

The measurements shown in fig.5 indicate that the indent depth/impact angle variation differs significantly from a simple $\sin\theta^{1.0}$ relationship. The best-fitting curve is a $\sin\theta^{1.52}$ function.

Fig.6 illustrates the experimental arrangement employed for obtaining Almen saturation values as a function of impact angle. This arrangement included a sliding gate to regulate exposure times, a fixed gun-to-strip distance, D, of 332mm and an Almen strip holder rotatable about an axis at R. Fig.7 shows the relative Almen saturation values obtained using N strips and S110 cast steel shot.

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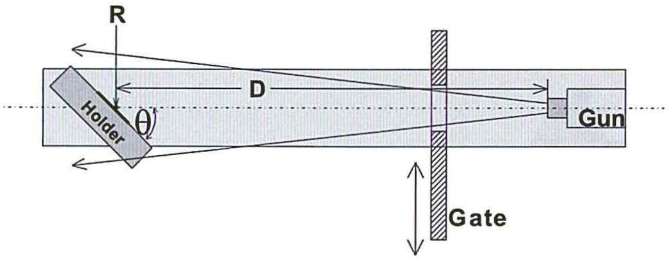

Fig.6 Schematic representation of Almen strip holder rotated to angle, θ, about point R.

The best-fitting curve is a $\sin\theta^{1.49}$ function, shown together with a simple sine curve.

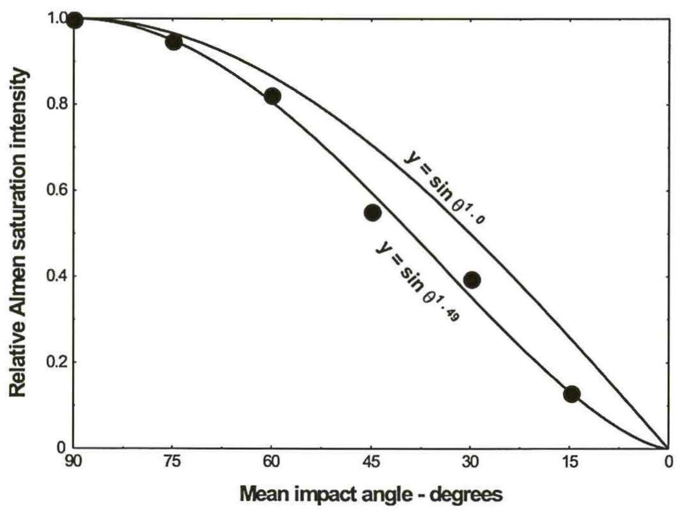

Fig.7 Effect of mean impact angle on Almen saturation intensity, N strips, S110 shot.

DISCUSSION

Impact angle has been shown to have a significant effect on indent depth, indent shape and Almen saturation intensity. Both indent depth and Almen saturation intensity have been found to obey a function close to $\sin\theta^{1.5}$. Most of the 'power term' 1·5 comes from the velocity resolution effect with the remainder being contributed by ellipticity and restitution factors. The existence of a direct correlation between indent depth and Almen saturation intensity has been confirmed. That correlation arises because the bending moment imposed by peening clamped strips is directly proportional to the depth of deformation in the peened surface layer. That depth is, in turn, directly proportional to the depth of indentations.

Fig.7 illustrates the several differences between predictions based on a $\sin\theta^{1.0}$ function as compared with a $\sin\theta^{1.5}$ function. At high impact angles the two functions have very similar values.Differences increase with decrease in impact angle. When $\theta = 30°$ then $\sin\theta^{1.0}$ has a value of 0.5 – implying that we can achieve 50% of the saturation intensity that we achieve with perpendicular impacting. $\sin 30^{1.5}$, on the other hand, has a value of 0.35 implying only 35%. At a very shallow impact angle, 5°, the predicted values are 9 and 3% respectively. This research confirms that specification requirements for a minimum impact angle are justified.

The observed similarity of indent depth and Almen saturation intensity functions confirms that they are directly connected. Indent diameter is easier to measure than indent depth but diameter/depth conversion is simple for reasonably spherical shot particles. Faced with having to use a particular combination of shot type and size, our primary intensity control is by means of shot velocity. The 'constant' in equation (2) gives a guide as to the effects of other shot parameters. The shape and size of indentations will, of course, change during practical peening as indentations overlap one another and work-hardening occurs. That does not invalidate the conclusions - practical peening conditions were employed for the experimental work on Almen saturation intensity variation.